HENRY ROYCE INSTITUTE

ADVANCED MATERIALS RESEARCH & INNOVATION

A National Framework for Materials 4.0

Interim Report for Consultation

December 2025

Foreword

The publication of this Interim National Framework for Materials 4.0 marks an important moment for the UK materials community. For the first time, we have set out the path to a shared national language, structure and ambition for a digitally enabled materials ecosystem that has the potential to transform how we discover, design, manufacture, deploy and eventually recycle the materials that underpin our economy and our society.

Materials innovation is entering a period of profound change with advances in AI, high-performance computing, sensing, inspection/characterisation, data infrastructure and modelling converging to reshape scientific methods. "Materials 4.0" is of course a core cross-cutting theme of the National Materials Innovation Strategy, and it offers us the exciting opportunity to accelerate discovery, reduce development and scale up costs, optimise our use of resources and their sustainability. It ultimately helps us to strengthen national resilience in an era where sustainability, robust supply chains and competitiveness are inseparable.

This new Framework is the product of detailed engagement – including interviews, a national review of current activity and a rigorous international benchmarking exercise. It represents not just analysis, but a collective commitment from stakeholders across research, industry and government to work together toward a new materials "paradigm". By organising Materials 4.0 into lifecycle-oriented materials processes and the digital capabilities that connect them, the framework provides a flexible foundation that crosses diverse sectors.

This work aligns strongly with the UK Government's recent AI for Science strategy, reinforcing a shared national trajectory toward standardised, AI-ready data and a world-class digital research infrastructure.

We must also acknowledge the challenges. While the UK has hosted a remarkable 5,928 Materials 4.0-relevant projects since 2005, critical enablers such as materials data standards, ontologies and interoperable infrastructure remain underdeveloped. Addressing these gaps is now essential. Our next phase of work will therefore focus on defining practical data standards, building cross-sector interoperability and delivering demonstrator projects that validate the framework within an industry context.

Royce was established to bring together the UK's materials research strengths, and this framework exemplifies that mission. However, its success ultimately depends on the commitment of the wider community, and I therefore invite researchers, industrial partners, professional bodies and policymakers to engage actively with this work.

I would like to extend my sincere thanks to the Institute for Manufacturing, Perspective Economics, Frazer Nash and Urban Foresight for their expert convening, analysis and insight. Their contributions have been invaluable in bringing this ambitious National Framework to life.

Professor David Knowles FREng, FIMMM,
CEO, Henry Royce Institute

Executive Summary

This interim report presents a preliminary outline of a Materials 4.0 framework for review and future development, drawing on evidence from in-depth interviews with strategic stakeholders, a detailed review of existing Materials 4.0 research and innovation activity in the UK, and a comprehensive international benchmarking exercise.

Introduction to Materials 4.0

Materials 4.0 was identified in Royce's National Materials Innovation Strategy as a core cross-cutting theme across all sectors. The strategy defined it as 'an umbrella term for the ongoing transition to a digitally enabled materials sector. This will be underpinned by a materials informatics framework that combines capabilities in materials modelling, large data, AI and machine learning, in silico modelling, manufacturing informatics, and life-cycle simulation'.

Materials 4.0 promotes seamless data flows - supported by appropriate infrastructure, algorithms and digital tools - across different parts of the materials value chain. This has the potential to generate economic value and national resilience by accelerating the adoption of material innovations, reducing reliance on scarce raw materials, promoting cleaner manufacturing with less waste, and reducing environmental impact by supporting a circular economy.

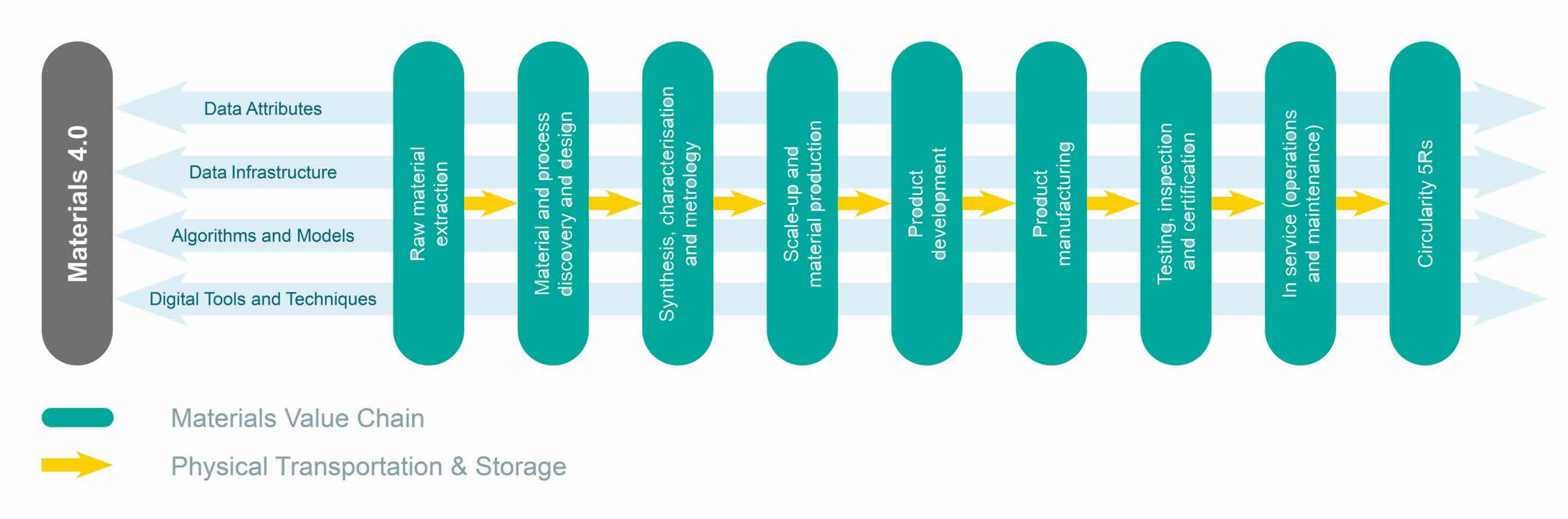
This framework

This study has found that while the benefits and potential of Materials 4.0 are widely recognised, they are yet to be quantified under a common definition. This framework provides guidance on strategic Materials 4.0 planning, project development and research and investment activities through a common definition, scope and language. It is built around two key components:

1. **Materials processes:** The steps taken in a material's lifecycle to derive value from it and where data and digital processes can be applied. These are represented in the framework by vertical discrete elements in a generic supply chain through which materials are transported physically.
2. **Digital elements:** The data and digital ecosystem that wrap around and enable these processes. These are horizontal cross-cutting processes and activities with unifying/common methods and language which flow throughout the vertical material value chain elements.

Although different materials journeys will take various routes through the value chain and combine different digital elements, the framework is adaptable to this.

The Materials 4.0 Framework



The potential

The UK is the right place to be developing this technology, as there is already the desire and nascent innovation activity across the country in Materials 4.0, totalling 5,928 projects since 2005. Coordination of these innovation and implementation projects could unlock latent potential in the use case examples and other Materials 4.0 applications.

The recently published AI for Science strategy from UK Government (DSIT) aligns with this framework, by also calling for standardised, AI-ready data, investment in infrastructure, and the development of high-value demonstrator datasets. Digital materials science and technology activities are emphasised within this as a priority area.

To highlight the opportunity Materials 4.0 offers alongside the potential benefits derived, five high-potential and strategically valuable use cases have been identified as exemplars to illustrate and test the framework's development:

- Composite materials for wind turbine blades
- Battery materials
- Sustainable packaging
- Functional polymers for coatings and paints
- Steels for nuclear applications

Next steps

Most of the current Materials 4.0 activity in the UK appears to be focused on two main areas: the development of algorithms and models, and digital tools and techniques – particularly in material discovery and design.

In contrast, key enablers to support translation and common pathways – the data ontology, attributes and infrastructure elements of the framework – are underrepresented in development. There are two main opportunities therefore for the UK moving forward:

- Focussing on developing and establishing practical data ontology, attributes and infrastructure elements – balancing out the investment already being made in tools and processes by industry and researchers.
- Encouraging cross-sectoral learning on Materials 4.0 between sectors and materials classes, again, balancing the current uneven distribution of focus.

In the following stage of this framework's development, a roadmap defining the pathways to implementation will be developed, alongside the delivery of demonstrator projects and further definition of the data attributes and infrastructure.

Royce welcomes contributions and insight into the implementation of this high-level Materials 4.0 Framework from active stakeholders across industry, academia and policy.

Our next stage will focus on the data attributes and some exemplars. If you wish to connect your activity into these developments, then please contact Royce by emailing info@royce.ac.uk.

Contents

Introduction to Materials 4.0

Materials 4.0 is the digital backbone of materials innovation. The structured and comprehensive introduction of Materials 4.0 tools and practices has the potential to accelerate and transform materials innovation in the UK and globally.

This interim report presents a preliminary outline of a Materials 4.0 framework for review and future development, alongside a landscape assessment of Materials 4.0 in the UK. This Materials 4.0 framework highlights how data attributes, data infrastructure, algorithms and models, and digital tools and techniques operate and interact throughout the materials value chain. The framework has been developed through a mixed-methods approach employing both quantitative (e.g. literature reviews, text analytics, web-scraping etc.) and qualitative strategies (e.g. interviews, workshops etc.) for data collection and analysis[1].

The framework is intended to provide the basis for further investment in a high-potential technology capability that the UK could lead global efforts in.

Definition of Materials 4.0

The launch of Royce's National Materials Innovation Strategy (NMIS)[2] in the UK highlighted the importance of accelerating innovation in materials for protecting the UK's position in the global science and technology landscape and capturing significant socioeconomic benefits.

Materials 4.0 emerged as a core cross-cutting theme across all sectors (Figure 1). The strategy defined Materials 4.0 as *'an umbrella term for the ongoing transition to a digitally enabled materials sector. This will be underpinned by a materials informatics framework that combines capabilities in materials modelling, large data, AI and machine learning, in silico modelling, manufacturing informatics, and life-cycle simulation'*.

Figure 1. The NMIS implementation plan, which defines Materials 4.0 as a priority cross-cutting theme that will interact with all other innovation workstreams and themes.

[1] Further details of the methods employed are given in Appendix 1 and a bibliography of sources given in Appendix 2.
[2] https://www.royce.ac.uk/wp-content/uploads/2025/05/Royce_NMIS_booklet-digital_FINAL-SINGLE.pdf

The case for Materials 4.0

Materials 4.0 has the potential to generate economic value by directly enhancing the speed, quality, and sustainability of materials development at every stage of the materials value chain. Seamless data flows across the different elements of the materials value chain can provide valuable knowledge and lead to long-term competitive advantage.

Limited data is available regarding the specific economic impact of Materials 4.0 in the UK. However, analyses in other jurisdictions, and of related concepts such as Manufacturing 4.0, point to significant opportunities for achieving economic value added from Materials 4.0 investments.

For example, a 2013 report by the National Institute of Standards and Technology in the US suggested that an improved materials innovation infrastructure to support the Materials Genome Initiative (MGI) could generate between $123bn and $270bn in economic impact annually, through a combination of reduced R&D project attrition, a 35% acceleration in getting R&D projects to market, and a 71% improvement in R&D efficiency[3].

For the UK to fully benefit from Materials 4.0 and build upon its strengths in materials science, advanced manufacturing, and digital engineering, a coherent and actionable national framework is required. This will provide the structure needed to embed Materials 4.0 capabilities into the UK's materials innovation ecosystem.

A detailed assessment of the rationale and potential impact of Materials 4.0 in the UK is given in Appendix 5.

This Materials 4.0 Framework

The purpose of this framework is to provide the basis for the widespread development and adoption of Materials 4.0 in the materials innovation ecosystem and industrial supply chain in the UK. It defines the common structures, practices and languages of Materials 4.0.

Demand for Materials 4.0 research and innovation has been increasing steadily in recent years. Since 2015, the total number of Materials 4.0 related research and innovation projects funded has more than trebled[4], and the total value of Materials 4.0 research and innovation projects has increased more than fivefold[5]. However, while demand for Materials 4.0 research and innovation is increasing, it is not currently well co-ordinated, or effectively focussed across Materials 4.0 elements, sectors or use cases.

[3] Based on interviews with 100 experts spanning research, development, innovation and manufacturing. https://www.nist.gov/system/files/documents/2020/02/06/MGI%20Final%20Report.pdf
[4] By 212% overall, and by an average of 15% year on year.
[5] By 419% overall, and by an average of 45% year on year.

Materials 4.0 can be used to enable intra- and inter-organisation and sector collaboration and alignment. For example, it could be used to provide the foundation for AI-aided materials discovery and performance optimisation by:

- → Developing appropriate robotic platforms that can rapidly synthesise new material structures.
- → Integrating with sensors to optimise efficient materials process control, manufacture and in-service performance.
- → Promoting smart sensing and in-situ monitoring to add valuable data into a digital material passport.
- → Using smart sorting using sensors and spectral signatures to ensure efficient material recycling.

The outline of this Materials 4.0 framework established within this document provides a starting point to help to identify, coordinate and align the various activities and investments associated with Materials 4.0. When finalised it will allow focus on important opportunities, foster collaboration across sectors and realise the tangible benefits of the UK's significant materials innovation ecosystem and industrial supply chain.

As a strategic and pervasive tool, it has been developed in collaboration with industry, academic researchers, and other key innovation actors – providing decision-makers with a direct representation of the needs of the sector.

Scope of the framework

The framework scope is designed to have the flexibility to:

- → Be adaptable to different material types, from (e.g.) functional polymers through composites to foundational steels.
- → Cover all stages of the materials value chain, from materials design through manufacture to recycling and disposal.
- → Work with all types of materials data, from experimental data in materials discovery including characterisation and testing through to operational data from in-situ analysis.
- → Cover the range of technologies needed to enable Materials 4.0.

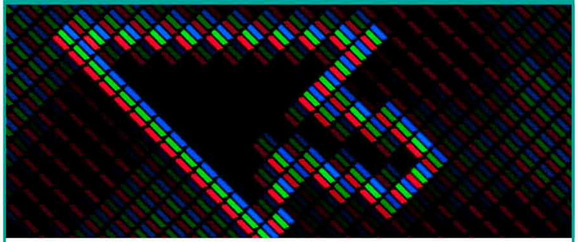
This recognises the wide variety of needs the materials community has and the potential benefits of exploiting data and digital processes and tools for improved performance.

The overarching framework is presented in Figure 2. It is constructed from two key components:

Materials Processes

The steps taken in a materials lifecycle to derive value from it, and where data and digital processes can be applied. These are represented in the framework by vertical discrete elements through which materials are physically transported. The vertical elements of the framework are defined in Table 1, alongside examples of how Materials 4.0 can benefit each value chain element.

Digital Elements



The data and digital ecosystem that wrap around and enable these processes. These are horizontal cross-cutting processes and activities which flow throughout the vertical material value chain elements. These elements are presented in Table 2 to provide a common reference point.

The framework guides actions by providing a common definition, scope and language of Materials 4.0. Although different materials journeys will take various routes through the value chain and combine different digital elements, the framework is adaptable to this. This means that the scope of the activities adopted can be adjusted to specific sectors, projects and desired Materials 4.0 outcomes (from guiding overall national level planning for areas of focus to supporting discrete projects by providing a template for key considerations). The digital elements will ensure only the essential and necessary data is passed between the different organisations, which constitute the materials value chain.

The outline framework demonstrates how these could be pulled together into an integrated manner for Materials 4.0.

There is of course a human layer to the use of Materials 4.0, in terms of the skills and culture required to implement it. Whilst this framework defines the technical elements of Materials 4.0, its implementation will require consideration for this lens.

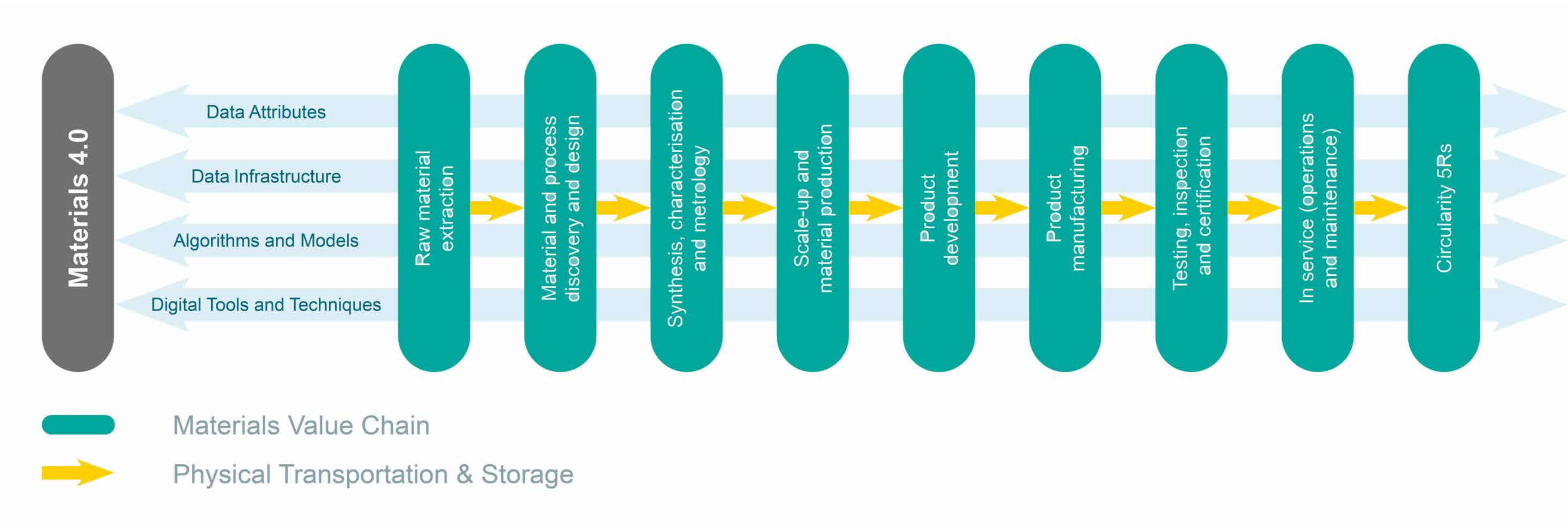


Figure 2: Materials 4.0 across the processes in the materials value chain.

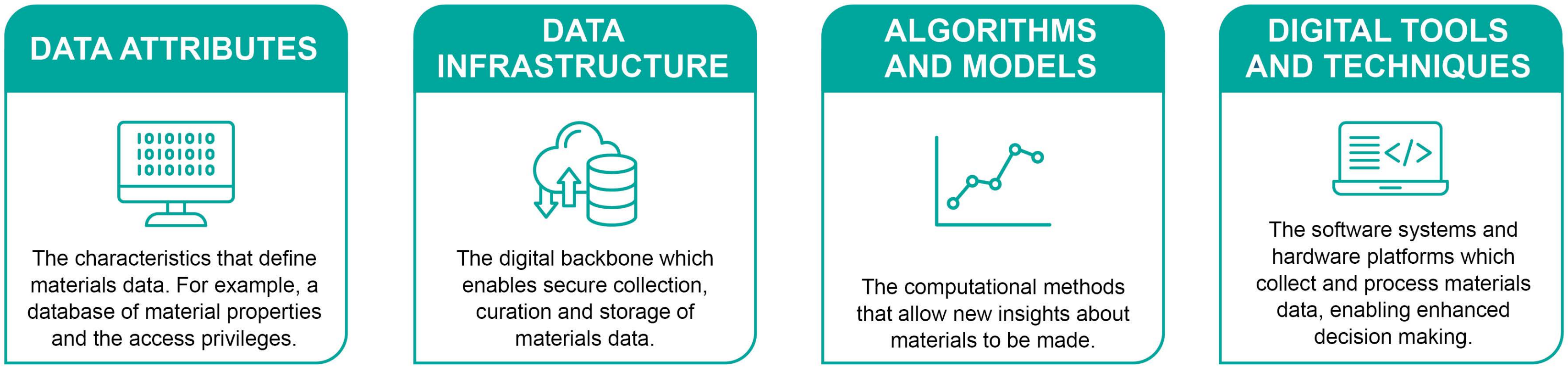


Figure 3: The digital elements of the Materials 4.0 framework.

Table 1: Definitions of the vertical value chain elements of the Materials 4.0 Framework with examples of their application and benefits (suggested by Royce's Materials 4.0 Steering Group).

Framework Element	Definition	Example
Raw material extraction	The activities and processes needed to extract crude, unprocessed materials from the environment for use as feedstock for a processing operation.	**Material/application**: Rare Earth Magnets **Industry challenge**: Limited access to or having to import raw materials. **Materials 4.0 solution**: Material Digital Passports of constitute raw materials and treatments will allow for optimisation of recycling processes and for improved material re-use. **Benefit**: Strategic materials supply chain. National resilience, industrial growth & innovation.
Material and process discovery and design	The activities involved in: → The search for new materials and their subsequent simulation, optimisation and testing that can be pursued experimentally or computationally. → The novel processing and manufacture of existing materials and materials systems.	**Material/application**: Materials substitution (for all sorts of industries) **Industry challenge**: Limited access to critical raw materials. Increasing demand (consumer and policy) for sustainable and biodegradable material alternatives. **Materials 4.0 solution**: Use AI/data-driven materials discovery to realise materials substitution (i.e. avoid the need for the critical raw material in question by finding another material that works just as well in the application at hand). This could include unsupervised learning algorithms, which are potentially suitable for uncovering patterns between material chemistry and performance characteristics. **Benefit**: National resilience, industrial growth & innovation
Synthesis, characterisation and metrology	The process of converting one molecule into another, for the creation or fabrication of a target material, which can be achieved via single or multi-step operations. Characterisation refers to the measurement and analysis of a material, describing its composition, structure and properties to allow its identification and use. Metrology is concerned with the need to measure the properties of materials with greater precision and accuracy.	**Material/application**: Synthesis and characterisation of polymers **Industry challenge**: Design of polymers with end-of-life functionality and sustainability is critical. **Materials 4.0 solution**: Digital/in silico design and testing of polymer functionality prior to experimental testing and manufacture. **Benefit**: Cost reductions in materials synthesis and reduced time to market of new sustainable polymers.
Scale-up and material production	The process of adapting a laboratory protocol and deploying it to industrial production scale by extending volumes in individual process steps, setting up mini plants and pilot plants.	**Material/application**: All **Industry challenge**: Modelling across multiple different length scales is difficult. Knowing what information is parsed & what can be disposed of is a challenge. It can be difficult to translate models from an academic context into something that's useable within industry. **Materials 4.0 solution**: Use of multi-scale modelling to inform location-specific material properties for high integrity components utilising thermodynamic/kinetics-based predictions, material processing simulations through to structural integrity assessments and end-of-life predictions. Creation of a modular simulation framework & workflow loops to run optimisation/design of experiments and simulations.

Framework Element	Definition	Example
		Benefit: Increase current technical knowledge and understanding. Improve the development path from concept to design and manufacture enabling 'right first time' development.
Product development	The process of identifying user needs and devising how the material can be employed to deliver real-world products or systems, taking into account functional performance requirements, manufacturability, sustainability and integration with other systems.	**Material/application**: Caloric energy-harvesting materials **Industry challenge:** Slow product development based on trial-and-error R&D as caloric materials are highly sensitive to composition, microstructure, and processing history. **Materials 4.0 solution:** Combine multiscale modelling, with simulation of processing routes to explore composition-processing-performance relationships. **Benefit**: Accelerated discovery of optimal caloric materials with reduced prototyping cycles, and lower R&D costs.
Product manufacturing	The transformation of materials into value-added products (and services) by means of multiple materials processing, assembly operations and packaging steps, as well as in-process testing and inspection for quality control.	**Material/application**: Battery manufacturing **Industry challenge**: Battery cell production is complex involving hundreds of precise steps. Tiny inconsistencies in particle distribution, coating thickness, or moisture lead to performance variation or safety risks. **Materials 4.0 solution**: AI-based vision systems for real-time defect detection (e.g., coating uniformity, electrode cracks). **Benefit**: Safer and greener manufacturing processes with less waste.
Testing, inspection and certification	Interlinked processes carried out to ensure that the materials and products are produced in accordance with standardised performance (and other relevant) requirements. Upon satisfactory testing and inspection, the product, material, or manufacturer may be awarded a certificate attesting that it adheres to relevant third-party rules or national or international regulations.	**Material/application**: Building the safety case for a novel, high-risk product (e.g. medical devices, nuclear energy componentry, aerospace, the built environment) **Industry challenge**: Collating the required material data (and proving it) is labour-intensive and time consuming. This is often the case in industries with long time-to-market and therefore a lower appetite for risk in investing in innovative solutions and a resistance to change. **Materials 4.0 solution**: Accurate, reliable material data from the supply chain and/or other regulated products, available in the format required to develop the evidence for a safety-critical application. Integration of this data with rapid digital analysis and integration of in-situ inspection data to provide an up-to-date view on material state. **Benefit**: Accelerated regulatory pathways.
In service (operations and maintenance)	The activities and processes carried out during regular operation of the product/material in its usual operating environment to ensure that the design intent and predicted material behaviour hold true. Maintenance activities are those aimed at extending the product/material lifetime and reducing the frequency of service interruptions, which can	**Material/application**: Surface degradation of coated steel **Industry challenge**: Materials are taken out of use earlier than may be necessary to manage risk. **Materials 4.0 solution**: In-use monitoring and real-time analysis of data for in-use monitoring (and repair). **Benefit**: Longer in-use life of materials.

Framework Element	Definition	Example
	be reactive (taken after service failure), preventive (following a pre-defined schedule), and predictive (as needed).	
Circularity 5Rs	The activities and processes carried out to ensure that the products/materials align with the broader context of waste reduction, thereby improving resource utilisation within the system and regenerating natural systems. The 5Rs are Rethink (rethinking approaches to waste and habits), Refuse (refusing waste generation), Reduce (reducing resource consumption and waste generation), Reuse (reusing products or components for original or alternative purposes) and Recycle (recycling waste to transform it into new products/materials).	**Material/application:** Construction 5Rs **Industry challenge:** Understanding the source, use, impurities, and length of service of materials in the built environment. **Materials 4.0 solution:** Materials identity (specific data from across the supply chain). **Benefit:** Enables circularity and adds value (e.g. value of buildings can be more than land and value of building during life – the post-life/circularity value can be significant but only if the materials identities are available).
Transportation and storage	The activities carried out to physically move and store materials and products across the various steps of the value chain.	**Material/application**: Protected and high-value material provenance **Industry challenge**: Tracing the supply chain of rare and valuable materials. **Materials 4.0 solution**: Shared records of the material's provenance, using distributed ledger technology. **Benefit**: Increased supply chain trust and transparency, including in sectors where fraudulent activity is a risk. Benefits relating to climate and conservation, e.g. in reducing polluting mining processes.

Table 2: Definitions of the digital elements of the Materials 4.0 Framework.

Framework Element	Definition	Consists of	Example
Data Attributes	The descriptive and governance characteristics that define material data and its context throughout the materials value chain. The data attributes capture what the data represents, how it is structured, and how it can be accessed, shared, and trusted. They include organisation through an interoperable ontology, compliance with FAIR[6] principles, and supporting metadata for provenance and traceability.	**Data ontology:** A vocabulary that defines the terms, definitions, and relationships for material entities, processes, and properties within an interoperable digital ecosystem. It contains: → **Entities:** specific objects within the materials ecosystem to track. → **Relationships:** links between entities and attributes. → **Metadata:** contextual details, provenance, and versioning. A singular instance of the ontology applied to a discrete material becomes its Digital Material Passport[7]. → Overall compliance with FAIR principles. → Data ownership, security, access, sharing and governance structures. → Data value, quantity, quality, trust and traceability.	**Material/application**: All **Industry challenge**: Supply chains use an array of executive systems to store, analyse, report etc materials/manufacturing data. The complex ecosystem of data moving between multiple suppliers causes a loss in data fidelity, e.g. a material test house will measure material properties and then often send those results within a report (usually in PDF format). Sometimes these results form part of a product compliance pack that could be stitched together/scanned etc before being sent to the customer. This often forces customers/higher tier suppliers to transform data, and hence material pedigree is often limiting or difficult to trace. **Materials 4.0 solution**: Creation of a cloud-based Product Lifecycle Management (PLM) system allowing suppliers/material test houses to upload data & accompanying test reports etc with similar functionality to Teamcenter (a PLM product from Siemens) with appropriate role-based access controls, so the right information is accessible by the right parties. **Benefit**: Huge time & cost savings across supply chain. Common data ontology. Highly agile.

[6] Findable, Accessible, Interoperable, Reusable.
[7] A Material Digital Passport the "identify card" for a specific physical asset or component. It should contain static and dynamic information records of the material asset.

Data Infrastructure	The digital backbone that enables secure collection, storage, curation, and sharing of material data throughout its lifecycle, operationalising the data ontology and associated attributes, including governance security and compliance. This integrated digital architecture and linking of information through all elements of the materials value chain is also known as the digital thread.	→ Structured databases and knowledge graphs. → APIs and interoperability layers. → Data pipelines for acquisition and transformation. → Cloud and edge computing architectures.	**Material/application**: Data characterisation and data across the materials value chain. **Industry challenge**: Opportunity to characterise materials in great depth, by collating, storing and making accessible the right information. **Materials 4.0 solution**: Potential for data sifting and compression to make available for future retrieval. **Benefit:** Use in future ML/AI activities, downstream performance, future material discovery (largely around knowledge retention through data).
Algorithms and Models	Computational frameworks that capture, predict, or optimise the relationships among materials' structure, processing, properties, and performance.	→ Physics-based models. → Data-driven and machine learning models. → Surrogate and hybrid models. → Optimisation algorithms. → AI Models. → Uncertainty quantification and sensitivity analysis methods.	**Material/application**: All **Industry challenge**: Legacy data is difficult to locate and difficult to transform into a useable machine-readable format. It is also highly dependent on the data governance framework at that time (noting that this seems to have improved over the past decade or so). **Materials 4.0 solution**: Development of an LLM-based model to convert legacy materials data and bring the standard in line with current data governance processes and policies. **Benefit**: Integration of legacy data into decision making in a cost-effective method.
Digital Tools and Techniques	The software systems, automated workflows, analytical platforms, and operational technologies that leverage the data infrastructure to collect, process, model, and visualise material data across its lifecycle.	→ Digital twins and simulation platforms (which embed algorithms and models). → Data management and acquisition systems. → IoT sensor networks and smart manufacturing tools. → Analytics and AI platforms. → Product lifecycle management (PLM) systems. → Dashboards and reporting interfaces.	**Material/application**: Composite materials **Industry challenge:** Design for recyclability of cross-linked thermosets & resins. **Materials 4.0 solution**: Use Robotic platforms to rapidly synthesize and test recyclable thermosets. **Benefit**: Faster discovery & lower R&D costs.

The UK Materials 4.0 landscape

A strategic framework for Materials 4.0 will advance materials innovation and accelerate translation by improving visibility of, and connection between, existing Materials 4.0 activity across the UK. Greater visibility and coordination of Materials 4.0 activity will help to better target public and private investment towards elements of Materials 4.0 activity that are expected to deliver greatest economic benefit and/or that are currently lacking investment. Further, establishing a high-level framework for Materials 4.0 activity will allow integration across the supply chain enabling innovation activity to be more intentionally designed and better positioned within the existing landscape.

As a starting point for better understanding the current Materials 4.0 landscape, the study team has analysed titles and abstracts/public descriptions relating to more than 150,000 research and innovation projects recorded within UKRI's Gateway to Research platform and Innovate UK's own project database. Key findings from this analysis are presented below and further detail is available in Appendices 4 and 5.

Research and innovation activity

Based on a multi-stage analysis that applied expert-trained machine learning models and frontier large language model capabilities, a total of 5,928 projects funded since 2005 were identified as being relevant to Materials 4.0 activity.

Overall observations

The primary observations are that:

- **There is an increasing demand for Materials 4.0 research & innovation**
  Research and innovation project data suggests that the level of interest in leveraging Materials 4.0 opportunities has been increasing steadily in recent years. Since 2015 the total number of Materials 4.0 related research and innovation projects funded has more than trebled, and the total value of Materials 4.0 research and innovation projects has increased more than fivefold.
- **The majority of Materials 4.0 projects are focussed primarily on the development of algorithms and models, and digital tools and techniques – particularly in material discovery and design**
  Projects primarily focussed on developing models and algorithms make up more than two fifths (44%) of all of the Materials 4.0 research and innovation projects identified, within which 20% of projects funded are focussed on materials and processing discovery and design. On this basis, the Materials 4.0 framework should provide a mechanism through which under-investment in certain aspects of Materials 4.0 can be redressed. By contrast, just over 5% of all projects identified focus primarily on developing data attributes and ontologies, or data infrastructure[8] (Figure 4).

[8] 5.1% if projects are allocated on the basis of their 'best-fit' Materials 4.0 category. More often than not a project will address more than a single Materials 4.0 element. Percentage increases to 5.6% if based on analysis of multiple tags per project.

Materials 4 0 Best-Fit (Grouped)	Raw material extraction	Materials & processing discovery & design	Synthesis, characterisation ..	Scale-up & material production	Product development	Product manufacturing	Testing, inspection & certification	In-service (operations & maintenan..	Circularity	Grand Total
Data Attributes & Ontologies		0.2%	1.0%	0.2%	0.1%	0.2%	0.5%	0.1%	0.3%	2.6%
Data Infrastructure	0.0%	0.6%	0.3%	0.0%	0.1%	0.3%	0.1%	0.2%	0.7%	2.5%
Algorithms & Models	0.3%	20.0%	4.2%	2.2%	5.1%	4.2%	3.0%	3.2%	1.2%	43.6%
Digital Tools & Techniques	0.1%	3.4%	6.9%	2.9%	5.5%	16.4%	6.4%	6.9%	2.9%	51.3%

Figure 4. Materials 4.0 R&I Projects by M4.0 Element and Value Chain Position

→ **By contrast, the data ontology, attributes and infrastructure elements of the framework are underrepresented in research and innovation**
Just over 5% of all projects identified focus primarily on developing data attributes and ontologies, or data infrastructure.

→ **Research and innovation activity is not evenly spread across sectors**
Just over one fifth of all Materials 4.0 related research and innovation projects are primarily focussed on the foundation industries. Nuclear and renewable energy, and aerospace each account for around one sixth of all Materials 4.0 research and innovation projects, and there are also notable proportions of research and innovation projects focussed on health, life science and medical (combined), and automotive (Figure 5).

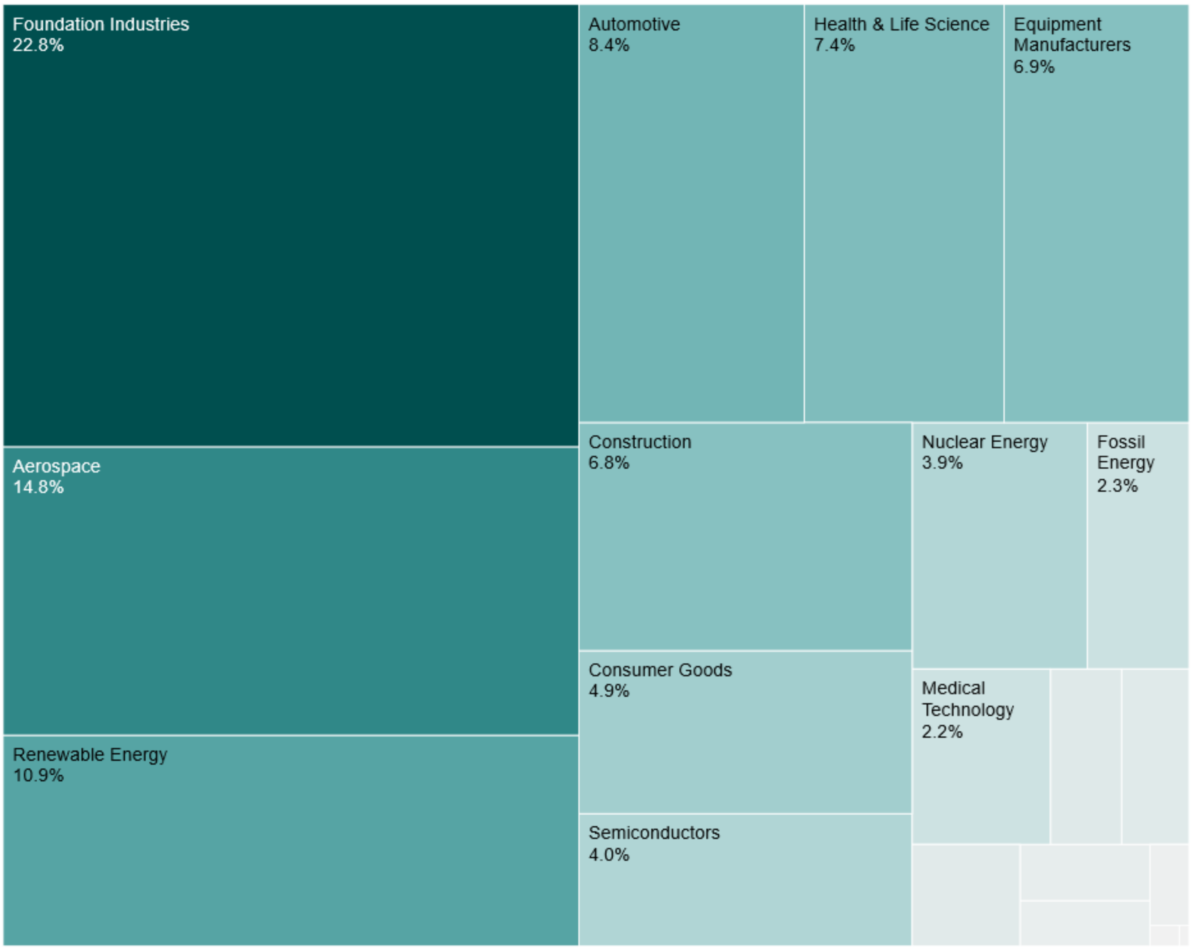


Figure 5. Materials 4.0 R&I Projects by Sector

- **Sectors are each investing in different areas of the materials value chain**
  The construction, automotive, aerospace, equipment manufacturing and fossil energy sectors have comparatively more activity within product development, manufacturing and testing/inspection, whereas foundation industries, nuclear and renewables, semiconductors, health, life science and medical technology, and communications and computing have comparatively more activity at earlier stages of the value chain (materials processing and discovery, and synthesis and characterisation). Consumer goods and construction have most circularity-related Materials 4.0 activity (Figure 6).
- **High value research and innovation initiatives are addressing multiple aspects of the Materials 4.0 framework**
  Approximately half of the top 50 highest value Materials 4.0-related research and innovation projects are addressing all four elements of the framework. These initiatives will be generating valuable knowledge and insights that may not currently be effectively shared across sectors or material types.

Materials Classes Best (group)	Raw material extraction	Materials & processing discovery & design	Synthesis, characterisation ..	Scale-up & material production	Product development	Product manufacturing	Testing, inspection & certification	In-service (operations & maintenan..	Circularity	Grand Total
Glass & Optical Materials		8.3%	16.7%		6.3%	45.8%	10.4%	10.4%	2.1%	100.0%
Textiles & Fibres	3.4%	10.3%	6.9%		10.3%	6.9%	20.7%	3.4%	37.9%	100.0%
Construction & Structural Materials	0.9%	11.9%	8.8%	0.9%	11.9%	14.2%	13.3%	23.5%	14.6%	100.0%
Metals & Alloys	0.6%	17.0%	9.0%	3.7%	9.3%	32.7%	12.6%	11.0%	4.0%	100.0%
Composites		24.0%	7.8%	3.7%	13.4%	24.4%	15.7%	7.8%	3.2%	100.0%
Polymers & Plastics		27.0%	12.7%	6.7%	3.9%	27.3%	3.9%	2.4%	16.1%	100.0%
Electronic & Semiconductor Materi..		32.1%	19.7%	3.0%	14.5%	14.5%	6.8%	5.1%	4.3%	100.0%
Energy Storage & Conversion Materials	0.4%	38.1%	11.8%	6.6%	14.2%	6.8%	8.0%	9.1%	5.1%	100.0%
Biomaterials	0.6%	41.8%	21.5%	9.0%	6.6%	15.5%	2.1%	0.9%	2.1%	100.0%
Nanomaterials		42.9%	37.0%	11.0%	1.8%	3.7%	2.7%	0.9%		100.0%
Ceramics		45.1%	20.6%	4.9%	2.9%	14.7%	2.0%	6.9%	2.9%	100.0%
Smart & Functional Materials		48.7%	13.6%	3.9%	12.4%	5.5%	4.1%	11.3%	0.5%	100.0%
Functional Materials		50.0%	33.3%			16.7%				100.0%
Functional Polymers		66.7%	16.7%		16.7%					100.0%

Figure 6: Materials 4.0 R&I Projects by Material Class and Value Chain Position

→ **Research and innovation spending is evenly distributed across the value chain in structural material classes, potentially because their applications are more mature**
Metals and alloys, glass and optical materials, composites, polymers, electronic and semiconductor materials, and energy storage and conversion materials, have research activity evenly proportioned across the value chain. By comparison, functional materials (including nanomaterials) have more activity at the materials processing, discovery and design phases.

Examples of Materials 4.0 opportunities

To validate the Materials 4.0 framework and its applicability to different sectors, five high-potential and strategically valuable use cases have been developed. These were created in collaboration with industry and academic stakeholders.

They have been selected to demonstrate and interrogate the priority opportunities identified in Royce's National Materials Innovation Strategy as being necessary in accelerating materials innovation across all sectors. These priority opportunities are:

1. Access to trusted materials data based on national standards and protocols for materials-related data acquisition, curation and access.
2. Next-generation materials modelling, application of machine learning techniques, and its combination with high-fidelity experimental and process data.
3. Development of materials passports.

The NMIS Steering Group on Materials 4.0 have further highlighted three key barriers to progressing these opportunities, which need to be addressed:

- → **IP protection and ownership of shared data**
  Industry's sharing of materials data is consistently recognised as the biggest barrier to Materials 4.0 adoption. Losing a competitive edge and protecting their IP will hold businesses back in sharing proprietary materials data without any protections in place.
- → **Data standards and ontology**
  Consistent standards need to be defined for machine access to data but would add to an already complex standards landscape.
- → **Governance of data infrastructure**
  Empower Materials 4.0 stakeholders to confidently develop, govern and manage the digital infrastructure, including quality control, security and change management.

These strategic use cases demonstrate the value of addressing these barriers through the framework, and routes to achieving the priorities.

Table 3. Illustrative examples of five strategic use cases of Materials 4.0

	Use Case	Consultees
	Composite materials for wind turbine blades	National Composites Centre Avalon Consultancy Services Frazer Nash Consultancy
	Battery materials	The Faraday Institution
	Sustainable packaging	Keane Scientific Consulting The University of Strathclyde
	Functional polymers for coatings and paints	The Royal Society of Chemistry
	Steels for nuclear applications	Rolls-Royce Frazer Nash Consultancy

Figure 7 below illustrates the extent of research and innovation activity for these five example strategic use cases – highlighting the latent impact of a better connected and increasingly supported Materials 4.0 ecosystem.

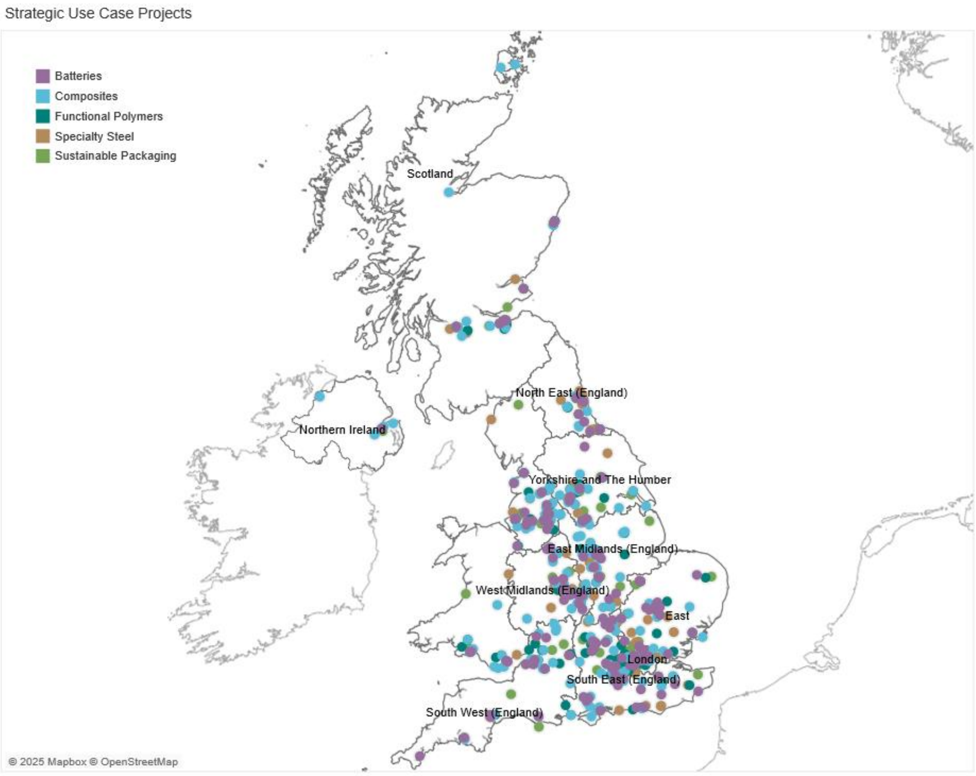


Figure 7. Current research and innovation projects aligned with the exemplar use cases of Materials 4.0.

The following sections present some of the current challenges faced by those sectors and how Materials 4.0 could be used to address them[9].

[9] Further details on each use case are presented in Appendix 4.

Composite materials for wind turbine blades

The opportunity

The UK is particularly competitive and strong in the development of advanced composite materials, especially in research, innovation, sustainability and advanced manufacturing. NCC is leading several Materials 4.0 and manufacturing innovations in this sector for the UK, including the use of the Isambard supercomputer for analysing large datasets.

Currently, there is still an opportunity for the UK to develop strong competitive advantage in digital manufacturing tools for improved quality control and testing and the recycling of composite materials. This will lead the next generation of product development (larger blades, floating wind, circular composites). The UK could also be at the forefront of setting global standards for composites through pilot lines and demonstrators.

The role of this framework

Materials 4.0 can accelerate development cycles and productivity through automation and AI, strengthen SME competitiveness via access to shared datasets and tools, enable the measurement and reduction of embedded CO_2 within composites, support net zero manufacturing by improving process control and reducing waste, reduce domestic demand for critical materials such as virgin carbon fibre, and reduce reliance on imported materials and processes.

This framework can support the realisation of these opportunities by:

→ Establishing national ontologies for materials within and across related sectors.
→ Incentivising data capture, sharing, and demonstrators across industry to ensure that similar terminology is used.
→ Creating accessible, standardised digital infrastructures and policy alignment (for example, composite recycling regulations) to embed Materials 4.0 principles across sectors.

Battery materials

The opportunity

For next-generation batteries, Materials 4.0 is essential to accelerate discovery, optimise manufacturing, and strengthen sustainability across all battery elements i.e. electrodes, membranes, cases, electrolytes etc. By focusing on digitalisation, recycling, and data governance, the UK can secure strategic advantage developing the next generation battery technology even without matching Asia's manufacturing scale.

Recycling and materials circularity, supported by digital traceability, is the most viable entry point for UK leadership within the global battery supply chain. Developing UK digital and industrial capability would reduce dependencies and improve supply chain transparency.

The role of this framework

This framework can support AI-aided materials discovery to find new compounds with the desired voltage, capacity, and stability, as well as for: real-time defect detection during manufacturing, and defining the materials data and processes needed to introduce digital materials and product passports for batteries – enabling efficient recycling feedstock management and the recovery of critical minerals. It can also be used to define the digital activities required to monitor in-service operational conditions and use this data to optimise in-service life and material degradation. This will pre-empt growing requirements for battery passports and meet a global market demand for Digital Materials Passport (DMP) and Digital Product Passport (DPP) enabled solutions.

Sustainable packaging

The opportunity

The UK sustainable packaging market was estimated to be worth between $1.5[10] to $9.71[11] billion in 2024 with a strong growth potential (CAGR ~7.56%)[12]. Market and policy demand for sustainable alternatives to hydrocarbon-based packaging is driving this growth.

The UK is strong on innovation and has several organisations and initiatives in place, such as WRAP[13] and the Smart Sustainable Plastic Packaging (SSPP) Challenge[14], to support research, innovation and link academia and industry. It also has leadership in digital and industrial biotechnology supporting fermentation and bioprocessing innovation, an emerging AI-based materials design expertise and a growing network of collaborative research across universities and SMEs.

However, the recycling infrastructure is a major bottleneck. Bioplastics are often excluded from mechanical recycling streams due to fears of contamination with conventional polymers (i.e. polyethylene, polypropylene, PET), which constitute about 98% of the current market. This penalises bio-based materials, even though in principle they could be mechanically recycled or chemically depolymerised.

The role of this framework

Materials 4.0 offers a pathway to revolutionise the packaging sector and gain a strong international position, primarily through two ways:

1. The accelerated discovery, development and scale-up of sustainable alternatives to traditional raw material feedstocks and processing of bio-based materials with equivalent performance characteristics to conventional polymers.
2. Improved and advanced processing and characterisation of recycling feedstocks (e.g. for more efficient waste stream separation), to grow the confidence of the recycling sector in handling these materials.

The framework will facilitate the standardised platforms and data sharing protocols that could enable these solutions.

[10] https://www.kenresearch.com/uk-sustainable-packaging-and-bioplastics-market
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[13] https://www.wrap.ngo
[14] https://www.ukri.org/what-we-do/browse-our-areas-of-investment-and-support/smart-sustainable-plastic-packaging/

Functional polymers for coatings and paint

The opportunity

Paints and coatings have a diverse range of applications, across various industries such as construction, automotive, and aerospace. Functional polymers and, in particular, acrylic resins dominate a large percentage of certain market segments. For example, acrylics and epoxy resins are 57%[15] of the architectural market. More recently, regulatory pressure has encouraged technology development and innovation of sustainable paints and coatings based on non-fossil feedstocks.

The UK has deep expertise in formulation science and polymer chemistry and a strong skills base for new product development and materials characterisation. There is also an established collaborative ecosystem with experience in pre-competitive research. It could be an instrumental market in the development and scaling of sustainable functional polymers for coatings and paints.

The role of this framework

The Materials 4.0 framework could help create a digital thread that connects feedstock sourcing, synthesis, formulation, characterisation, manufacturing, and biodegradation in one cohesive system. This digital thread could then be used to support key implementable initiatives such as:

- → Using digital models to optimise and screen domestic sustainable feedstock capacity to ensure supply chain security and reduce dependencies on imported petrochemicals.
- → Improve product performance e.g. consistent pigment dispersion, milling, particle size control etc. and reduce manufacturing variability.
- → Reducing R&D time and cost through digital screening and AI modelling of a large database of chemicals, including registering the new chemical under EU REACH, expected regulatory compliance on producing digital material and digital product passport and modelling its functionality, stability, and shelf life.

[15] https://www.mordorintelligence.com/industry-reports/united-kingdom-architectural-coatings-market

Steels for nuclear applications

The opportunity

The nuclear industry has strict regulations, complex supply chains, and long product lifecycles. Through these 60- to 80-year lifecycles, there are multiple product owners (governance bodies) and material data sharing between them could be improved to stimulate innovative solutions and inform operations and maintenance to extend product lifetimes.

Innovation in the industry is currently stifled by these long lead times and multi-stakeholder processes. The introduction of a new product requires extensive testing of materials to prove the safety case. These are very labour-intensive processes, involving highly qualified staff manually reviewing test and process data, which directly impacts the agility of the sector.

Sharing of materials data throughout the production and operation of nuclear systems would support:

→ Innovation in R&D, through more informed design on the use of different materials.
→ In-use lifetime reliability and security, as there is a thorough understanding of material behaviours in-use and more active sharing of standardised materials data.

The role of this framework

The framework will demonstrate to industry the benefits of using Materials 4.0 and the best methods to go about it. It will break the “chicken and egg” problem of innovative practices not progressing whilst the benefits are unproven and best practices unknown.

A demonstrator project to prove the case for sharing metallurgy and processing information throughout the nuclear supply chain is needed. Two potential options are:

→ Support both top-down direction and bottom-up push to implement Materials 4.0 across the supply chain. This can be from automated and real-time measurement of impurity elements of raw materials to evaluate thousands of alloy candidates in silico, to modelling of material structural performance during manufacturing, to facilitating autonomous inspection in hostile environments and finally to establishing digital materials passports for decommissioned steel.
→ SMRs (Small Modular Reactors) have one owner-operator throughout their lifecycle and would make a less complex case for through-life material data management.

International position

A review of the international programmes most relevant to the UK's Materials 4.0 ambitions examined activities in China, France, Germany, Japan, and the United States. It found that the UK's international competitiveness in Materials 4.0 lies primarily in early-stage material discovery and research, supported by industrial capabilities in renewable energy, automotive, nuclear, aerospace, defence and medical materials. A full review of this position is attached in Appendix 6.

The UK excels in early-stage discovery, explainable materials modelling, and high-quality validation, supported by a distributed R&D infrastructure linking universities, the Catapult network, and industry. Key UK industries, including renewable energy, automotive, nuclear, aerospace, defence and medical materials, act as testbeds to demonstrate digital material technologies.

However, compared with the countries reviewed, the UK lacks nationwide data governance, leaving ontologies and metadata fragmented. Automation remains limited to isolated centres, while links between modelling, process optimisation, and manufacturing are weak. The international review also highlighted clear opportunities for the UK to strengthen end-to-end data continuity and lifecycle traceability across the materials value chain.

Strategically, the UK is well positioned to lead in ontology development and international interoperability, fostering trusted data exchange with partner countries by drawing on its collaborative research culture and distributed infrastructure base.

As the US, Germany (which is closely aligned with EU priorities such as data ontology), China and Japan advance more rapidly through automation and design-to-manufacture integration, coordinated action on data strategy, automation diffusion, and skills development would be essential for the UK to maintain competitiveness in the global transition toward digitalised materials innovation.

Strengths (S)	**Weaknesses (W)**
→ Early-stage material discovery and research → Explainable materials modelling → Validation capabilities → Distributed research infrastructure → Industrial anchoring	→ Lack of nationwide data governance → Automation limited to isolated centres of excellence → Limited manufacturing integration → Limited lifecycle and circularity integration
Opportunities (O)	**Threats (T)**
→ Ontology leadership → Interoperability advantage across partner countries → Industries as testbeds	→ Accelerating gap with leading countries → Platform exclusion risk → Manufacturing integration competitors → Talent and funding competition

Table 4. SWOT analysis of the UK's international position compared to other Materials 4.0 specific global initiatives.

Next steps

The outline framework presented provides the basis to help realise Materials 4.0 in the UK through the establishment of a coordinated national roadmap. This will require a collaborative effort from industry, academia, policymakers and researchers, supported by Royce, to embolden investment.

Most of the current Materials 4.0 activity in the UK appears to be focused on two main areas: the development of algorithms and models, and digital tools and techniques – particularly in material discovery and design. In contrast, the data ontology, attributes and infrastructure elements of the framework are underrepresented in research and innovation. There are two main opportunities therefore for the UK moving forward:

- Focussing of the development of common methods on the data ontology, attributes and infrastructure elements – balancing out the investment already being made in tools and processes by industry and researchers.
- Encouraging cross-sectoral learning on Materials 4.0 between sectors and materials classes – again, balancing the current uneven distribution of focus.

The details of the proposed framework need to be finalised and then will require ongoing development to fully map the structure of Materials 4.0. This framework and roadmap development will be undertaken in parallel to the implementation of demonstrator projects that help to both validate and inform the framework. Further, the development and implementation must be integrated with existing activities (including, crucially, gaps in existing activities) in Materials 4.0 and materials innovation in general.

By focussing equally on the three nodes of development, implementation, and integration, a “virtuous circle” of activity will build momentum behind the framework and ensure it is robustly delivered.

Suggested next steps across these activities and future time horizons are listed in Table 5. The key recommendations for Phase 2 of this Material 4.0 framework delivery and roadmapping are defined in Horizon 1.

The recently published AI for Science strategy from UK Government (DSIT) aligns with these next steps, by also calling for standardised, AI-ready data, investment in infrastructure, the development of high-value demonstrator datasets and highlighting advanced materials as a key opportunity sector.

Table 5: Next steps in creating a national framework for Materials 4.0.

	Development	Integration	Implementation
Horizon 1 Stage 2 of this study	**Understand key data attributes and flows** • Define the data layers that innovators require – begin to establish the required data ontology, curation, storage, federated access, standards etc. • Explore how data will be transferred between value chain actors. **Understand data security and data sharing protection mechanisms** • Review successes in secure data sharing between businesses in other industries – suggestions include finance and pharmaceutical drug discovery. • Explore potential data sharing protection mechanisms, which is particularly important in emerging markets, e.g. the clean energy sector. Detailed profiling of any barriers other than secure data sharing at each stage of the value chain.	**Develop a Materials 4.0 roadmap that includes:** • Vision for Materials 4.0. • Cross-sector challenges. • Current and desired initiatives, projects and demonstrators. • Mechanisms for implementation of the initiatives, projects and demonstrators. • Clear recommendations on key activities required including implementation pathways. **Map:** • Current relevant projects, industry implementation and research onto this Materials 4.0 framework. • Existing sources of materials data (largely in industry). • Relevant Materials 4.0 initiatives, projects and demonstrators.	• Conduct initiatives, projects and demonstrators in areas already engaged in Materials 4.0 that prove its impact (which will help to reduce the investment risk for industry). • Use the initiatives, projects and demonstrators to model and refine the data processing requirements, to determine the computing power requirements of Materials 4.0.

Horizon 2 **1 - 2 years**	**Understand data security and data sharing protection mechanisms** • Detailed profiling of any barriers other than secure data sharing at each stage of the value chain. **Engage with regulators on the use of materials data in safety-critical applications.**	**Economic analysis of current and future initiatives, projects and demonstrators** • Detailed economic analysis and impact of current Materials 4.0 demonstrators using evidence from current demonstrators and industry input. • Economic analysis and impact of future initiatives, projects and demonstrators (as agreed from the roadmap).	• Further investment in demonstrators in high-potential use cases that have not yet been explored.
Horizon 3 **3 - 5 years**	• *To be developed*	• *To be developed*	• Launch of a materials data platform and wrap-around infrastructure.

Appendices

Appendix 1: Framework Development Methodology

The methodology outlined for the development of the Materials 4.0 National Framework (M4.0 NF) encompasses six main steps, divided across two stages (see Figure 6**Error! Reference source not found.**). Overall, we followed a mixed-methods approach employing both quantitative and qualitative strategies for data collection and analysis.

Quantitative research involved extensive data collection and analysis, building upon work undertaken previously to inform the advanced materials and NMIS evidence bases – with expanded reach to include mapping of Materials 4.0 assets across the research and innovation ecosystem (within both academia and industry). It also involved desk-based review of existing literature and international benchmarking to highlight opportunities, strengths, gaps and barriers drawn from both the data collection and review of other comparable national and international frameworks.

Qualitative research included strategic engagement via in-depth consultations with key actors across academia, industry, Catapults, government and standards bodies, and facilitation of expert workshops to co-develop and test emerging findings and recommendations. This mixed methods approach ensured that the understanding of the UK's Materials 4.0 landscape was comprehensive including input from the materials, manufacturing and data science communities. Central to the outlined approach was the framework development.

The outputs of our methodology were created with full consideration for their use with both technical and non-technical (policy) audiences by Royce, the UK Government, and UKRI.

	Stage 1. Landscape and gap analysis			Stage 2. NFD&I Strategy		
	Scoping and design	**Data collection and analysis**	**Preliminary synthesis**	**Scoping and design**	**Data collection and analysis**	**Synthesis and reporting**
Methods/ Approach	Desk research and consultations with Steering Group	Desk research, and consultation with key stakeholders	Consultation with key stakeholders	Desk research and consultations with Steering Group	Desk research, survey, framework development process	Synthesis workshop and desk work
Activities/ Instruments	• Literature review • Co-design workshop	• Market analysis • International benchmarking • Interviews and/or focus groups • Text analytics, web-scraping • Interview protocols	• Validation workshop with Steering Group and key stakeholders • Synthesis of M4.0 framework requirements	• Plan stakeholder engagement activities • Plan workshop logistics. • Plan exemplar projects tender	• Design surveys and stakeholders' pre-workshop activities • Collect and summarise data from stakeholders prior to workshops • S-plan workshop methodology	• Synthesis workshop with Steering Group and key stakeholders • Reporting and dissemination
Outputs	Materials 4.0 taxonomy Materials 4.0 definition and scope Materials 4.0 data management and governance overview	Comprehensive mapping of UK's M4.0 landscape Key opportunities for UK M4.0 strategy Summary strengths, gaps and barriers (tech., org., reg.) Lessons learned from int'l frameworks	Initial data framework for materials 4.0 Outline of M4.0 framework development approach	Revised timeline List of stakeholders to involve in the framework development Tender draft	Scalable, inclusive, and agile M4.0 NF Recommendation for roles and responsibilities Integration pathways across organisations Phased timeline and goals (1-5 years)	Consolidation of the M4.0 NF Consolidation of the M4.0 NF roadmap Dissemination activities
Deliverables	Preliminary report, summary slide deck and detailed timeline for Stage 2			Tender draft for 2 exemplar projects	Final report, detailed framework, presentation and stakeholder briefing pack	

Figure 8: Overview of the methodology to be employed throughout the project.

Appendix 2: Bibliography for Materials 4.0 Framework development

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Appendix 3: Detailed use case examples

Composite materials for wind turbine blades

The UK has an established composites sector with important materials and technology development activities. Some market reports estimate that the UK *advanced composites* market size will reach £6.3 billion by 2035[16]. The sector employs ~30,000 employees and has over 400 companies in the UK.

The UK is particularly competitive in the development of advanced composite materials – especially in research, innovation, sustainability and advanced manufacturing. NCC is leading several Materials 4.0 and manufacturing innovations in this sector for the UK with advancing digital factory models using IoT sensors, AI, and control systems. Other initiatives include development of federated data architectures, material passports, and the use of the Isambard supercomputer for analysing large datasets. The UK also has strengths in its research and development base, especially in digital manufacturing and metrology.

However, the UK lags other countries (particularly China/Asia or large European players) in terms of industrial adoption - although research capability is strong, uptake across manufacturing is still slow - volume and cost competitiveness of large-scale blade/composite manufacturing. There is fragmented coordination and data sharing with inconsistent data formats and a lack of shared repositories that hinder interoperability. There is also a skills gap with industry lacking sufficient expertise in data management, AI integration, and ontology use.

There is an overall need for organisations to become 'open' to host, curate, and desensitise datasets for wider industrial use.

Currently, there is still an opportunity for the UK to develop strong competitive advantage in recycling, digital manufacturing, and advanced materials in order to lead the next generation (larger blades, floating wind, circular composites). It could also be in the forefront for setting global standards for composites through pilot lines and demonstrators.

Materials 4.0 can accelerate development cycles and productivity through automation and AI, strengthen SME competitiveness via access to shared datasets and tools, enable the measurement and reduction of embedded CO_2 within composites, support net zero manufacturing by improving process control and reducing waste, reduce domestic demand for critical materials such as virgin carbon fibre, and reduce reliance on imported materials and processes.

To achieve this vision, the UK must:

- Incentivise data capture, sharing, and demonstrators across industry.
- Establish national ontologies for materials.

[16] https://iuk-business-connect.org.uk/wp-content/uploads/2021/07/Opportunities-in-the-UK-Composites-Industry-Lucintel-Public-Version.pdf

- Create accessible, standardised digital infrastructures and policy alignment to embed Materials 4.0 principles across sectors.

Error! Reference source not found. Figure 9 below summarises this use case and shows some examples of how Materials 4.0 could offer solutions to some of the industrial challenges. It also indicates the wider opportunities and benefits that can be derived as a result.

A more detailed map of how the framework provides a template for the data created and moves through the different elements of the materials value chain for a wind turbine composite is shown in Appendix 7.

	Raw material extraction	Material and process discovery and design	Synthesis and characterisation	Scale-up and material production	Product development	Product manufacturing	Testing / Inspection / Certification	In service (operations and maintenance)	Circularity 5Rs
Actors in value chain	Material producers	Material producers	Material producers	Material producers	Tier 1,2,3	Tier 1,2,3	Tier 1,2,3	Wind farm operators	Recycling companies
Industry Challenges		**Design for recyclability** of cross-linked thermosets & resins			• Detecting **manufacturing-induced and sub-surface defects** in large composite laminates e.g. dry spots, porosity, voids etc.		• Fatigue & environmental degradation of polymer composites • Leading-edge erosion (LEE) of coatings/composites		Hard to **recycle cross-linked thermosets at scale**
Materials 4.0 solutions		• Use **ML models to** predict depolymerization energy, re-processability, or solvent compatibility from monomer structure or cross-link density • Use **Robotic platforms** to rapidly synthesize and test recyclable thermosets			• Integrated **Digital Twins** of composite manufacture to predict voids or resin-poor regions are likely to form • **Smart Sensing & In-situ Monitoring** that enables a digital material passport. • **AI-enhanced Non-Destructive Testing**		• **Digital Twins** and **Predictive Degradation Models** of the composite system (laminate + matrix + fibres + environment) to simulate fatigue damage accumulation + environmental effects in-service		**Smart sorting & digital material passports** using RFID and spectral signatures
Opportunities / Benefits		• Faster discovery & lower R&D costs • Reduced reliance on scarce raw materials • Cleaner manufacturing			• Lower scrap & warranty costs, higher asset uptime • Reduced material & energy waste • Support of circular-economy, Industry 4.0 and green-jobs		• Better lifetime prediction; • Optimised inspection/maintenance intervals • Improved design margins with less over-design		• Longer lifetime • Reduced environmental impact

Figure 9. Summary of the composites for wind turbine blades use case.

Battery materials

The UK battery market is currently valued to be between $4[17]–$7[18] billion, depending on specific market definitions e.g. all batteries vs rechargeable only. The market is forecast to grow rapidly over the next 5–10 years, due to the electrification of mobility and the green energy transition.

The UK has a defined strategy for batteries, 'The UK Battery Strategy'[19]. According to the strategy, the UK "*ranks third in the world in terms of research quality into industrial batteries.*" This sets out a vision for a globally-competitive supply chain by 2030 supported by a strong research base on battery materials and a strong start-up ecosystem for EV battery materials – the second in Europe in enterprise value, high venture-capital funding and the second highest in value in Europe's automotive sector supporting battery innovations. In addition, the UK has many academic/industrial

[17] https://www.nextmsc.com/report/uk-battery-market
[18] https://www.fortunebusinessinsights.com/uk-battery-market-114177
[19] https://assets.publishing.service.gov.uk/media/656ef4871104cf000dfa74f3/uk-battery-strategy.pdf

partnerships (e.g., the Faraday Institution). The UK also has an established industrialisation infrastructure, such as the:

- UK BIC (Battery Industrialisation Centre), a large-scale pilot line for gigafactory-scale manufacturing.
- AMBIC (Active Materials Battery Industrialisation Centre) that scales new materials from grams to kilograms.
- Innovative modelling and digitalisation capabilities (e.g., UK firms working on physics-based battery models).

Despite those strengths, battery manufacturing is dominated by Chinese global companies with CATL and BYD supplying over 60% of global battery demand. These companies are vertically integrated, controlling the mining and refining of raw materials, synthesising active material, and manufacturing battery cells.

The global battery supply chain of critical minerals is also currently dominated by China. Over 90% of active materials are sourced from China, which controls the supply of lithium, nickel, and previously cobalt (from DRC).

In Europe, efforts to establish secure, local supply chains have faced setbacks. For example, Northvolt in Sweden went bankrupt in June 2025 after operating its factory at just 5% capacity due to manufacturing challenges and limited know-how transfer from Chinese suppliers.

By contrast, US companies have partnered with Korean manufacturers to gain expertise. There is now recognition that partnerships and technology transfer are critical for scaling up battery technology.

In the UK additional limitations exist in a lack of large-scale manufacturing know-how and heavy dependence on imported expertise and machinery, insufficient recycling capacity, and a fragmented data and regulatory landscape, limiting interoperability between different stakeholders and an increased automotive transition risk. The UK must electrify its automotive sector or risk losing it entirely, as the sector is set to remain the largest global market for batteries over the next 20 years.

For next-generation batteries, Materials 4.0 is essential to accelerate discovery, optimise manufacturing, and strengthen sustainability. By focusing on digitalisation, recycling, and data governance, the UK can secure strategic advantage even without matching Asia’s manufacturing scale.

Recycling and materials circularity, supported by digital traceability emerge as the most viable entry point for UK leadership within the global battery supply chain. Developing UK digital and industrial capability would reduce dependency and improve supply chain transparency.

Overall, Materials 4.0 can support innovation in several high-impact areas:

- **Materials discovery and optimisation:** Use of modelling and data-driven discovery for new chemistries (solid-state, sodium-ion, redox flow, and metal-air).

- **Process optimisation:** Simulation and data capture to refine manufacturing routes and scale-up processes (e.g., improving cathode/anode material performance).
- **Battery management and operation:** Transitioning from empirical data models to physics-based models for battery management systems (BMS), improving performance prediction and grid integration.
- **Energy system integration:** Enabling vehicle-to-grid and grid storage applications through real-time digital visibility.
- **Recycling and circularity:** Digital passports and materials identity data can ensure efficient recycling feedstock management and recovery of critical minerals.
- **Digital materials passports** to align with the EU's 2027 battery passport regulation, which the UK is expected to follow.
- **Digital twins and advanced BMS:** Facilitating monitoring operational conditions and predict faults, improving battery safety, lifespan, and reliability across energy storage and electric vehicle (EV) applications.

Figure 10 below summarises this use case and provides some examples of how Materials 4.0 could offer solutions to some of the current industrial challenges. It also indicates the wider opportunities and benefits that can be derived as a result.

	Raw material extraction	Material and process discovery and design / Synthesis and characterisation / Scale-up and material production	Product development / Product manufacturing / Testing / Inspection / Certification	In service (operations and maintenance)	Circularity 5Rs
Actors in value chain	Mining companies Refining and chemical processing companies	Active material producers	Battery manufacturers	Battery integrators /users	Recycling companies
Industry Challenges	Geographic concentration of critical battery materials	• The performance **of active materials depends on crystal structures and precise atomic substitutions** • **Degradation and interface instability** of electrochemical interfaces • Ensuring that research materials maintain their behaviour and performance when are scaled-up to large volumes.	• Battery cell production is complex involving hundreds of precise steps — coating, drying, calendaring, stacking, electrolyte filling, and formation. Tiny inconsistencies in particle distribution, coating thickness, or moisture lead to performance variation or safety risks.		Manual sorting of mixed chemistries and battery conditions is slow and inaccurate
Materials 4.0 solutions	**AI-driven exploration** using geospatial data and machine learning to identify new deposits faster and more sustainably.	• **AI-aided materials discovery** to find new compounds with desired voltage, capacity, and stability. • **In situ sensor data coupled with ML models** to predict and prevent degradation • **Digital twins of synthesis reactors** (co-precipitation, calcination) with AI control loops for precise temperature, pH, and precursor flow.	• **AI-based vision systems** for real-time defect detection (e.g., coating uniformity, electrode cracks). • **Self-optimizing production loops** using reinforcement learning for adaptive control.		**Digital passports** and **materials identity data** can ensure efficient recycling feedstock management.
Opportunities / Benefits	National security and supply chain resilience	Speed-up innovation and development of new chemistries	Enabling green energy transition in the mobility and energy sectors		Efficient recovery of critical minerals

Figure 10. Summary of battery materials use case.

Sustainable packaging

The UK sustainable packaging market was estimated between $1.5[20] to $9.71[21] billion in 2024 with a strong growth potential (CAGR ~7.56%). A sub-category of sustainable packaging is bio-based packaging which is using partly or entirely biological (renewable) feedstocks as raw input.

Polylactic Acid (PLA) is a representative material derived from sugar feedstocks (corn fermentation), and then polymerised to lactic acid, following film production, conversion into packaging and end-of-life management (composting or recycling).

Most PLA production occurs overseas (e.g., NatureWorks, TotalEnergies Corbion), with the UK mainly active at the downstream packaging-conversion stage. Upstream activities such as bio-refining, monomer synthesis, polymerisation are largely absent domestically.

The UK is strong on innovation and has several organisations such as WRAP22 and various initiatives in place such as the Smart Sustainable Plastic Packaging (SSPP) Challenge23, to support research, innovation and link academia and industry. It also has leadership in digital and industrial biotechnology supporting fermentation and bioprocessing innovation, an emerging AI-based materials design expertise and a growing network of collaborative research across universities and SMEs.

The UK has a limited pilot-scale infrastructure and mid-TRL funding for biopolymers. The industrial landscape is fragmented with a lack of large domestic players and over ~4000 small companies operating with limited coordination.

One of the main UK weaknesses is the loss of polymer and metallurgy knowledge base. The UK currently has a few degree programmes remain in these disciplines. This is exasperated by a disconnect between disciplines with polymer scientists, composite engineers, and materials chemists often work in silos, reducing cross-sector innovation.

Another issue is the policy misalignment where taxation and recycling regulations currently disadvantage the use of bio-based materials.

Finally, the recycling infrastructure is a major bottleneck. Bioplastics are often excluded from mechanical recycling streams due to fears of contamination with conventional polymers (i.e. polyethylene, polypropylene, PET), which constitute about 98 % of the current market. This penalises bio-based materials, even though in principle they could be mechanically recycled or chemically depolymerised.

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[20] https://www.kenresearch.com/uk-sustainable-packaging-and-bioplastics-market
[21] https://www.imarcgroup.com/uk-sustainable-packaging-market
[22] https://www.wrap.ngo
[23] https://www.ukri.org/what-we-do/browse-our-areas-of-investment-and-support/smart-sustainable-plastic-packaging/

Materials 4.0 offers a pathway to revolutionise the packaging sector and regain a strong international position. For example, Materials 4.0 could be instrumental in the following areas:

- **Raw material extraction:** Designing bio-based materials with performance equivalent to fossil-derived plastics remains difficult. There is a need to diversify feedstocks beyond sugar to UK-accessible sources such as algae, agricultural residues, and seafood waste. AI- enabled feedstock optimisation could be used to enable this.
- **Materials design and discovery:** Accelerated molecular and formulation design can be enabled by AI, machine learning, and high-throughput screening.
- **Process scale-up:** Digital twins and modelling can support fermentation and polymerisation optimisation, enhancing yields, reducing energy input, and lowering costs.
- **Recycling and end-of-life management:** Advanced spectroscopic and analytical techniques are required for automated identification and sorting of materials to integrate them into existing recycling infrastructure.
- Facilitate **data sharing and traceability** through standardised platforms, ensuring interoperability between industrial partners.
- Incorporate **materials passports** and life-cycle data for transparent monitoring of carbon, recyclability, and performance metrics.

Figure 11 below summarises this use case and provides some examples of how Materials 4.0 could offer solutions to some of the current industrial challenges. It also indicates the wider opportunities and benefits that can be derived as a result.

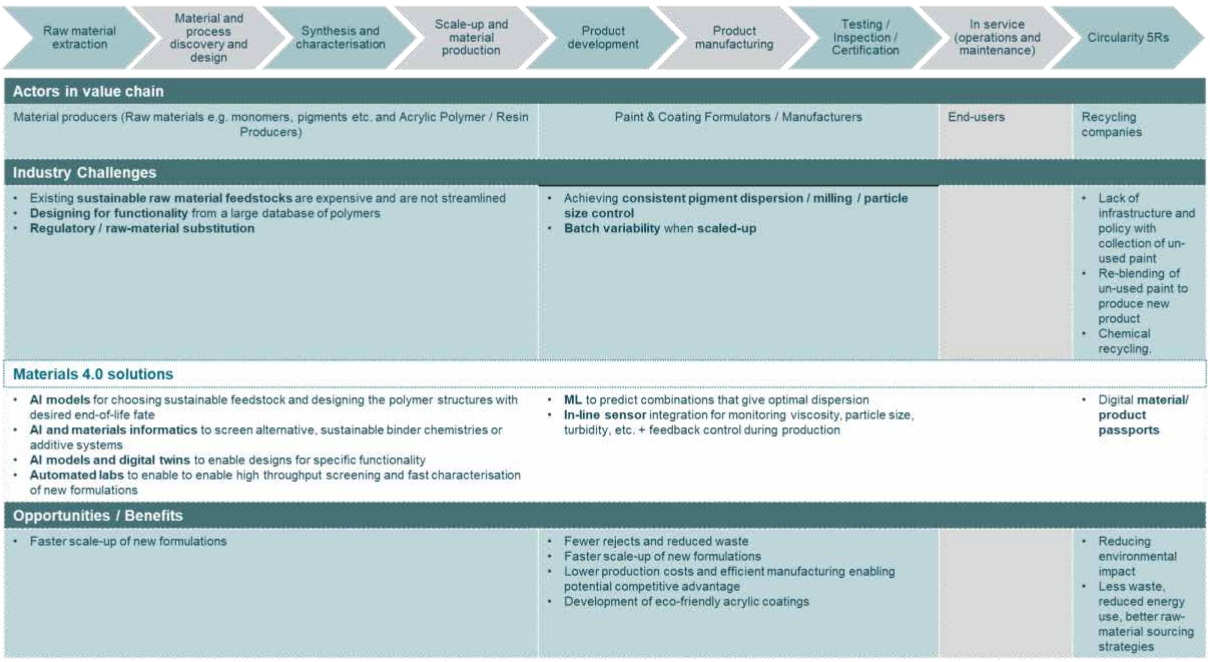

Figure 11. Summary of the sustainable packaging use case.

Functional polymers for coatings and paint

The UK paints & coatings market was valued between $4.0-9.6 billion in 2024 with a CAGR of 3.84% through 2029[24,25,26]. It has diverse range of applications, across various industries such as construction, automotive, aerospace etc. Functional polymers and in particular acrylic resins dominate a large percentage of certain market segments i.e. acrylics are 57%[27] of the architectural market. More recently, regulatory pressure has encouraged technology development and innovation of sustainable paints and coatings.

Using acrylic resins as an example, a typical value chain starts from a raw material converted into a resin which is then formulated to a paint or coating, is volume manufactured and distributed to end-users before is finally recycled.

The UK has deep expertise in formulation science and polymer chemistry and a strong skills base for new product development and materials characterisation. There is also an established collaborative ecosystem with experience in pre-competitive research.

The UK does not have a UK-centric manufacturing value chain**.** Many functional polymer supply chains rely on overseas feedstock and production. What is lacking is a national feedstock strategy that provides guidance and clarity on priorities between selecting biomass, fossil or recycled feedstock inputs. This has immediate cost implications as uncertainty about the right feedstock selection can duplicate the required infrastructure increasing costs. It also impacts the ability of the UK to scale-up low TRLs sustainable polymer innovations. Finally, large variations in formulation and batch of sustainable polymer manufacturing increase the final price of these products hindering their wider market adoption.

Materials 4.0 could help create a **"**digital twin of the entire materials value chain**"** that connects feedstock sourcing, synthesis, formulation, characterisation, manufacturing, and biodegradation in one cohesive system. This vision could be broken down to key implementable initiatives such as:

- Use digital models to optimise and screen domestic feedstock capacity to reduce dependency on imported petrochemicals.
- Reduce R&D time and cost through digital screening and AI modelling of a large database of materials.
- Digital innovation could replace reliance on "identical" chemicals across multiple products, enabling safe, functional alternatives designed via AI and modelling.
- Integration of safety and sustainability ("Safe and Sustainable by Design") innovations into formulation processes using digital tools.
- Energy and process efficiency improvements during scaling-up and manufacturing. The UK's high energy costs reduce its manufacturing

[24] https://coatings.org.uk/page/IndustryStatistics
[25] https://www.techsciresearch.com/report/uk-paints-coatings-market/4820.html
[26] https://www.marketresearchfuture.com/reports/uk-paints-coatings-market-45635
[27] https://www.mordorintelligence.com/industry-reports/united-kingdom-architectural-coatings-market

competitiveness. Digital optimisation could help deliver low-cost, low-carbon process energy and lower energy consumption during manufacturing.
- Use digital design to ensure non-toxic, safe polymers that degrade effectively at end-of-life while remaining stable during shelf life.

Figure 12 below summarises this use case.

Raw material extraction	Material and process discovery and design / Synthesis and characterisation / Scale-up and material production	Product development / Product manufacturing / Testing / Inspection / Certification	In service (operations and maintenance)	Circularity 5Rs
Actors in value chain				
Feedstock Producers	Raw material producers (e.g. Lactic acid production, PLA resin production)	Product Manufacturing	End-users	Recycling companies
Industry Challenges				
Need to **diversify feedstocks** beyond sugar to UK-accessible sources such as **algae, agricultural residues, and seafood waste** that do not compete with food production	Difficult to **design bio-based materials** with **performance equivalent** to fossil-derived plastics. Feedstock impurity and variability	• Brittleness and limited mechanical strength • Thermal sensitivity of PLA which degrades or discolors at high temperatures and narrow processing windows (170–190 °C).		**Lack of recycling infrastructure for** Bioplastics which are often **excluded from mechanical recycling streams** due to fears of contamination with conventional polymers
Materials 4.0 solutions				
• **ML-driven analysis** of regional biomass streams and process compatibility. • **AI-assisted genetic design** of microorganisms that can use diverse carbon sources.	• Accelerated molecular and formulation design enabled by **AI, machine learning, and high-throughput screening.** • **Modelling and simulation** to accelerate formulation development, and desired material performance • Machine learning models predict fermentation behaviour based on feedstock profile, automatically adjusting nutrient or pH control.	• **Modelling and simulation** to optimise fermentation yields • AI-Enhanced Material Formulation to identify ideal biodegradable plasticizer or nucleating agent mix to improve heat resistance while maintaining compostability		Advanced **spectros copic and analytical techniques** are required for automated identification and sorting of materials to integrate them into existing recycling infrastructure.
Opportunities / Benefits				
New income sources for farmers, cooperatives, and smallholders.	• Lower production cost and therefore cheaper bioplastics for consumers and industry. • Rural industrialization and knowledge-intensive employment creation outside large urban centres.	• Makes PLA packaging price-competitive with fossil plastics, expanding markets increasing national industrial output and GDP contribution • Decentralized industrialization reduces regional inequality.		Creates new high-quality jobs in waste valorization, automation, and circular logistics.

Figure 12. Summary of the functional polymers for coatings and paint use case.

Steels for nuclear applications

The nuclear industry has strict regulations, complex supply chains, low volumes of manufacture, and long product lifecycles. Through these 60- to 80-year lifecycles, there are multiple product owners (governance bodies) and material data sharing between them could be improved to stimulate innovative solutions and inform operations and maintenance to extend product lifetimes.

The challenge

Innovation in the industry is currently stifled by these long lead times and multi-stakeholder processes. The introduction of a new product requires extensive testing of materials to prove the safety case. These are very labour-intensive processes, involving highly qualified staff manually reviewing test and process data, which directly impacts the agility of the sector.

Likewise, any existing problems in the supply chain require manual tracing of componentry through the supply chain and potentially decades-old data. In an industry with very high integrity, and the potential for very serious safety claims, processes like these absorb large volumes of resource.

There is no agreed standard on digitising materials data or sharing it between supply chain actors. Some commercial manufacturer-operators are producing more digitally-enabled solutions in Gen4.0 reactor technologies – adopting Industry 4.0 practices. Combining these with Materials 4.0 capabilities will enable materials lifetime tracking, increasing the viability and agility of innovations in this sector.

5Rs in the nuclear sector are underdeveloped. This is in part due to the risk of the high reactivity components.

The opportunity
Sharing of materials data throughout the production and operation of nuclear systems to better understand the property-process-microstructure-performance relationship, and the use of LLM, ML, AI and NN (neural networks) would support:

1. Safety substantiation
2. Prediction of through-life degradation (e.g. irradiation/thermal embrittlement/environmental degradation etc)
3. More streamlined component sentencing (e.g. automated certification)
4. Management of in-service issues (e.g. safety concerns, deviations from safety case, maintenance & inspection etc)
5. Management of manufacturing concessions

The UK's Office for Nuclear Regulation (ONR) is regarded globally as an expert regulator that is open to innovative solutions. It operates a model where the supplier must prove the safety case of their solution, rather than meeting pre-defined design and safety codes (a model used by other international regulators, including in the US). This allows suppliers to develop novel solutions to a relatively open brief.

In defence and dual-use applications, the Ministry of Defence (MoD) is an active customer – exploring new modes of working with suppliers, including secure data hubs.

The Materials 4.0 CDTs are addressing the gap between academic research and industry uptake of innovations.

Barriers to Materials 4.0
Skills, culture, and ways of working, and the complex supply chain all present a barrier to Materials 4.0 innovations in this sector. It is also a less competitive market than (e.g.) aerospace, with a lower precedent for digital innovation.

The IP protection of material data is a barrier, as supply chain actors don't have full access to (e.g.) the microstructure data of their products. Private companies throughout the supply chain will use different data management and modelling systems, which may not integrate.

Role of this framework
The framework will demonstrate to industry the benefits of using Materials 4.0 and the best methods to go about it. It will break the "chicken and egg" problem of innovative practices not progressing whilst the benefits are unproven and best practices unknown.

Next steps

A demonstrator project to prove the case for sharing metallurgy and processing information throughout the nuclear supply chain is needed. Two options are:

1. Support both top-down direction and bottom-up push to implement Materials 4.0 across the supply chain. This can be from automated and real-time measurement of impurity elements of raw materials to evaluate thousands of alloy candidates in silico, to modelling of material structural performance during manufacturing, to facilitating autonomous inspection in hostile environments and finally to establishing digital materials passports for decommissioned steel.
2. SMRs (Small Modular Reactors) have one owner-operator throughout their lifecycle and would make a less complex case for through-life material data management.

Figure 13 below summarises this use case.

Raw material extraction	Material and process discovery and design	Synthesis and characterisation	Scale-up and material production	Product development	Product manufacturing	Testing / Inspection / Certification	In service (operations and maintenance)	Circularity 5Rs
Actors in value chain								
Mining companies	Public Sector, National Labs and industry		Alloying	Steel makers (melting and refining) (Nuclear-qualified)	Fabrication	Independent inspectors/ Certifiers	Users and integrators	Decommissioning
Industry Challenges								
Nuclear-grade steel normally require extremely low impurity levels	Designing alloys for extreme environments (irradiation, corrosion, high temperature)		Alloy homogeneity in massive ingots and large forgings i.e. 50–200+ tonne forgings	Controlling chemistry in a dynamic melt environment	Welding 50–300 mm thick sections without defects	Human-dependent interpretation of non-destructive testing data	Detection, Characterisation & Monitoring of Defects In Service	Sorting, Recycling & Re-manufacturing of Nuclear Steels
Materials 4.0 solutions								
Automated and real-time measurement of impurity elements down to ppm levels	**High-throughput computational screening** to evaluate thousands of alloy candidates in silico vs. a handful physically.		**Digital twins** of solidification to simulate macro-segregation of alloying elements during casting	**Real-time spectroscopic monitoring**	**Physics and data models** of arc, heat flow, microstructure, and stresses	**AI-assisted** ultrasonic/radiographic or computed tomography testing analysis of data	**Robotics and autonomous inspection** that enables high-precision inspections in hostile or submerged environments	**Digital materials passports** for decommissioned steel
Opportunities / Benefits								
Reduces variability and improves yield of nuclear-compliant steel	Massive acceleration of alloy discovery and reduction of costly experimental iterations.		Reduces chemical banding, lowers the risk of mechanical property gradients.	Tighter control over nuclear chemistry windows	Reducing reject rates and fabrication costs	Speed-up conventional qualification process	Reduced operator variability and fewer false positives	• Cost savings on waste and new material procurement • Lower carbon footprint and resource intensity

Figure 13. Summary of the steels for nuclear applications use case.

Appendix 4: The UK Materials 4.0 Landscape

Materials 4.0 can transform the materials supply chain by reducing resource dependency, making supply chains more resilient, understanding carbon emissions, accelerating materials discovery and innovation, optimising complex processes, and maximising the lifespan and reuse value of materials.

Recognising the value of Materials 4.0

Materials 4.0 has the potential to generate economic value by directly enhancing the speed, quality, and sustainability of materials development at every stage of the materials value chain.

For example, digitalisation creates value in the extraction of raw materials and feedstocks by improving supply chain resilience and reducing reliance on virgin or critical sources. Machine learning (ML) and artificial intelligence (AI) can accelerate materials discovery and design, and digital twins enable simulation of material behaviours in a controlled environment. Materials 4.0 oriented digital tools in manufacturing can optimise material processing, leading to higher quality, efficiency and material customisation. Leveraging Materials 4.0 capabilities while materials are 'in-service' can improve predicted materials performance and extend component lifespans, and application of Materials 4.0 tools at end of life can improve the efficiency and effectiveness of material recovery, produce more robust life cycle assessments and can enable material design for sustainability.

Based on the research conducted in Stage 1 of this study, limited data has been identified regarding the specific economic impact of Materials 4.0 in the UK. However, analyses in other jurisdictions, and of related concepts such as manufacturing 4.0 in the UK, point to significant opportunities for achieving economic value added from Materials 4.0 investments.

For example, a 2013 report by the National Institute of Standards and Technology in the US suggested that an improved materials innovation infrastructure to support the Materials Genome Initiative (MGI) could generate between $123bn and $270bn in economic impact annually, through a combination of reduced R&D project attrition, a 35% acceleration in getting R&D projects to market, and a 71% improvement in R&D efficiency[28].

In the UK, a recent evaluation of the Made Smarter Innovation Challenge estimated that manufacturing 4.0 activities generated direct Gross Value Added (GVA) of ~£168mn across 243 participating SMEs (almost £700k per SME or £27k per employee assuming an average of 25 employees per SME).

While further work is required to produce credible evidence regarding the specific economic value of Materials 4.0 in the UK, these proxies point to potentially significant future returns on public investment in Materials 4.0.

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[28] Based on interviews with 100 experts spanning research, development, innovation and manufacturing. https://www.nist.gov/system/files/documents/2020/02/06/MGI%20Final%20Report.pdf

Building on existing Materials 4.0 activity

To understand Materials 4.0 related activity across the UK the study team analysed titles and abstracts[29] for ~155k research and innovation projects recorded within UKRI's Gateway to Research platform and Innovate UK's own project database[30]. Based on a multi-stage analysis that applied expert-trained machine learning models and frontier large language model capabilities, a total of 5,928 projects funded since 2004 were identified as being relevant to Materials 4.0 activity. The sub-sections below use this research and innovation data to provide an overview of existing Materials 4.0 activity across the UK.

Meeting increasing demand for Materials 4.0 research & innovation

Research and innovation project data suggests that the level of interest in leveraging Materials 4.0 opportunities has been increasing steadily in recent years. Since 2015 the total number of Materials 4.0 related research and innovation projects funded has more than trebled[31], and the total value of Materials 4.0 research and innovation projects has increased more than fivefold[32] (Figure 14Figure 14).

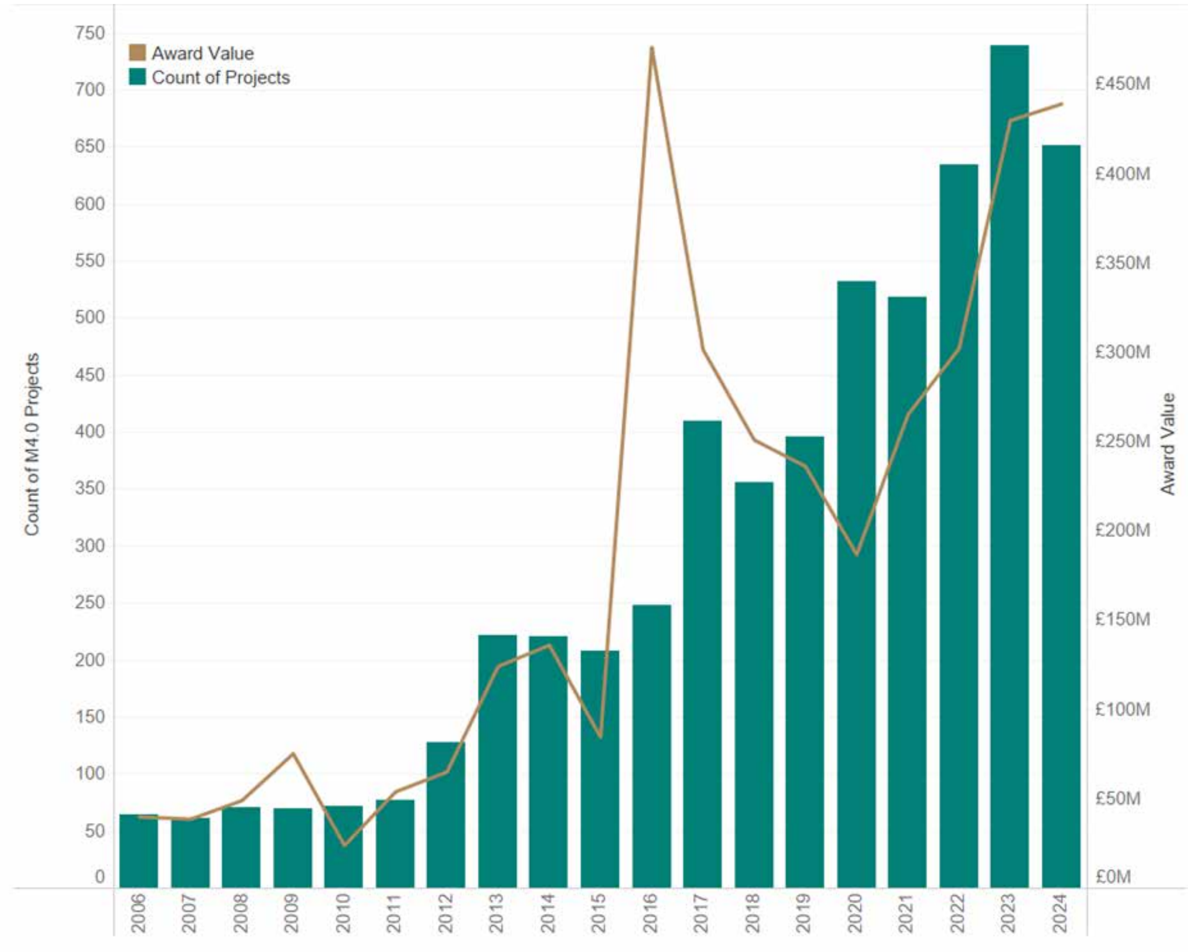

Figure 14. Number of Research and Innovation Projects Funded (% increase since 2015)

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[29] Public descriptions within Innovate UK data

[30] https://gtr.ukri.org/ and https://www.ukri.org/publications/innovate-uk-funded-projects-since-2004/ - overlaps between UKRI GtR records and Innovate UK project data were removed, as were projects for which no abstract was available. From a total of just over 170k projects 154,848 were processed.

[31] By 212% overall, and by an average of 15% year on year.

[32] By 419% overall, and by an average of 45% year on year.

Framework-related Materials 4.0 activity

Using research and innovation project titles and abstracts for the ~6,000 Materials 4.0 projects, a frontier-level large language model was used to tag each project across the range of criteria set out belowTable 6. This analysis is intended to help provide a better understanding of framework-related Materials 4.0 activity across the UK, and to identify examples of where Materials 4.0 activity could be connected across strategic use cases.

Table 6. Materials 4.0 Project Classifications

Classification Criteria	Classification Options	
Materials 4.0 Elements	• Data attributes • Data infrastructure	• Algorithms & models • Digital tools & techniques
Materials Value Chain Position	• Raw material extraction • Materials & materials processing discovery & design • Materials synthesis, characterisation & metrology • Scale-up & material production • Product development	• Product manufacturing • Testing, inspection & certification • In-service (operations & maintenance) • Circularity
Materials Classes	• Metals & Alloys • Polymers & Plastics • Ceramics • Composites • Electronic & Semiconductor Materials • Energy Storage & Conversion Materials	• Biomaterials • Nanomaterials • Glass & Optical Materials • Smart & Functional Materials • Construction & Structural Materials • Textiles & Fibres
Sectors	• Foundation Industries • Construction • Consumer Goods • Aerospace • Automotive • Space • Defence • Health & Life Science • Medical Technology • Genomics	• Communications • Semiconductors • Computing • Thermal Engineering • Equipment Manufacturers • Renewable Energy • Nuclear Energy • Fossil Energy • Consultancy Services • Other Sectors
Strategic Use Cases (Framework Aligned)	• Specialty Steel • Sustainable Packaging • Functional Polymers	• Composites • Batteries

Framework activity across the value chain

Taking the first two classifications together (i.e., the digital elements and value chain position) most Materials 4.0 projects are focussed primarily on the development of algorithms and models, and digital tools and techniques, and predominantly with respect to materials & processing discovery and design.

Materials 4 0 Best-Fit (Grouped)	Raw material extraction	Materials & processing discovery & design	Synthesis, characterisation ..	Scale-up & material production	Product development	Product manufacturing	Testing, inspection & certification	In-service (operations & maintenan..	Circularity	Grand Total
Data Attributes & Ontologies		0.2%	1.0%	0.2%	0.1%	0.2%	0.5%	0.1%	0.3%	2.6%
Data Infrastructure	0.0%	0.6%	0.3%	0.0%	0.1%	0.3%	0.1%	0.2%	0.7%	2.5%
Algorithms & Models	0.3%	20.0%	4.2%	2.2%	5.1%	4.2%	3.0%	3.2%	1.2%	43.6%
Digital Tools & Techniques	0.1%	3.4%	6.9%	2.9%	5.5%	16.4%	6.4%	6.9%	2.9%	51.3%

Figure 15: Materials 4.0 R&I Projects by Digital Element and Value Chain Position

While the focus on materials and processing discovery and design is not surprising given the significant economic potential associated with reduced R&D project attrition and accelerated commercialisation of materials R&D[33], it does suggest a need to consider the overall balance of Materials 4.0 innovation activity.

Projects primarily focussed on developing models and algorithms make up 44% of all the Materials 4.0 research and innovation projects identified, within which 20% of projects funded are focussed on materials and processing discovery and design.

Projects focussed on developing digital tools and techniques also make up ~51% of all research and innovation activity, although these projects are more evenly spread across the materials value chain (41% of all projects are primarily concerned with

[33] Improved materials innovation infrastructure to support the Materials Genome Initiative (MGI) reduce R&D project attrition, accelerate the pace of commercialisation by 35% and deliver a 71% improvement in R&D efficiency.

developing digital tools and techniques at latter stages of the materials value chain i.e., from scale up and material production through to circularity).

By contrast, just over 5% of all projects identified focus primarily on developing data attributes and ontologies, or data infrastructure[34].

Materials 4.0 activity across sectors

Approximately two thirds of research and innovation projects are primarily focussed on five sectors – foundation industries, aerospace, renewable energy, automotive, and health & life sciences. Just over one fifth of all projects are primarily focussed on the foundation industries, around one sixth are focussed on nuclear and renewable energy (combined) and on the aerospace sector, and notable proportions are focussed on health, life science and medical (combined), and automotive.

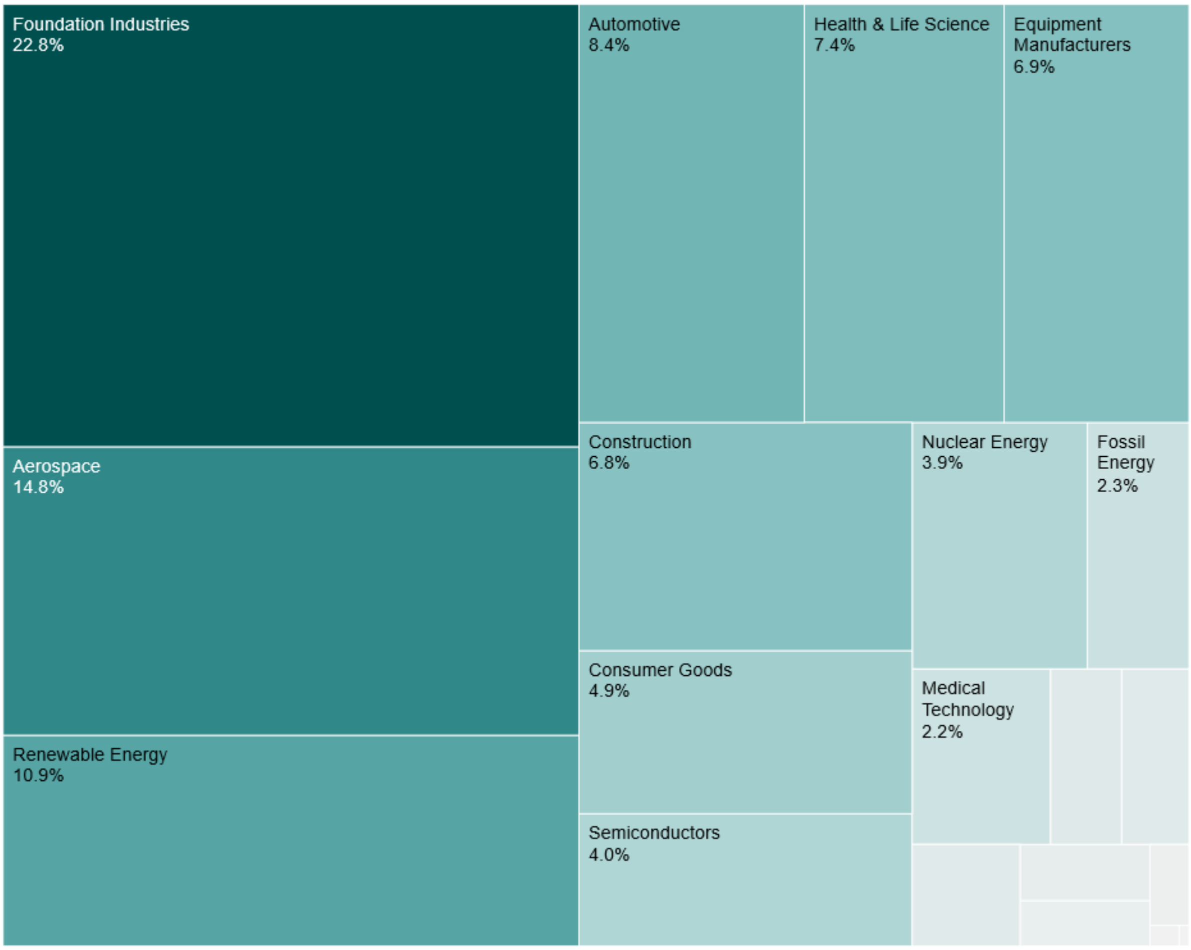

Figure 16. Materials 4.0 R&I Projects by Sector

Framework activity across sectors

Just under one third of foundation industry projects focussed on materials and processing discovery and design, and just under one quarter focussed on product manufacturing. Around a fifth of projects in nuclear and renewable energy are

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[34] 5.1% if projects are allocated on the basis of their 'best-fit' Materials 4.0 category. More often than not a project will address more than a single Materials 4.0 element. Percentage increases to 5.6% if based on analysis of multiple tags per project.

concerned with in-service operations and maintenance, and there is a significant focus in aerospace and automotive on product development, manufacturing and test.

Sectors Best-Fit (Group)	Raw material extraction	Materials & processing discovery & design	Synthesis, c haracterisat ion ..	Scale-up & material production	Product dev elopment	Product ma nufacturing	Testing, inspection & certification	In-service (operations & maintenan..	Circularity	Grand Total
Foundation Industries	1.1%	28.4%	15.2%	7.9%	2.7%	23.6%	7.1%	6.0%	8.0%	100.0%
Nuclear & Renewable Energy	0.2%	33.0%	12.1%	4.0%	8.7%	5.7%	10.6%	21.0%	4.6%	100.0%
Aerospace		16.6%	5.4%	5.4%	14.0%	35.2%	15.1%	7.5%	0.7%	100.0%
Health, Life Science & Medical Technology		41.2%	24.5%	7.0%	6.8%	17.1%	3.0%		0.4%	100.0%
Automotive	0.2%	13.0%	5.0%	8.0%	24.3%	24.7%	10.6%	5.4%	8.7%	100.0%
Construction		10.2%	3.6%	2.5%	16.5%	14.0%	15.1%	26.4%	11.8%	100.0%
Equipment Manufacturing		2.7%	14.1%	1.9%	16.4%	39.8%	11.7%	13.3%	0.3%	100.0%
Semiconductors		35.5%	28.6%	6.0%	8.3%	14.7%	5.1%	0.5%	1.4%	100.0%
Consumer Goods	0.4%	16.9%	9.0%	5.9%	12.2%	25.9%	12.2%	1.6%	16.1%	100.0%
Fossil Energy	6.6%	11.5%	6.6%	3.3%	9.8%	3.3%	17.2%	40.2%	1.6%	100.0%
Communications & Computing		64.4%	8.2%	2.7%	8.2%	6.8%	2.7%	4.1%	2.7%	100.0%
Defence		33.9%	17.7%	1.6%	14.5%	8.1%	19.4%	4.8%		100.0%
Other Sectors	0.5%	23.8%	11.6%	0.5%	19.0%	10.1%	9.0%	21.2%	4.2%	100.0%

Figure 17. Materials 4.0 R&I Projects by Sector and Value Chain Position (% of projects in sector)

The emphasis on Materials 4.0 activity is different across sectors. The construction, automotive, aerospace, equipment manufacturing and fossil energy sectors have comparatively more activity within product development, manufacturing and testing/inspection, whereas foundation industries, nuclear and renewables, semiconductors, health, life science and medical technology, and communications and computing have comparatively more activity at earlier stages of the value chain (materials processing and discovery, and synthesis and characterisation). Consumer goods and construction have most circularity-related Materials 4.0 activity.

These different emphases may point to opportunities for cross-sectoral learning on Materials 4.0 advances.

Materials 4.0 activity by material classes

Analysis of project data by material class largely mirrors the profile of Materials 4.0 activity across sectors, with higher shares of activity in product manufacturing, testing and in-service operations among structural materials, and higher shares of earlier stage Materials 4.0 activity within advanced functional and specialised materials.

Materials 4.0 appears to be more mature (i.e., with more activity across the value chain) within metals and alloys, glass and optical materials, composites, polymers, electronic and semiconductor materials and energy storage and conversion materials, which have activity in more even proportions across the value chain (Figure 18). This level of maturity is partly due to the fact that these are structural and functional materials classes.

Materials Classes Best (group)	Raw material extraction	Materials & processing discovery & design	Synthesis, characterisation ..	Scale-up & material production	Product development	Product manufacturing	Testing, inspection & certification	In-service (operations & maintenan..	Circularity	Grand Total
Glass & Optical Materials		8.3%	16.7%		6.3%	45.8%	10.4%	10.4%	2.1%	100.0%
Textiles & Fibres	3.4%	10.3%	6.9%		10.3%	6.9%	20.7%	3.4%	37.9%	100.0%
Construction & Structural Materials	0.9%	11.9%	8.8%	0.9%	11.9%	14.2%	13.3%	23.5%	14.6%	100.0%
Metals & Alloys	0.6%	17.0%	9.0%	3.7%	9.3%	32.7%	12.6%	11.0%	4.0%	100.0%
Composites		24.0%	7.8%	3.7%	13.4%	24.4%	15.7%	7.8%	3.2%	100.0%
Polymers & Plastics		27.0%	12.7%	6.7%	3.9%	27.3%	3.9%	2.4%	16.1%	100.0%
Electronic & Semiconductor Materi..		32.1%	19.7%	3.0%	14.5%	14.5%	6.8%	5.1%	4.3%	100.0%
Energy Storage & Conversion Materials	0.4%	38.1%	11.8%	6.6%	14.2%	6.8%	8.0%	9.1%	5.1%	100.0%
Biomaterials	0.6%	41.8%	21.5%	9.0%	6.6%	15.5%	2.1%	0.9%	2.1%	100.0%
Nanomaterials		42.9%	37.0%	11.0%	1.8%	3.7%	2.7%	0.9%		100.0%
Ceramics		45.1%	20.6%	4.9%	2.9%	14.7%	2.0%	6.9%	2.9%	100.0%
Smart & Functional Materials		48.7%	13.6%	3.9%	12.4%	5.5%	4.1%	11.3%	0.5%	100.0%
Functional Materials		50.0%	33.3%			16.7%				100.0%
Functional Polymers		66.7%	16.7%		16.7%					100.0%

Figure 18. Materials 4.0 R&I Projects by Material Class and Value Chain Position

Connecting Materials 4.0 activity

This initial framework development work has identified a series of Materials 4.0 use cases that could act as exemplars of the potential impact that better connected and increasingly supported Materials 4.0 activity could have on the economy, the environment and society.

To better understand where opportunities may exist to connect Materials 4.0 activity for these strategic use cases, the study team has also classified each research and innovation project according to its ‘best-fit’ strategic use case. These classifications have been used to identify example Materials 4.0 projects across the supply chain, and to illustrate where connections across initiatives may prove beneficial.

N.B. These projects are illustrative only and do not purport to present a complete picture of all Materials 4.0 activity associated with each strategic use case.

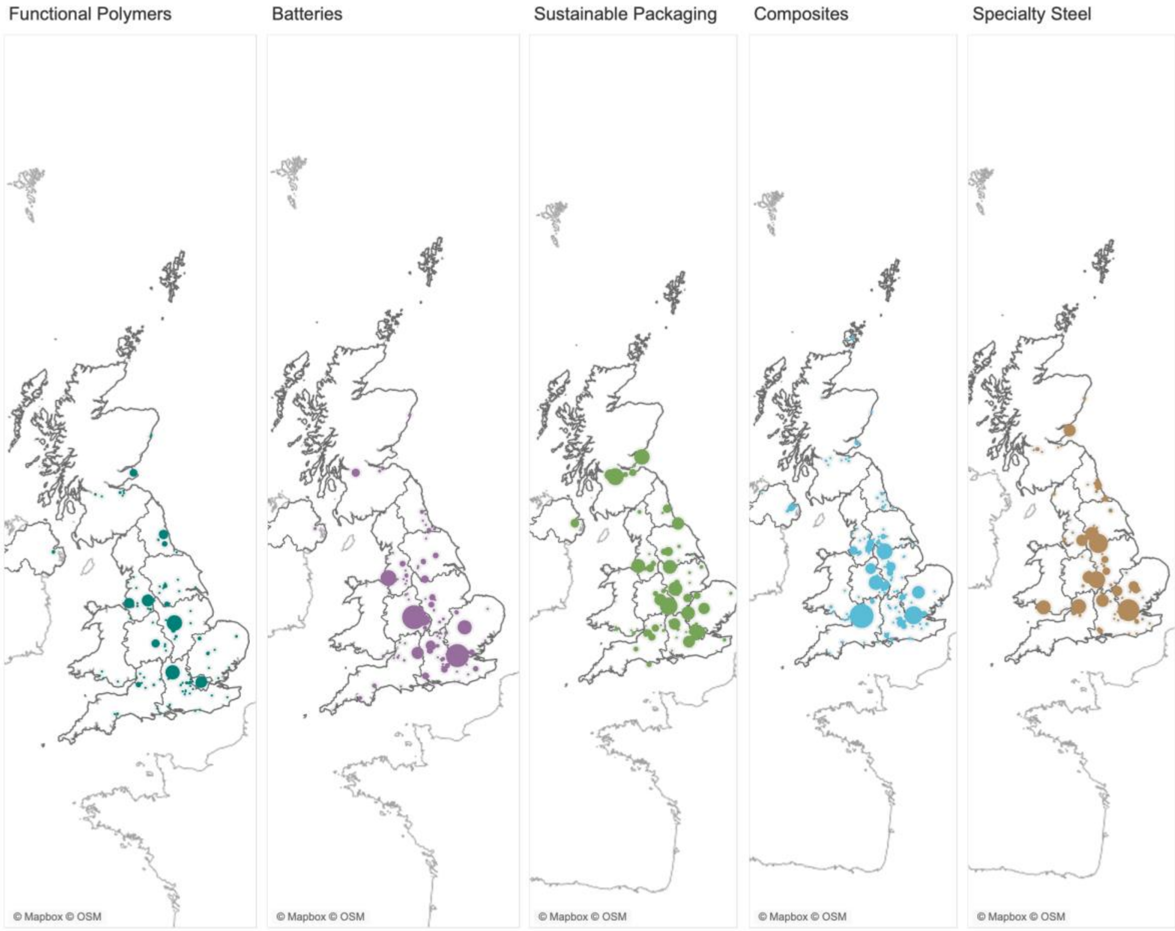

Figure 19. Current research and innovation projects aligned with the exemplar use cases of Materials 4.0.

Appendix 5: Rationale and potential impact of Materials 4.0

Materials 4.0 has the potential to transform the materials supply chain by reducing resource dependency, making supply chains more resilient, understanding carbon emissions, accelerating materials discovery and innovation, optimising complex processes, and maximising the lifespan and reuse value of advanced materials. Economic opportunities are generated by directly enhancing the speed, quality, and sustainability of materials development at every stage.

Adoption of Materials 4.0 involves the development of integrated tools, protocols and methods, infrastructure, and skills across the materials discovery, manufacturing and reuse stages. Developments in materials informatics and materials digitalisation are driving governing bodies (e.g., in the USA, China, and EU) to establish initiatives that support, enhance and capitalise on the systematic and widespread application of digital technologies in the materials lifecycle.

However, Manufacturing 4.0, Industry 4.0, and Materials 4.0 are often conflated within literature, and the economic potential of Materials 4.0 specifically is less well represented within the current list of sources. As a result, direct evidence of the differential benefits that Materials 4.0 may have across sectors or use cases is not readily available. Some preliminary evidence from existing literature indicates the following potential benefits.

Productivity and efficiency improvements

Quantified productivity gains

Several sources affirm the positive economic potential that digital adoption within manufacturing can have. Estimates of productivity gains range from 2% annually in Japan to 30% in Canada and Singapore within 5 years.

The Made Smarter Review estimated that UK industry could achieve a 25% increase in productivity through digital adoption by 2025[35], and a comprehensive review of literature drawn from other international locations points to similar levels of productivity improvements:

- Austria: 20% productivity gains over the next 5 years with Industry 4.0 applications.
- Canada: Productivity gains of 'up to 30% by 2025' with the adoption of digital technologies in the industry.
- Singapore: 30% boost in labour productivity by 2024 with the adoption of Industry 4.0.
- Japan: Over 2% labour productivity gains annually in manufacturing industries.

Programme monitoring data recorded as part of the Made Smarter Innovation Challenge indicated ~10% productivity improvement across the Challenge.

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[35] IfM / Innovate UK Digital Technology Impact Report

Specific operational improvements
Studies include some references to specific improvements in manufacturing efficiency, ranging from 15% - 30% as reported by manufacturing companies[36].

- 30% improvement in manufacturing efficiency achieved by local companies with the adoption of digital technologies.
- 15-20% increment in output observed by SMEs that have applied digital technologies.
- 20% efficiency gains (primarily SME results, reported in case studies).

Process-specific benefits
In some cases, process-specific benefits have been quantified. For example, an evaluation of the Made Smarter Innovation Challenge reported commercial benefits within case studies, including "150 workdays saved each year through automated production", and a "40% increase in the volume of sales resulting from increased speed and reliability of production".

Cost reduction
Literature provides empirical evidence regarding cost reductions made possible by digital applications within manufacturing businesses. For example:

- A survey of manufacturing SMEs in Korea suggested direct cost savings of 15% from a range of digital applications applied within manufacturing SMEs.
- Six companies involved in the Smart Manufacturing Data Hub (SMDH) reported a 22% decrease in energy consumption (equivalent to 162 tonnes of CO_2) due to the application of various industrial digital technologies (IDTs).
- Monitoring data from the Made Smarter Innovation Challenge reported an 11% reduction in waste due to the use of IDTs.

Quality improvements
Reports regarding the impact of digital manufacturing technologies highlight a range of quality improvements, including defect and error reduction (~45% reduction in defective product ratio), improved supply chain quality (70% reduction in the supply-demand imbalance), which leads to less waste, better quality control and improved product availability.

Delivery and time-to-market benefits
Digital manufacturing technologies have been shown to reduce delivery time. For example, Tata Steel used a machine learning algorithm to improve existing simulation process control modelling, ultimately reducing the time taken to determine optimised parameters for the process control model from six months to one week and resulting in a 90% reduction in reworks[37].

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[36] Ibid
[37] Made Smarter Innovation Challenge Evaluation

Employment and job creation

Various studies point to job creation as a benefit of digitalisation of manufacturing. Figures include 6 million jobs worldwide by 2025[38], 175,000 additional jobs throughout the UK economy[39], 390,000 jobs created due to Industry 4.0 over 10 years in Germany[40], or 50,000 jobs created by a 'Digital Technology Supercluster' between 2017-2027[41].

Some reference is made to UK-specific employment outcomes, including ~580 jobs created by the Made Smarter Innovation Challenge across 243 SMEs. These employment gains are estimated to be ~15% higher than two comparison groups[42].

Revenue and turnover growth

Digital manufacturing technologies are also reported to have increased revenues and turnover. Examples include a 20% increase in sales achieved by a company implementing Internet of Things solutions for quality control[43].

Over 80% of Made Smarter Innovation Challenge beneficiaries reported achieved or expected increases in turnover, with five respondents anticipating that outcomes from their project would result in more than £1m in additional turnover[44]. Much of the increase in sales generated by MSI participants that provide IDT solutions is export driven (£4.26m of a total £7m increase in sales revenue).

Gross Value Added (GVA) and economic output

Manufacturing 4.0 is estimated to have generated direct GVA of ~£168m for 243 SMEs involved in the Made Smarter Innovation Challenge (almost £700k per SME). The Advanced Manufacturing Research Centre (AMRC) employs 520 employees directly, generating an estimated £55.8m in GVA (~£105k per employee)[45].

In Germany, digitalising industry was estimated to generate €425bn in cumulative value added between 2016-2020 (€85bn per year). The adoption of digital technologies in manufacturing in Spain was expected to generate €120bn between 2017 and 2025 (€15bn per year).

UK GDP impact projections

A report on the potential GDP impact of emerging technologies suggests that the key technologies involved in Materials 4.0 could deliver a ~4% increase in UK GDP by 2035, and up to more than 5%, equivalent to between £103.4bn and £140.6bn[46].

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[38] Department of Business Enterprise & Innovation Ireland
[39] Made Smarter Review
[40] IfM / Innovate UK ibid
[41] Ibid
[42] Made Smarter Innovation Challenge Evaluation Report
[43] Department of Business Enterprise & Innovation Ireland
[44] Made Smarter Innovation Challenge Evaluation Report
[45] AMRC economic impact report
[46] The wider economic impacts of emerging technologies in the UK

Appendix 6: International benchmarking

Introduction

This section benchmarks leading international initiatives to identify key lessons and best practices to inform the development of a UK national framework for Materials 4.0. The review focuses on international programmes most relevant to the UK's Materials 4.0 ambitions, including:

- China: Materials Genome Initiative (MGE) & National New Materials Data Infrastructure
- France: DIADEM (PEPR)
- Germany: NFDI-MatWerk
- Japan: Materials DX Platform
- United States: Materials Genome Initiative (MGI)

SWOT analysis assessing the UK's relative position across the materials value chain is then outlined. Further details about each programme listed above are provided in the second part of this Appendix.

Insights from international programmes reviewed

Key findings from the international review are summarised in Table Table 77, while further details about each initiative are provided in the following sections.

Table 7. International review summary

Countries and leading national initiatives	Priorities across the Digital Elements	Priorities across the Materials Value Chain	Materials in focus
China: Materials Genome Initiative & National New Materials Data Infrastructure	• Data Attributes • Data Infrastructure • Algorithms and Models • Digital Tools and Techniques	• Material and process discovery and design • Synthesis, characterisation and metrology • Product development • Testing, inspection and certification	• Energy materials • Semiconductors and functional materials • High-temperature structural alloys • Biomedical materials • Composite materials
France: DIADEM Programme	• Data Infrastructure • Algorithms and Models	• Material and process discovery and design • Synthesis, characterisation and metrology • Testing, inspection and certification	• Innovative and sustainable materials • Advanced structural materials • Bio-sourced and recyclable materials • Hybrid and architectured materials • Nanomaterials and polymers

Germany: NFDI-MatWerk	• Data Attributes • Data Infrastructure	• Material and process discovery and design • Synthesis, characterisation and metrology	• Structural alloys and metallic systems • Ceramics and composites • Energy-relevant functional materials • Architectured and microstructure-engineered materials
Japan: Materials DX Platform (ARIM / MDPF / DxMT)	• Data Infrastructure • Algorithms and Models	• Material & process discovery and design • Synthesis, characterisation and metrology • Product development • Testing, inspection and certification	• Electrochemical energy storage and hydrogen-related materials • Magnetic and spintronic functional materials • Semiconductor, dielectric, and ferroelectric device materials • High-strength, extreme-environment structural alloys • Bio-adaptive and recyclable polymers for circular systems
United States: Materials Genome Initiative (MGI)	• Data Attributes • Data Infrastructure • Algorithms and Models • Digital Tools and Techniques	• Material & process discovery and design • Synthesis, characterisation and metrology	• Functional materials • Structural materials • Soft and biological materials • Critical and rare-earth-free materials

China's materials digitalisation strategy includes the Materials Genome Engineering (MGE) programme and the "1+N" National Materials Data Infrastructure to shift from trial-and-error experimentation to model-driven and data-centric innovation. The MGE, launched in 2016, integrates computational modelling, automated synthesis, and high-throughput characterisation. The "1+N" framework links a national data platform with domain-specific nodes across universities, laboratories and industries. Together, they accelerate discovery-to-application cycles and support strategic sectors such as aerospace, energy, semiconductors and biomedical materials.

Led by the Ministry of Science and Technology, Ministry of Industry and Information Technology and the National Data Administration, the strategy is highly centralised, focusing on data standardisation, infrastructure and automation. Unified metadata frameworks and interoperable platforms ensure traceable, comparable data across institutions. Industrial participation occurs through consortia that connect research with prototype development, particularly in high-performance and critical materials. Downstream manufacturing and circularity are handled by separate policies.

France’s DIADEM Priority Research Programme and Equipment (PEPR), launched in 2022 under the France 2030 investment plan, aims to accelerate the discovery, design, and deployment of new materials by integrating simulation, AI, data management and high-throughput experimentation. With a total budget of €85 million (2022–2030), it seeks to shorten materials development cycles, strengthen technological sovereignty, and support green transition.

The programme emphasises digital infrastructure and AI-enabled modelling, supported by national high-throughput and characterisation facilities. However, ontology and data standardisation remain fragmented, and automation adoption is uneven. Industrial engagement focuses on energy, aerospace, and advanced manufacturing, while the programme’s main activities span design, synthesis, characterisation, and testing within the materials value chain. Its research agenda centres on sustainable and high-performance materials, including bio-sourced, recyclable, architectured, and nanostructured systems.

Germany’s National Research Data Infrastructure for Materials Science and Engineering (NFDI-MatWerk), launched in 2021, serves as the country’s central initiative to standardise and integrate materials research data. Currently in its first funding phase (2021–2026) with €13–15 million in support, it aims to build a FAIR-compliant, ontology-aligned, and community-governed data ecosystem that connects experimental, computational and analytical workflows. The programme aims to address the fragmentation of laboratory data practices, enhance reproducibility, and enable interoperability among research groups and infrastructures across the materials domain. It aligns closely with broader German and European priorities on research data sovereignty and Open Science, supporting integration with oneNFDI and the European Open Science Cloud (EOSC).

The initiative concentrates on design, synthesis and characterisation in the materials value chain. The German Research Foundation (DFG) leads the coordination. The implementation is conducted across universities, Helmholtz, Fraunhofer and specialised research centres. Industry engagement focuses on advanced manufacturing, automotive materials, and energy technologies. Other programmes under the NFDI (Nationale Forschungsdateninfrastruktur) consortium, led by the DFG, include FAIRmat, which focuses on condensed matter and the chemical physics of solids.

Japan’s Materials DX Platform is a national initiative to accelerate materials innovation through automated experimentation, data-centric research and AI-driven modelling. The initiative unites three key programmes: ARIM, a nationwide network of shared experimental facilities; MDPF, a unified materials data platform; and DxMT, a data-driven R&D programme targeting strategic materials. With over ¥78 billion (~ £385.6 million) in investment, the initiative seeks to strengthen Japan’s position in automotive, hydrogen, semiconductors and energy sectors, where research directly supports product development.

The initiative builds on Japan’s established strengths in semiconductors, precision alloys, and energy materials, while advancing recyclable and functional polymers aligned with national sustainability goals. The platform combines robust data infrastructure and model-driven design.

The Materials Genome Initiative (MGI), launched in 2011, is the United States' flagship strategy to accelerate the discovery, design and deployment of advanced materials. Its primary goal is to shorten innovation cycles and strengthen U.S. industrial competitiveness. MGI brings together major federal agencies, including the DOE, DoD, NSF, NIST, and NASA, alongside universities, national laboratories and industry associations such as Manufacturing USA. Over USD 500 million has been invested in its first five years.

MGI drives progress across all four elements of Materials 4.0. The initiative emphasises full value-chain integration and links research outputs with applications in energy, aerospace, defence and healthcare. Priority materials include functional, structural, and soft/biological systems, as well as critical and rare-earth-free materials that enhance supply chain resilience.

Overall, the U.S. and China lead in both the comprehensive coverage of Materials 4.0 elements and strong industrial integration. Germany and Japan excel in data standardisation and model-driven design, while France demonstrates an advantage in AI-enabled and integrated experimentation. Beyond these flagship programmes, however, many countries are also pursuing targeted initiatives to accelerate the adoption of advanced materials in manufacturing and downstream value-chain applications across industries, including Made in China 2025 and Manufacturing USA.

The UK's position in Materials 4.0 compared to international programmes

Table 8. SWOT analysis summary (compared to international programmes)

Strengths (S)	Weaknesses (W)
• **Early-stage material discovery and research**: The UK's core strengths lie in materials and process discovery, synthesis and characterisation, and testing, inspection and certification. • **Explainable materials modelling**: The UK leads in explainable materials modelling, built on mature structure-property-process ontologies spanning academia and industry. This foundation supports transparent and traceable model inference. Unlike the U.S. and China, which prioritise scale and autonomous optimisation, the UK focuses on scientific interpretability and validation-led model design. • **Validation capabilities**: In-situ and operando characterisation and advanced metrology infrastructures create closed verification loops linking simulation, experimentation and certification. • **Distributed research infrastructure**: The Henry Royce Institute, Catapult Centres, and regional advanced manufacturing hubs form a distributed R&D-to-prototype	• **Lack of nationwide data governance**: The UK excels in mechanism-informed modelling within research domains but lacks a national coordination body to align semantic standards, data schemas and metadata conventions across sectors. This results in fragmented data ontology and limits interoperability within the data infrastructure. In contrast, Germany and China have established central coordination authorities for integration. • **Automation limited to isolated centres of excellence**: The UK hosts advanced digital laboratories and automated characterisation environments, but these remain concentrated in select institutions. Compared to the U.S., where automation supports data accumulation at scale, and Japan, where lab clusters are embedded in industry, the UK's digital maturity is node-strong but network-weak. • **Limited manufacturing, lifecycle and circularity integration**: The UK is strong in modelling and validation, yet translation into manufacturing, use-phase monitoring,

network, supporting mid-TRL (technology readiness level) scale-up. • **Industrial anchoring**: Key UK industries, including renewable energy, automotive, nuclear, aerospace, defence and medical materials, act as testbeds, demonstrating early adoption of digital materials.	repair/refurbishment and circularity (5Rs) remains discontinuous. In contrast, China and Japan maintain design-to-manufacture pipelines that shorten R&D-to-production transitions.
Opportunities (O)	**Threats (T)**
• **Ontology leadership**: As Materials 4.0 advances toward model credibility, semantic consistency, and structured knowledge representation, the UK see the chances to lead the creation of shared materials ontologies and validation frameworks grounded in mechanism-based modelling and traceable evidence. • **Interoperability advantage across partner countries**: With its distributed research infrastructure and collaborative culture, the UK can act as a bridge between Europe, North America, and Asia-Pacific, fostering interoperability and trusted data exchange across international materials innovation networks. • **Industries as testbeds**: The UK's strengths in renewable energy, automotive, nuclear, aerospace, defence and medical materials provide practical demonstration environments for Materials 4.0, including model-based design, closed-loop experimentation, and evidence-based qualification.	• **Accelerating gap with leading countries**: The U.S. is rapidly advancing autonomous laboratories, AI-powered experiment design and high-throughput discovery pipelines, accelerating the refinement and deployment of models. The UK's strengths in modelling and validation are not yet matched by comparable automation and execution, creating a potential speed gap in materials innovation cycles. • **Platform exclusion risk**: Germany and China are building national-scale materials data platforms and interoperability frameworks, setting structural standards for materials knowledge storage, exchange and certification. Without a coherent national data integration and exchange strategy, UK research outputs might risk becoming semantically incompatible with emerging global ecosystems. • **Manufacturing integration competitors**: China and Japan continue to advance design-to-manufacturing integration, aligning modelling, process optimisation, prototyping and production. UK's strength in discovery, modelling and verification may remain confined to the research phase unless methods and data structures extend into process qualification, scale-up and lifecycle traceability. • **Talent and funding competition**: The EU and U.S. are expanding targeted investments in materials data science, computational materials engineering and digital laboratory operations, supported by strong incentives for facility-based research careers. The UK faces increasing pressure to retain and attract interdisciplinary talent capable of integrating materials science, computation, measurement and automation.

China – Materials Genome Initiative & National New Materials Data Infrastructure

Summary table

China – Materials Genome Initiative & National New Materials Data Infrastructure			
Leading institutions: • Ministry of Science and Technology • State Council Science and Technology strategy bodies • Ministry of Industry and Information Technology • National Data Administration		**Less emphasis**	**Primary emphasis**
Policy focuses	Investment		●
	Infrastructure		●
	Public–research–private collaboration		●
	Skills	●	
4 key elements of Materials 4.0	Data Attributes		●
	Data Infrastructure		●
	Algorithms and Models		●
	Digital Tools and Techniques		●
Stakeholders	National		●
	International	●	
Material value chain	Raw material extraction	●	
	Material & process discovery and design		●
	Synthesis & characterisation		●
	Product development		●
	Product manufacturing	●	
	Testing / inspection / certification		●
	In-service (operation & maintenance)	●	
	Circularity 5Rs	●	
Focused materials	o Energy materials o Semiconductors and functional materials o High-temperature structural alloys o Biomedical materials o Composite materials		

Overview

China's materials digitalisation strategy is anchored in the **Materials Genome Engineering (MGE) programme**, launched in 2016 and advanced through successive rounds of the National Key R&D Programme. The initiative promotes a transition from trial-and-error experimentation to model-driven, data-centric materials discovery and optimisation[47].

In parallel, China has established a national **"1+N" materials data infrastructure** (initiated between 2018–2021 and now expanding),[48] comprising a central data platform

[47] Ministry of Industry and Information Technology (2017), "材料基因工程关键技术与支撑平台"重点专项 2017 年度项目申报指南, 国家重点研发计划

[48] Ministry of Industry and Information Technology (2024), 关于印发《新材料大数据中心总体建设方案》的通知.

linked to distributed domain-specific resource nodes across universities, national laboratories and key industrial sectors. This system provides standardised data governance, graded security controls and interoperable interfaces for computational design, high-throughput experimentation and applied validation.

Together, these two pillars aim to **shorten development cycles and accelerate industrial deployment**, integrating digital R&D into strategic domains such as **aerospace, energy systems, semiconductors, advanced manufacturing, and biomedical materials.**

Leading institutions

- Strategic direction and policy coordination are led by **the Ministry of Science and Technology (MOST)** and **State Council Science and Technology strategy bodies**, which define national priorities for materials digitalisation and align them with broader industrial and technological goals, including Made in China 2025 and the Strategic Emerging Industries framework.
- Oversight of the national materials data infrastructure is jointly managed by the **Ministry of Industry and Information Technology (MIIT)** and the **National Data Administration (NDA)**. These bodies oversee the **National New Materials Big Data Center** under the "1+N" architecture, setting standards for data formats, interfaces, security levels, and exchange protocols.

Policy focuses

Investment

Multi-year investment is channelled through the **National Key R&D Programme (NKP)**. The National New Materials Big Data Center is financed through **ministerial co-investment mechanisms**, ensuring sustained platform development and operation. Funding is allocated to consortia that integrate high-throughput modelling, automated experimentation, and structured data deposition. Projects are required to promote collaboration among universities, national laboratories and industrial research units.

Infrastructure

The **National New Materials Big Data Center** serves as the core of the "1+N" materials data infrastructure, linking a central national platform with domain-specific data nodes across laboratories, research institutes and industrial sectors. This structure operates under **unified data governance and security standards**.

Public–Research–Private Collaboration

Collaboration occurs through task-oriented joint development consortia, integrating computational modelling, automated experimentation and data deposition into application-focused material development pipelines—notably in **aerospace alloys, battery systems, and semiconductor materials**.

Skills

Skills development is largely institution-led, and a national professional training framework is still under development.

Four digital elements of Materials 4.0

Data Attributes

National standardisation bodies have developed unified metadata, classification, and provenance frameworks, enabling materials data to be structurally comparable and interoperable across research organisations and industrial sectors.

Data Infrastructure
The “1+N” national materials data infrastructure establishes a **central–distributed platform architecture**, linking a core national data centre with domain-specific resource nodes operating under graded security and controlled-access governance.

Algorithms and Models
Predictive modelling and machine learning tools are increasingly applied within MGE research consortia[49, 50].

Digital Tools and Techniques
High-throughput experimentation, automated synthesis and integrated data acquisition–analysis toolchains are established in key national institutes, enabling closed-loop iteration between simulation, experiment and property evaluation.

Stakeholders

- Research leadership is concentrated in leading universities and **Chinese Academy of Sciences (CAS) institutes,** which provide core capabilities in computational modelling, high-throughput experimentation and advanced characterisation.
- Industry participation occurs through application-oriented joint development, primarily in aerospace, semiconductors, battery technologies, and advanced manufacturing, where **performance requirements directly shape research priorities**.
- The broader ecosystem is connected through the “1+N” national materials data infrastructure, which links a central platform with domain-specific data nodes, circulating standardised data practices across institutions. International collaboration focuses on standards dialogue and research exchange.

Materials value chain

- The programmes **emphasise the mid–upstream segments of the value chain**, integrating model-driven design, high-throughput synthesis, characterisation and performance validation.
- **Prototype-level product development** is a key strength, particularly in aerospace alloys, battery materials, semiconductor, and biomedical materials, where application requirements are explicitly embedded in MGE task structures.
- **Large-scale manufacturing**, in-service performance monitoring and circularity strategies lie outside the core functions of the MGE framework and are instead **managed through separate industrial policy**.

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[49] Xie, K., et al. (2022). A Vision of Materials Genome Engineering in China. Engineering, 9(1), 1–12. https://doi.org/10.1016/j.eng.2021.12.008
[50] Ministry of Industry and Information Technology (2017), “材料基因工程关键技术与支撑平台”重点专项 2017 年度项目申报指南, 国家重点研发计划

Focused materials

China's Materials Genome Engineering (MGE) programme and related initiatives prioritise high-performance and strategically essential material systems, particularly those **supporting energy security, advanced manufacturing, national defense, and next-generation information technologies**. Key focus areas include:

- **Energy materials**: nuclear fuel and cladding, hydrogen-related materials, and catalytic systems.
- **Semiconductors and functional materials**: Including rare-earth functional materials for electronics and photonics applications.
- **High-temperature structural alloys**: Co-based and Nb-silicide alloys, and special steels for high-end equipment.
- **Biomedical materials**: Degradable stents, diagnostic materials, and therapeutic systems for tumour treatment.
- **Composite materials**: Metal, ceramic, and polymer-matrix composites, particularly those requiring high-throughput design and rapid demonstration.

France – DIADEM Programme (PEPR: Integrated Devices to Accelerate the Deployment of Emerging Materials)

Summary table

France – DIADEM Priority Research Program and Equipment (PEPR)			
Leading institutions: • **French National Research Agency (ANR)**		**Less emphasis**	**Primary emphasis**
Policy focuses	Investment		●
	Infrastructure		●
	Public–research–private collaboration	●	
	Skills	●	
4 key elements of Materials 4.0	Data Attributes	●	
	Data Infrastructure		●
	Algorithms and Models		●
	Digital Tools and Techniques	●	
Stakeholders	National		●
	International	●	
Material value chain	Raw material extraction	●	
	Material & process discovery and design		●
	Synthesis & characterisation		●
	Product development	●	
	Product manufacturing	●	
	Testing / inspection / certification		●
	In-service (operation & maintenance)	●	
	Circularity 5Rs	●	
Focused materials	o Innovative and sustainable materials o Advanced structural materials o Bio-sourced and recyclable materials o Hybrid and architectured materials o Nanomaterials and polymers		

Overview

Launched in 2022 under the France 2030 investment plan,[51] the DIADEM Priority Research Programme and Equipment (PEPR)[52] aims to accelerate the discovery, design and deployment of new materials by integrating simulation, artificial intelligence (AI), data management and high-throughput experimentation. The programme seeks to shorten materials development cycles, strengthen national technological sovereignty and support the energy transition and green industrialisation.[53]

Leading institutions

- **National Coordination**: The programme is coordinated nationally by **ANR** (the French National Research Agency) within the France 2030 strategic investment framework.
- **Research Implementation**: Activities are implemented through **CNRS** (the National Centre for Scientific Research) laboratories, universities, and national

[51] Government of France (2024). *Understanding France 2030: Grand Dossier.*
[52] PEPR DIADEM. Le PEPR. *Official website*
[53] Agence nationale de la recherche (ANR). *Call for Proposals – PEPR DIADEM 2023*

research organisations, supported by large-scale characterisation infrastructures such as **SOLEIL**[54] (the French national synchrotron) and **ESRF**[55] (the European Synchrotron Radiation Facility in Grenoble).

- **Industry Engagement**: Industry partners participate mainly through co-development projects focused on digitally enabled materials processing and design-to-manufacture integration.

Policy focuses

Investment

Funded through public research investment under the **France 2030 framework**, delivered via competitive PEPR calls. The programme has a **total budget of €85 million over eight years (2022–2030)**,[56] supporting national-scale collaboration in data- and AI-driven materials research.

Infrastructure

Focus on the development of **shared experimental and digital research infrastructure**, including high-throughput synthesis and characterisation platforms, data environments and integrated simulation tools.

Public–Research–Private Collaboration

Partnerships tend to form around existing academic networks, rather than through mandated cross-sector integration.

Skills

Skills development in AI, data management and computational materials is incorporated as a complementary activity.

Four digital elements of Materials 4.0

France demonstrates strong capability in digital infrastructure and modelling, while data attributes, standardisation and automation remain at early or uneven stages.

Data Attributes

Development of shared metadata and semantic structures is ongoing but fragmented, progressing mainly within individual research consortia rather than through a unified national framework.

Data Infrastructure

Substantial investment supports integrated experimental–digital facilities, including high-throughput platforms and national characterisation centres such as SOLEIL and ESRF, which provide coordinated access and consistent data environments.

Algorithms and Models

Artificial intelligence (AI), machine learning, and multi-scale modelling serve as core research engines within DIADEM, driving predictive materials optimisation and reducing iteration cycles.

Digital Tools and Techniques

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[54] Synchrotron SOLEIL. English Site.
[55] ESRF. Home Page.
[56] CNRS (2023). PEPR Emerging Materials – DIADEM.

Automation, robotics, and real-time workflow integration are adopted in selected leading laboratories, but deployment remains uneven and is not yet standardised across the national network.

Stakeholders

Primary stakeholders include universities, CNRS laboratories, national research organisations and large-scale research infrastructures. These actors contribute expertise in modelling, synthesis and advanced characterisation.

Industrial participation mainly takes place through co-development collaborations in strategic sectors such as **energy, aerospace, mobility, and advanced manufacturing** (e.g., Safran, Airbus). International involvement exists but remains limited, as funding eligibility and programme governance primarily prioritise French public research institutions and domestic strategic industries.

The broader research ecosystem functions through project-based consortia and thematic hubs, linking the material research and development from design to testing. Cross-border collaboration focuses mainly on knowledge exchange, keeping the programme predominantly nationally oriented.

Materials value chain

The DIADEM PEPR focuses on the upstream segment of the value chain, with strong integration across the stages of design → synthesis → characterisation → testing, while scale-up, deployment and circularity remain outside the programme's primary scope.

- **Strong emphasis on material and process discovery and design**, driven by computational modelling, AI-based exploration and hypothesis-free formulation.
- **Substantial involvement in synthesis and characterisation**, supported by high-throughput platforms and national synchrotron facilities (e.g., SOLEIL, ESRF) that enable rapid structure-property validation and iterative optimisation.
- **Strength in testing, inspection, and certification**, particularly through in-situ and operando characterisation, which supports quality assurance and reliability assessment during early development stages.
- Downstream manufacturing, in-service performance, and circularity considerations are not core priorities of the programme and are expected to be addressed through separate industrial, sectoral or other initiatives outside DIADEM.

Focused materials

- **Innovative and sustainable materials** for low-carbon energy and digital technologies
- **Advanced structural materials**, including alloys, ceramics and composites with high-entropy systems
- **Bio-sourced and recyclable materials** aimed at reducing environmental impact
- **Hybrid and architectured materials** developed through additive and 4D manufacturing
- **Nanomaterials and polymers** designed using AI-assisted modelling and high-throughput screening

France's materials research agenda places strategic emphasis on **advanced functional and structural materials** that support the **energy transition and reinforce national technological sovereignty**.

Germany – NFDI-MatWerk

Summary table

1.Germany – NFDI-MatWerk			
Leading institution: German Research Foundation		**Less emphasis**	**Primary emphasis**
Policy focuses	Investment		●
	Infrastructure		●
	Public–research–private collaboration		●
	Skills	●	
4 key elements of Materials 4.0	Data Attributes		●
	Data Infrastructure		●
	Algorithms and Models	●	
	Digital Tools and Techniques	●	
Stakeholders	National		●
	International	●	
Material value chain	Raw material extraction	●	
	Material & process discovery and design		●
	Synthesis & characterisation		●
	Product development	●	
	Product manufacturing	●	
	Testing / inspection / certification	●	
	In-service (operation & maintenance)	●	
	Circularity 5Rs	●	
Focused materials	o Structural alloys and metallic systems o Ceramics and composites o Energy-relevant functional materials o Architectured and microstructure-engineered materials		

Overview

Approved and launched in 2021, the National Research Data Infrastructure for Materials Science and Engineering (NFDI-MatWerk)[57] represents Germany's core strategy to standardise and integrate materials research data across institutions.[58] The initiative is currently in its **first five-year funding phase (2021–2026)**. It focuses on building a FAIR (Findability, Accessibility, Interoperability and Reusability)-compliant, ontology-aligned, and community-governed data ecosystem that connects experimental, computational and analytical workflows.[59]

The programme aims to **address the fragmentation of laboratory data practices, enhance reproducibility, and enable interoperability** among research groups and infrastructures across the materials domain. It aligns closely with broader German and

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[57] NFDI-MatWerk Consortium. *About the NFDI-MatWerk Project.*
[58] NFDI-MatWerk Consortium (2024). NFDI-MatWerk Renewal Proposal. National Research Data Infrastructure (NFDI).
[59] NFDI-MatWerk Konsortium (2021). Nationale Forschungsdateninfrastruktur für Materialwissenschaft & Werkstofftechnik.

European priorities on research data sovereignty and Open Science, supporting integration with oneNFDI and the European Open Science Cloud (EOSC).[60]

Leading institutions

- National coordination is implemented through the **National Research Data Infrastructure (NFDI) programme**, with NFDI-MatWerk operating under the **German Research Foundation (DFG)** oversight and guided by community-led governance structures.
- Operation is distributed across universities, Helmholtz and Fraunhofer centres, and specialised research institutes, which contribute to data generation and ontology standardisation.
- Industry engagement occurs mainly through applied research collaborations and standards alignment, while the core programme remains led by research institutions.

Policy focuses

Investment

Supported through a multi-year national investment under the National Research Data Infrastructure (NFDI) programme, with approximately **€13–15 million allocated for the first funding phase (2021–2026)** to establish a materials research data infrastructure. The funding is strategically targeted toward **data standardisation, ontology development and infrastructure coordination**.

Infrastructure

The initiative emphasises FAIR-compliant data services, high-performance computing (HPC) integration, cross-laboratory documentation and metadata standards, forming the backbone of its implementation strategy.

Public–research–private collaboration

Organised around community-led working groups and interoperability forums, the initiative promotes joint development of ontologies and data-sharing agreements, ensuring cross-institutional consistency and data reuse.

Skills

Training activities focus on data stewardship and research data management, delivered mainly through workshops and community knowledge exchange. These efforts are supportive, and the initiative does not yet include a large-scale professional development pathway.

Four digital elements of Materials 4.0

Germany's digitalisation efforts within NFDI-MatWerk emphasise **semantic standardisation and data infrastructure**, while model development is supported indirectly and tool-level implementation remains largely decentralised.

Data Attributes

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[60] European Commission. European Open Science Cloud (EOSC).

A central priority is the creation of unified ontologies and semantic standards to represent materials data consistently across experiments, simulations and characterisation. This includes the development of standardised metadata structures, controlled vocabularies and domain-level schema alignment.

Data Infrastructure
The programme makes substantial investments in FAIR-compliant data platforms, repository architectures, and HPC-enabled data services, ensuring long-term preservation, findability and cross-laboratory interoperability.

Algorithms and Models
Computational models are supported indirectly through integration frameworks, instead of through development of new algorithms or modelling engines.

Digital Tools and Techniques
Practical lab-to-digital toolkits, such as electronic lab notebooks (ELNs) and digital twin toolchains, remain heterogeneous across institutions. Their adoption depends largely on local capabilities and project-level initiatives.

Stakeholders
The NFDI-MatWerk programme is anchored in **Germany's public research system**, with participation centred on universities, Helmholtz Centres, Fraunhofer Institutes, and DFG-supported laboratories. Together, these institutions contribute deep expertise in structural materials, compositional processing, and high-resolution characterisation.

Industry engagement is selective and application-oriented, concentrated in sectors where Germany maintains long-standing competitive strengths, including **advanced manufacturing, automotive materials, mechanical systems, and energy technologies**.

International participation remains limited, as the initiative **prioritises domestic interoperability and data sovereignty**. Cross-border collaboration focuses mainly on knowledge exchange and alignment with European research frameworks, such as the European Open Science Cloud (EOSC).

Materials value chain
Germany's NFDI-MatWerk initiative focuses on design, synthesis and characterisation, while manufacturing and lifecycle integration fall outside the programme's core mandate.

Early Design and Discovery
The emphasis lies in materials discovery and design, where standardised data structures and computational–experimental integration enable systematic exploration of material systems.

Synthesis and Characterisation
These activities are well supported, leveraging shared data infrastructure, harmonised documentation practices and technology platforms that enable high-throughput validation and iterative refinement of material properties.

Product Development and Testing

Engagement in product development and testing occurs selectively, often when prototype validation requires traceability and reproducibility across multiple research sites.

Focused materials

- **Structural alloys and metallic systems**: High-performance steels, lightweight alloys, and systems critical to forming and processability.
- **Ceramics and composites**: Areas where microstructure–property relationships require high-resolution characterisation.
- **Energy-relevant functional materials**: Electrochemical, catalytic and semiconductor materials, where reproducibility and cross-laboratory comparability are essential.
- **Architectured and microstructure-engineered materials**: Iterative design–processing–validation loops supported by consistent data semantics.

Overall, Germany's materials work under NFDI-MatWerk is oriented toward **structural and functional materials**, consolidating long-standing national expertise while reinforcing data-centric innovation practices.

Japan – Materials DX Platform (ARIM / MDPF / DxMT)

Summary table

Japan – Materials DX Platform (ARIM / MDPF / DxMT)			
Leading institutions: • **Ministry of Education, Culture, Sports, Science and Technology** • **National Institute for Materials Science**		**Less emphasis**	**Primary emphasis**
Policy focuses	Investment		●
	Infrastructure		●
	Public–research–private collaboration		●
	Skills	●	
4 key elements of Materials 4.0	Data Attributes	●	
	Data Infrastructure		●
	Algorithms and Models		●
	Digital Tools and Techniques	●	
Stakeholders	National		●
	International	●	
Material value chain	Raw material extraction	●	
	Material & process discovery and design		●
	Synthesis & characterisation		●
	Product development		●
	Product manufacturing	●	
	Testing / inspection / certification		●
	In-service (operation & maintenance)	●	
	Circularity 5Rs	●	
Focused materials	o Electrochemical energy storage and hydrogen-related materials o Magnetic and spintronic functional materials o Semiconductor, dielectric, and ferroelectric device materials o High-strength, extreme-environment structural alloys o Bio-adaptive and recyclable polymers for circular systems		

Overview

Japan's Materials DX Platform[61] serves as a national strategy to accelerate materials innovation through the integration of automated experimentation, data-centric research, and AI-driven modelling across academia, national laboratories and industry.

The platform functions as a coordinated system of three interconnected programmes

- **ARIM (Advanced Research Infrastructure for Materials & Nanotechnology)**: Upgrades and networks shared experimental facilities nationwide.
- **MDPF (Materials Data Platform)**: Collects, structures, and manages high-quality materials data within a nationally unified data backbone.
- **DxMT (Data-Creation and Application-Oriented Materials R&D)**: Advances data-driven research in strategically important materials domains.

[61] National Institute for Materials Science (2025). Pioneering Material DX: Conquering the Challenging Path to Success. Interview article, Materials Data Platform (MDPF).

The initiative has evolved since the mid-2010s under Japan's Materials DX and Society 5.0 policy frameworks.

Its goal is to transform materials research from experience-based iteration to end-to-end data-driven innovation, reinforcing Japan's competitiveness in **energy systems, semiconductors, mobility materials, and sustainable manufacturing**.

Leading institutions

- The programme is coordinated by the **Ministry of Education, Culture, Sports, Science and Technology** (MEXT), with the **National Institute for Materials Science** (NIMS) serving as the central organising body responsible for strategic direction, data governance and cross-programme integration within the Materials DX framework.[62]
- The initiative operates through a distributed national research network comprising **ARIM shared research facilities**, the **Materials Data Platform (MDPF)** and **DxMT thematic research centres** hosted at major universities and national laboratories. Together, these components enable coordinated experimentation, data management and model-driven materials development.

Policy focuses

Investment

Supported through long-term strategic funding under MEXT, including approximately **¥14 billion (~ £69 million) for the DxMT programme**, **¥9 billion (~ £44.6 million)** for the establishment of the **Materials Data Platform (MDPF)**, and **¥55 billion (~ £272 million) for the ARIM national shared research infrastructure**, based on the FY2025 budget request.[63] The approach emphasises platform continuity and sustained capability building.

Infrastructure

Centred on the **ARIM national shared facility network** and the **Materials Data Platform (MDPF)**, the initiative provides coordinated access to **advanced experimentation, characterisation, and data management resources**.

Public–Research–Private Collaboration

The **DxMT programme** links universities, national laboratories, and industrial R&D teams through co-development clusters, embedding digital workflows directly into priority sectors such as **automotive, semiconductors, and energy systems and advanced manufacturing**.[64]

Skills

Skills development remains institution-led and decentralised.

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[62] Ministry of Education, Culture, Sports, Science and Technology (2024). マテリアル革新力強化戦略に基づく文部科学省の取組

[63] Ministry of Education, Culture, Sports, Science and Technology (2024). マテリアル革新力強化戦略に基づく文部科学省の取組

[64] National Institute for Materials Science (2024). NIMS 概要 2024.

Four digital elements of Materials 4.0

Japan's Materials DX Platform emphasises robust data infrastructure and model-driven R&D, while ontology standardisation and tool-level implementation remain distributed across institutions.

Data Attributes

Metadata standards and data structuring practices are actively promoted but not yet fully harmonised, with ontology adoption varying across institutions and research clusters.

Data Infrastructure

The ARIM shared facility network, and the Materials Data Platform (MDPF) provide nationally coordinated environments for data storage, access and integration, forming the backbone of Japan's Materials DX architecture.

Algorithms and Models

Model-based materials design and machine learning (ML) are central to DxMT, positioning computational guidance as a key driver of materials research and development.

Digital Tools and Techniques

Practical digital tools for laboratory research and manufacturing are developed on a project-by-project basis.

Stakeholders

Primary stakeholders include major universities, national laboratories and **NIMS-led research platforms**, supported by the **ARIM shared facility network** and the **Materials Data Platform (MDPF)**. These institutions contribute expertise in model-driven materials design, high-resolution characterisation and data-centric experiments.

Industrial participation occurs mainly through co-development projects in sectors such as **automotive, semiconductors, hydrogen and battery systems, and precision manufacturing**. Collaboration typically focuses on design, prototyping and reliability evaluation.

The broader ecosystem operates through distributed research consortia and thematic DxMT hubs, which coordinate modelling, synthesis and testing activities. International collaboration focuses on research exchange and interoperability discussions, while core governance and infrastructure development remain nationally led.

Materials value chain

Japan's Materials DX Platform **concentrates on the mid–upstream stages** of the materials innovation process, integrating design, synthesis, characterisation and prototype development into a unified data flow. Raw material sourcing, large-scale manufacturing integration, in-service lifecycle monitoring and circularity strategies fall outside the core objectives of Materials DX and are instead addressed through separate industrial and environmental policy frameworks.

Focused materials

Japan's Materials DX Platform follows a continuity strategy, building on **long-standing industrial strengths** in semiconductors, energy materials and precision structural alloys, while deliberately expanding into recyclable and functional polymer systems aligned with future sustainability goals. Key focus areas include:

- → Electrochemical energy storage and hydrogen-related materials
- → Magnetic and spintronic functional materials
- → Semiconductor, dielectric, and ferroelectric device materials
- → High-strength, extreme-environment structural alloys
- → Bio-adaptive and recyclable polymers for circular systems

United States – Materials Genome Initiative (MGI)

Summary table

United States – Materials Genome Initiative (MGI)			
Leading institutions: • White House Office of Science and Technology Policy (OSTP) • National Science and Technology Council (NSTC)		**Less emphasis**	**Primary emphasis**
Policy focuses	Investment		●
	Infrastructure		●
	Public–research–private collaboration		●
	Skills	●	
4 key elements of Materials 4.0	Data Attributes		●
	Data Infrastructure		●
	Algorithms and Models		●
	Digital Tools and Techniques		●
Stakeholders	National		●
	International	●	
Material value chain	Raw material extraction	●	
	Material & process discovery and design		●
	Synthesis & characterisation		●
	Product development	●	
	Product manufacturing	●	
	Testing / inspection / certification	●	
	In-service (operation & maintenance)	●	
	Circularity 5Rs	●	
Focused materials	o Functional materials o Structural materials o Soft and biological materials o Critical and rare-earth-free materials		

Overview

Launched in 2011, the Materials Genome Initiative (MGI) is a long-term national strategy designed to accelerate the **discovery, design, development and deployment of advanced materials** through the integration of data, computation and experimentation. The initiative's overarching goal is to reduce the time and cost associated with materials innovation while enhancing the competitiveness of U.S. manufacturing.[65]

MGI seeks to address three systemic challenges within the U.S. materials innovation ecosystem:

- Fragmentation of materials data and the absence of interoperable standards
- Slow translation of research outcomes into deployable technologies

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[65] The White House Office of Science and Technology Policy (2011). Materials Genome Initiative.

- Limited digital infrastructure and workforce capacity to support AI-driven materials R&D

By tackling these issues, MGI aims to establish **a cohesive national ecosystem** that connects research, data and industrial application across sectors including energy, defense, healthcare and sustainability. Since its inception, the initiative has been sustained through a series of strategic updates and continues to serve as a leading document of U.S. industrial and innovation policy in the materials domain.

Leading institutions

The Materials Genome Initiative (MGI) is coordinated under the **White House Office of Science and Technology Policy (OSTP)** through the **National Science and Technology Council (NSTC)**.[66]

Implementation is carried out across major U.S. authorities, each contributing distinct expertise and resources:

- **National Science Foundation (NSF)**: Supports integrated computation–experiment research programs, such as the Designing Materials to Revolutionize and Engineer our Future (DMREF).
- **Department of Energy (DOE)**: Advances digital and experimental materials innovation through its national laboratories and research networks.
- **National Institute of Standards and Technology (NIST)**: Develops measurement standards and leads efforts to establish shared materials data frameworks.

These authorities collaborate closely with universities, national laboratories, industry consortia and **Manufacturing USA** institutes to ensure alignment between fundamental research and strategic industrial applications. Key application areas include **energy, aerospace, microelectronics, and defense manufacturing**.

Policy focuses

Investment

Federal programmes provide ongoing support for integrated computational–experimental materials development. During **the first five years (2011-2016)** of the initiative, federal agencies including the **DOE, DoD** (the Department of Defense), NSF, NIST and NASA (the National Aeronautics and Space Administration) collectively invested **more than USD 500 million** in MGI-related R&D and infrastructure, aiming to embed advanced materials innovation in the US's existing and emerging industries.[67,68]

Infrastructure

National investments support to establish shared computational, data and experimental capabilities, enabling a coordinated approach to materials innovation across research and industry.

Public–research–private collaboration

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[66] National Science and Technology Council (2021). Materials Genome Initiative: Strategic Plan 2021.
[67] U.S. National Science and Technology Council (2016). *The First Five Years of the Materials Genome Initiative: Accomplishments and Technical Highlights*.
[68] National Institute of Standards and Technology (2016). "Revolution in Design: The Materials Genome Initiative."

Cross-agency coordination connects universities, national laboratories and industrial partners through multi-institutional research networks, strengthening the flow of data, knowledge and technology across the innovation ecosystem.

Skills
Workforce development in computational and data-driven materials research is incorporated into the initiative, while infrastructure investment remains the primary focus.

Four digital elements of Materials 4.0

Data Attributes
Ontology development remains decentralised and community-driven, leading to incremental and distributed progress. Ongoing efforts aim to improve metadata schemas and representation standards (e.g., MatML).

Data Infrastructure
Substantial investment in national-scale data and computational infrastructure, including high-performance computing (HPC) resources and shared research data platforms, supports broad access across universities, national laboratories and industry.

Algorithms and Models
The MGI emphasises multi-scale simulation and AI-enabled design, such as DFT-based modelling and machine-learning-driven property prediction, to accelerate the translation from theory to design.

Digital Tools and Techniques
Widespread use of high-throughput, automated and digitally integrated experimental platforms, including robotic synthesis and automated characterisation pipelines, to enable rapid iteration and reproducibility.

Stakeholders

National research agencies, national laboratories, universities and industry partners collaborate across the MGI ecosystem to advance research, data generation and early-stage technology development. The private sector contributes to scale-up and deployment, exemplified by the Materials Affordability Initiative led by Rolls-Royce (U.S.), which applies digital materials design and data-driven manufacturing to advanced metallic systems.[69]

The broader MGI network encompasses over **a thousand U.S.-based research organisations and companies**, complemented by select international collaborations through initiatives such as OPTIMADE (Open Databases Integration for Materials Design) and MaRDA (Materials Research Data Alliance).

Materials value chain

Early-Stage Discovery and Design

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[69] U.S. Department of Defense, Air Force Research Laboratory (AFRL). Metals Affordability Initiative (MAI).

Strong emphasis on materials discovery and design, driven by computational modelling and data-enabled screening.

Synthesis and Characterisation
Significant involvement in experimental synthesis and characterisation, where high-throughput and automated workflows accelerate validation and optimisation.

Product Development and Testing
Moderate engagement in product development and testing, mainly within the sectors such as energy technologies and aerospace materials.

Manufacturing and Scale-Up
Manufacturing and scale-up are not central to the MGI. These activities are instead supported through other **U.S. industrial and manufacturing programmes**, including the Manufacturing USA network and sector-specific initiatives led by the Department of Defense (DoD) and Department of Energy (DOE).[70]

Focused materials
The MGI supports research and innovation across a broad spectrum of material categories:

- **Functional materials**: Electronic, photonic, catalytic, and magnetic materials.
- **Structural materials**: Metals, ceramics, and composites, including high-entropy systems.
- **Soft and biological materials**: Polymers, biomaterials and regenerative materials.
- **Critical and rare-earth-free materials**: Addressing supply chain vulnerabilities and national security priorities.
- The U.S. places strategic emphasis on developing materials that strengthen **national competitiveness** and **supply chain resilience**, particularly through r**are-earth-free substitutes** and critical materials innovations, alongside advances in **functional, structural, and soft/biological materials** for next-generation technologies.

[70] Manufacturing USA. Network Overview. U.S. National Network for Manufacturing Innovation

Appendix 7: Detailed view of Materials 4.0 for a wind turbine composite

An example application of the Materials 4.0 framework for a composite wind turbine blade is shown Figure 20. At each stage of the materials value chain new data is generated, for example, the specific resin formulations within material extraction and supply. The data generated would have a certain set of attributes, such as an agreed and defined data ontology and then be stored and transmitted by the relevant data infrastructure. For a specific piece of material at the core is a digital materials passport, a consolidated digital record of the history of the material operations. Organisations can access relevant and needed data from the passport for use in their algorithms and models to give distinct Materials 4.0 opportunities. This is all operationalised for decision making by relevant digital tools and techniques. Finally, for the Materials 4.0 activities to be realised, a set of enabling actions can be identified for each organisation, as well as a cross-cutting setting of enabling activities across the whole value chain.

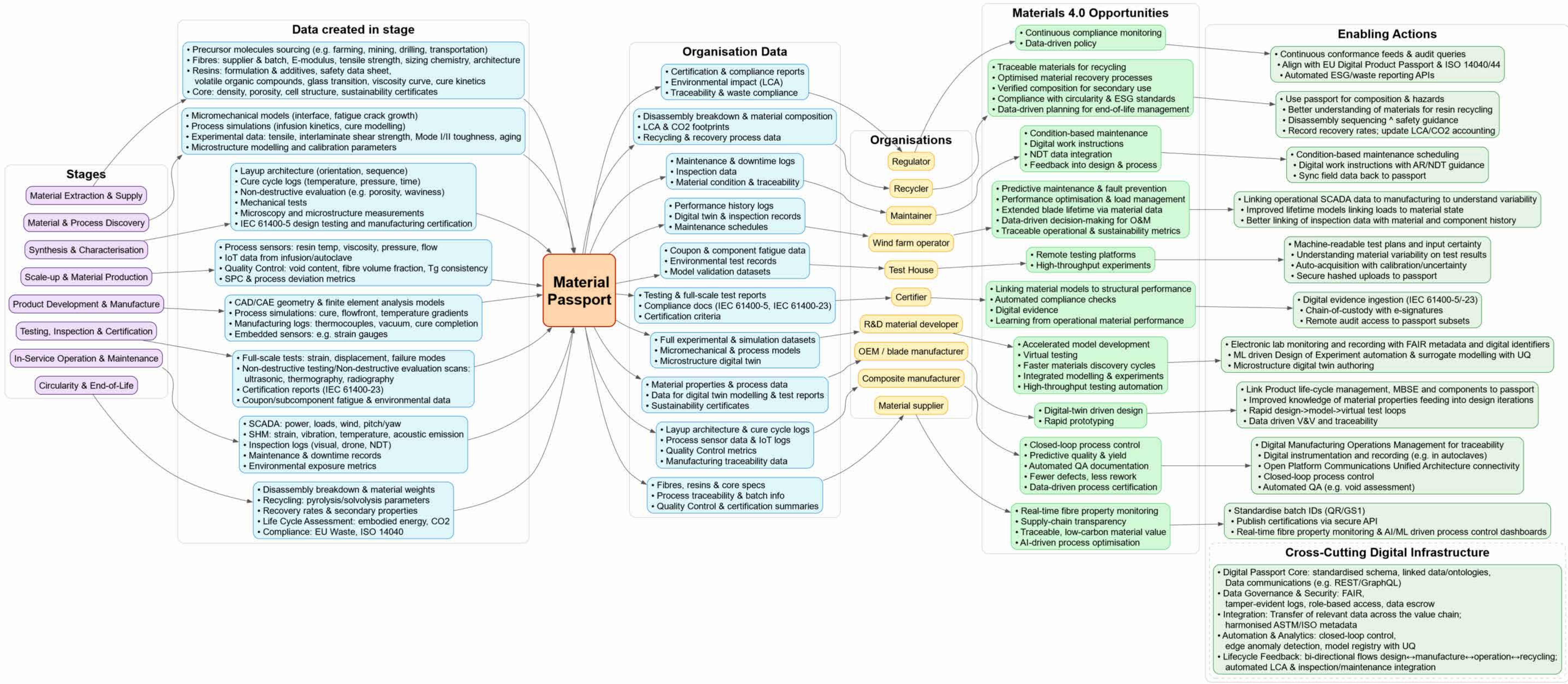

Figure 20. Application of the Materials 4.0 framework to an intermediate level of detail for a wind turbine blade composite.

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Institute for Manufacturing: IfM

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