THE GOVERNMENT
OF THE GRAND DUCHY OF LUXEMBOURG
Ministry of Research and Higher Education

NATIONAL RESEARCH PRIORITIES FOR LUXEMBOURG

Updated version 2026

Background and process

In 2020, the Government adopted the first National Research and Innovation Strategy, establishing the governance and framework for a targeted continued development of the Luxembourg research ecosystem. It aimed to accompany research and innovation activities in such a way that they contribute to the implementation of the Luxembourg 2030 vision of a sustainable knowledge society. It defined four major research priority areas considered as particularly important for the country's societal, ecological and economic development, which were reflected in the National Research Priorities for Luxembourg.

The 2023-2028 government programme foresees a regular revision of the National Research and Innovation Strategy, while maintaining and further developing the four major priority areas and placing a particular focus on artificial intelligence.

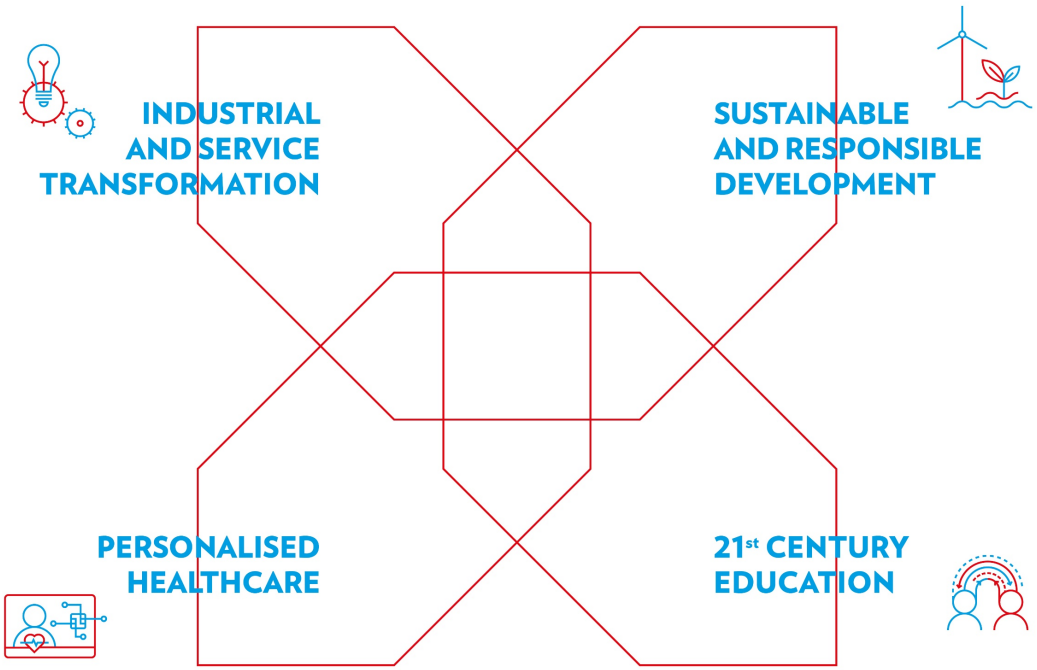
This revision was hence conducted in the second half of 2025, taking into account major developments in research and innovation since 2020 while maintaining the framework conditions, the governance principles and the four research priority areas defined in the first national strategy. It aimed among others to reflect the national strategies for data, artificial intelligence and quantum technologies adopted in May 2025 as part of the strategic initiative "Accelerating Digital Sovereignty 2030"[1]. It was conducted in consultation with the Strategic Steering Group which brings together executive representatives of the public research-performing institutions and the Luxembourg National Research Fund (FNR[2]), under the leadership of the Ministry of Research and Higher Education.

While the priority areas defined at the top level remained unchanged, in line with the governmental programme, the revision resulted in an adaptation of some of the sub-areas, reflected in the present National Research Priorities for Luxembourg. These will continue to be regularly reviewed in the future, in consultation with governmental, economic and societal stakeholders as well as the Strategic Steering Group. The National Research and Innovation Strategy was developed with a view to 2030[3]. A more in-depth review of the National Research Priorities is foreseen around the end of this validity period, following an external evaluation of the FNR's CORE programme, as the main funding instrument underpinning them.

[1] https://gouvernement.lu/en/dossiers.gouv2024_smc+en+dossiers+strategy-ads2030+strategy-ads2030.html
[2] https://www.fnr.lu/
[3] National Research and Innovation Strategy for Luxembourg, published by the Ministry of Research and Higher Education, February 2026.

Four interdisciplinary research priority areas to prepare Luxembourg for the future

At the top level, the National Research and Innovation Strategy defines four research priority areas, which have emerged to be of particular importance for the country's societal, ecological and economic development. These areas are not considered to be separate and independent from each other, but rather as areas that mutually influence each other, so that the sub-themes that define each area may also have ramifications into other areas.



The implementation of the research strategy will therefore place particular emphasis on interdisciplinary projects, which take into account that each of the four major priority research areas will benefit from results and projects situated in one or more of the other areas. The four chosen research priority areas should ensure that, beyond GDP growth, Luxembourg can warrant for a continuous and sustainable development of its population's well-being, including in particular health, environmental and educational factors.

National Research Priorities in view of interdisciplinarity

Interdisciplinarity and cross-institutional cooperation will be further fostered by the FNR, by building on the disciplinary strengths in Luxembourg, which are based on research excellence and scientific impact. Many of the topics described in the National Research Priorities are interdisciplinary and have ramifications into different priority areas. Researchers are encouraged to link tools and approaches from various disciplines to solve joint research questions and to create added value for the economy and society. The FNR will continue to strongly support interdisciplinary research across its funding portfolio.

The National Research Priorities are fully aligned with the research and innovation priorities and activities defined as part of the national strategies for artificial intelligence, quantum technologies and data. These three strategies aim to keep Luxembourg at the forefront of emerging technologies and to strengthen its digital sovereignty. Artificial intelligence is a key enabling technology in all research priority areas. While quantum technologies cannot be applied as broadly, they are also considered a pillar of the future digital transformation. A particular focus is placed on data excellence and the reproducibility and reusability of data as a basis for research and innovation.

Research in the defence sector also plays an increasing strategic role and will build on the expertise developed in the framework of the National Research Priorities. Research and innovation projects directly related to the field of defence will be supported as part of specific defence funding through calls for projects in collaboration between the FNR, the Directorate of Defence of the Ministry of Foreign and European Affairs, Defence, Development Cooperation and Foreign Trade and the Ministry of the Economy.

TABLE OF CONTENTS

THE GOVERNMENT
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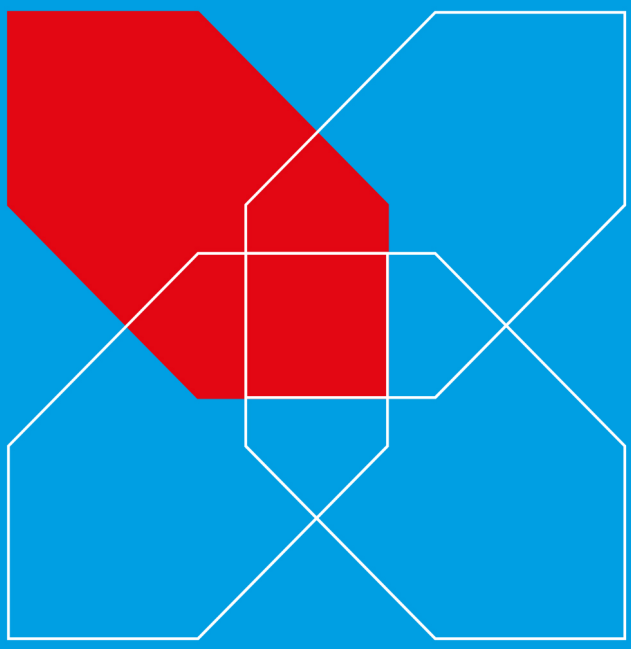
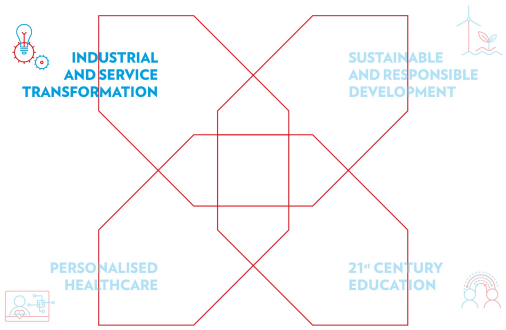
INDUSTRIAL AND SERVICE TRANSFORMATION



1. INDUSTRIAL AND SERVICE TRANSFORMATION



Luxembourg aspires to become a more knowledge-based, data-driven economy that leverages digitalisation to branch out into diverse industries and offer high value-added services. Scientific excellence will provide this process with a robust foundation to foster innovation and guarantee competitiveness as well as resilience and sustainability for Luxembourg's rapidly evolving industry and tertiary sector.

Research will further support the existing national economic focus areas of advanced materials, space components and technologies as well as automation and robotics. Artificial intelligence (AI), quantum technologies and advanced data analytics will impact research in these domains as enabling technologies. The combination of these technologies will speed up modelling, simulation and optimisation tasks, boost automation capabilities and enable new engineering opportunities and transformative services. In this context, software engineering will be a strategic focus area.

To deliver a trusted, human-centred technology ecosystem capable of secure and reliable human-machine collaboration that adequately addresses all concerns, research efforts need to span materials and hardware technologies, software tools, communications systems and data handling.

1.1. Materials science and technology

This theme realigns traditional materials and condensed matter science, a well-focused research community in Luxembourg. It takes the combined research areas of materials science and physics to a new level and encourages finding collaborative synergies in theoretical and experimental topics.

It goes beyond the traditional ways of distinguishing between fundamental and use-inspired, between experimental and theoretical condensed matter physics, between materials science and process engineering. It will create a sound basis for a truly innovative physics and materials science research programme and help to consolidate individual topics into an integrated perspective.

1.1.1. Multiscale modelling in materials science and physics

This topic aims at copying nature's successful strategy of making and utilising complex multi-scale materials. Their modelling combines existing and emerging methods from diverse scientific disciplines to bridge the wide range of time and length scales that are inherent in a number of essential phenomena and processes in materials science and engineering, e.g. complex excitations, light-matter interactions, interactions of materials with external fields.

This topic is explicitly not restricted to modelling activities but ranges from first-principle simulations up to experimental approaches.

1.1.2. Materials discovery through machine reinforced learning

This interdisciplinary research aims at extending the artificial intelligence paradigm to materials science, where data mining complements slow and cumbersome experiment-based investigations of new materials and properties. This subdiscipline enables the intelligent and data-driven discovery of new materials, the prediction of materials properties, as well as other purposes in multiple areas of application. A large part of this subdiscipline is concerned with data mining; discoveries are made indirectly by finding patterns in large data sets.

1.1.3. Fundamental phenomena defining materials function and devices

The scope of this subdiscipline covers condensed-matter physics research and investigations of elementary mechanisms that define the function of materials. Relevant applications are in the area of energy (e.g. solar cells, batteries and supercapacitors, fuel cells, thermoelectrics, superconductors, more efficient lighting, and hydrogen technologies) and the environment (e.g. environmental sensing applications).

Both modelling/theory and characterisation at relevant length scales are needed. Sensing applications are relevant for every domain and should be pursued. Selected themes in the field of quantum materials offer attractive challenges and applications: innovative use for quantum computing and communication, topological phenomena, quantum data storage and sensing, and other quantum technologies will result.

Even though this subdiscipline is driven by applications, a strong interaction with theory is necessary. The focus is not on incremental improvement of existing technology but rather on linking research on fundamental processes with their technological applications.

1.1.4. Interface-dominated materials

This topic addresses materials whose functions are dominated by the properties of an interface - either a surface, bulk or buried interface. Typical examples are nanocomposites and materials for sensing applications and catalysis, where the dominating processes occur at an interface. This topic also studies the interaction of materials with the environment, for instance the way nanomaterials interact with cells, as well as materials for safety-related applications.

This subdiscipline is of high relevance, as the fundamental development of interfaces is a key enabler of application-oriented systems. Interfaces are not limited to physics; a strong connection for example to biosystems will lead to a broader scope.

Examples of possible applications include topological materials, nanocomposites, material-environment interactions, sensing, catalysis, biomaterials, highly anisotropic materials (e.g. layered structures with strongly anisotropic, electric, and heat conductivities), chiral surfaces, switching mechanisms at surfaces – e.g. from hydrophilicity to hydrophobicity, from high to low friction, from radiation-transparent to reflecting behaviour.

1.1.5. Advanced manufacturing: multifunctional, multiclass, and multiscale materials, and their implementation

The broad topic of advanced manufacturing encompasses technologies and methodologies, but this subdiscipline focuses on the development of materials for – and their integration into – advanced manufacturing process technologies.

The focus lies on complex materials such as functionally or compositionally graded polymeric materials. Thus, this research topic combines developing complex materials and understanding the necessary process engineering in order to be able to implement them in the manufacturing process.

This subdiscipline should be viewed as an integrative part of theme "Materials science and technology" as a whole and should not be seen as a vehicle for studying advanced manufacturing in general. Rather, the goal would be to study it in depth and not breadth, i.e. to find a niche and cover everything from the basics up to process engineering therein. A possible niche would be for space-related applications: for example, in situ manufacturing as well as manufacturing parts for spacecraft.

1.1.6. Physics of active and living matter

This emerging topic is a new overarching and highly interdisciplinary theme involving biomedicine, ICT, and sustainability. This integrated research focus provides opportunities for the research community to cross disciplinary boundaries and to impact new fields. It is indispensable that researchers with diverse interests and backgrounds in fields such as soft matter, complex matter physics, biological physics, statistical physics, and biology combine their efforts towards promising discoveries in this area.

The topic aims at understanding the complex dynamics of active and living matter and being able to build such systems using a bottom-up approach starting from molecules. Such systems are in non-equilibrium and are made up of units that consume energy and transform it into mechanical work. An example is groups of bacteria and their basic physical interactions, which form complex collective behaviour.

Research in this area may include mechanisms of synthetic and biologically active matter, such as cell-cell communication, collective behaviour, self-assembly and organisation, swarming, pattern formation, molecular motors, and cooperative transport.

Understanding these systems could enable us to create synthetic and biological materials vastly different from the equilibrium materials we know now, with capabilities such as self-healing, self-motility, and synchronisation.

The real added value of research in this area lies in grouping scientists from physics, biology, and computer science.

1.1.7. Materials life cycle

In today's world, it is increasingly important to look beyond the mere function of a material and include into its development sustainability considerations related to sourcing processing, manufacturing, use, reuse, and disposal.

Addressing sustainability issues all along the value chain of materials has huge societal significance. Finding ways to address the negative aspects of how we manufacture, use, and disperse materials (potential hazards to human health and the environment) are important sustainability challenges. At international level, no one is pursuing these questions on a larger scale. Consequently, national groups could make a significant impact despite their limited capacity in this area.

The overall idea is to view this topic as an integrated process, for instance by including the planning of a material's life cycle into its development process. Therefore, it offers possible interdisciplinary links to the area of Sustainable and Responsible Development.

This topic specifically does not address life cycle assessments or sustainable materials in general; instead, it serves to encourage considering sustainability aspects in all other topics and will consequently be integrated into the review process.

1.1.8. Scientific instrumentation and characterisation

Luxembourg has strong expertise in scientific instrumentation and advanced characterisation and testing. This expertise is applied across a wide range of disciplines, from physics to chemistry, and covers the full spectrum of

science, from fundamental research to industrial applications in diverse fields such as environmental sciences, advanced materials, physics, ICT, biotechnology.

Scientific instrumentation and characterisation enable the study of matter from the atomic to the macroscopic scale. It therefore relies on intense interaction with the researchers in all of these domains and can also be applied to quantum technologies, medical health diagnostics, and space.

1.2. Trusted data-driven economy and critical systems

1.2.1. Security and cybersecurity, reliability and trust

Security, cybersecurity, reliability, and privacy of data and data processing systems are important properties of ICT systems that rely on each other.

Increasing the security and privacy properties of digital systems has a high societal impact. Digital systems have become part of daily activities, and the trust put by society in them is therefore of the utmost importance. Information security and cybersecurity in ICT systems have been a priority worldwide for many years and will continue to be important in the future.

Research in topics such as cryptographic schemes and protocols, cybersecurity, security risk management, security design and anomaly detection, and critical infrastructures will be essential to ensure that society is less vulnerable from exposure to new trustworthy value-sensitive technologies.

Further research topics should address questions related to data privacy and integrity, especially in view of European GDPR (General Data Protection Regulation) rules and the future of financial centres (e.g. the optimal level of regulation / deregulation). Such topics could comprise: regulatory technology, including interdisciplinary research linking law, regulations and their applications or implications for ICT systems, secure and future-proof e-democracy and e-governance, as well as privacy for recommender systems.

1.2.2. Cyber-physical systems

Cyber-physical systems – systems that link the physical world (e.g. through sensors or actuators) with the virtual world of information processing – are increasingly present in many elements of our daily lives, such as smart buildings, logistics, healthcare, energy networks, factories, automated warehouses, as well as planes and trains. All these physically entangled systems, which include digital, analogue, physical, and human components, are of crucial importance for the quality of life of the citizens and for the economy. Luxembourg has the potential to act as a test bed for many of the applications emerging from this research. Their importance to the public and industry sectors will play a catalytic role in increasing private R&D investment. With the rise of Artificial Intelligence and Digital Twins, a new generation of Cyber-Physical Systems has emerged in the recent years, where they become more cognitive, and user-centric, following the objectives of the Industry 5.0 paradigm. Research on cognitive cyber-physical systems and digital twins, collaborative robotics and human-machine collaboration will be key to taking the industry to the next level and prepare Luxembourg industries for human-machine collaboration. The convergence of Artificial Intelligence with cyber-physical systems and digital twins enables predictive maintenance, real-time optimisation and resilient processes that can lead to smarter, more sustainable production environments.

1.3. Future computer and communication systems / quantum computers and networks

This theme focuses on wireless networks, including mobile, radio, and satellite networks, software for improving network efficiency, and machine learning techniques for next-generation communication systems.

Luxembourg could act as a living test bed for such development, in particular thanks to the strong economic links with local private actors in the field. The area of new mobile services, including evolved 5G and 6G networks, represents a huge opportunity not only for innovation and deployment, but also for building more resilient, human-centric and responsible infrastructures. These efforts will enable programmable and distributed infrastructures connecting devices, edge resources and the cloud, improving efficiency, reliability and security across the edge-cloud continuum.

Societal, scientific, and economic needs are the drivers for the next generation of high-performance computing (HPC) with exa-scale performance. Luxembourg is part of the EuroHPC Joint Undertaking project, which will initially operate from 2019 to 2026 and will allow researchers to study and understand complex phenomena involving graphics processing units (GPUs), heterogeneous systems, and HPC. It will also help to develop with industry the next generation of HPC applications, services, architectures, and systems, that are trustworthy, and aligned with European values, including careful attention to the energy efficiency of computing and datacenters.

1.4. Autonomous and intelligent systems and robotics for earth and space

This area includes interdisciplinary research on robotics, artificial intelligence (AI), machine learning, advanced manufacturing, mining technologies, and 3D printing resources on Earth and in space. It focuses on secure and safe autonomous systems and cooperative vehicles for extreme environments which embed AI, ML, robotics and advanced materials. Applications concentrate on space exploration and resource utilisation, and terrestrial deep-sea exploration. Links to other research areas should be followed, if necessary. Technology spill overs from space research into other areas will become an important source of intellectual property creation and knowledge transfer as well as a huge opportunity for new applications to be used on Earth.

Together with subdiscipline “resources in space”, this theme forms the backbone of a coherent interdisciplinary research programme.

1.5. Space telecommunications, earth observation and space resources

1.5.1. Resources in space

This area focuses on technologies for the exploration and utilisation of space resources. It includes the sub-discipline of exo-hydrology, which refers to the application of science and principles in hydrology on the investigation of water resources in space. Important feedback on hydrological principles and lessons for sustainable resource management in terrestrial systems could be gained. The topic can be further extended to the extraction and use of water and regoliths for life support, building habitats, propellants, and manufacturing in space.

Furthermore, it includes all activities related to the identification, characterisation, extraction and use of resources from space, from prospecting to production. For prospecting, the focus is on the use of data (remote and in situ) to develop tools to support and guide future exploration for resources, in addition to technologies and approaches to support data acquisition (remote and in situ). For production, technologies are required that can use the resources of the Moon, Mars and Asteroids to support human life, refuelling of spacecraft, construction of habitats

and manufacturing of tools. Sustainability is a key theme, including zero waste and circularity for the space environment and sustainable resource management. These concepts have direct application to Earth resources.

1.5.2. Remote sensing and combination with multiscale data

Research in this area focuses on new technologies for sensing the environment (e.g. biosensors, portable sensors) and combining these small-scale applications with large-scale approaches such as remote sensing. Furthermore, the new paradigms of machine learning and Big Data analysis are very relevant approaches in this context. Research on sensing tools requires interdisciplinary approaches and applications.

1.6. FinTech / RegTech and transformative applications of technologies

A highly interdisciplinary research area focuses on implementing regulatory compliance and developing advanced methods for analysing the impact of regulatory changes, to ensure that financial institutions can adapt effectively to evolving legal frameworks in various fields at the intersection of areas such as law, finance, regulations, and ICT, including financial, regulatory, and insurance technologies (FinTech, RegTech, and InsurTech).

This includes modelling financial data using innovative models and their calibration, as well as the implementation of robust statistical techniques for estimating financial models. These capabilities are essential for risk management, pricing and forecasting in complex financial ecosystems. Transformative technologies such as AI are playing an increasing role in fraud detection, credit scoring and personalised financial services. Further, digital identity portfolios are becoming essential for secure and user-centered financial ecosystems.

By combining AI-based analytics with compliance automation and identity management, Luxembourg can strengthen trust, transparency and resilience not only in the financial sector, but also in the eGov sector, thus improving the efficiency and transparency of public services.

An interesting focus for Luxembourg is the resilience aspects of distributed systems, with particular links to research in privacy and in digital transformation applications.

1.7. Fundamental tools and data-driven modelling and simulation

Mastering control and understanding of the data revolution requires multidisciplinary research at the interface between computer science and mathematics (as a tool to gain insight into highly complex systems) and application domains such as engineering, life sciences, physics, as well as the social sciences.

A key novel topical area is the integration of hypothesis-driven mathematical models in complex systems with data-driven machine learning (ML) algorithms (differentiation of causality vs. correlation). This represents, the transition from Small Data (hypothesis-driven) to Big Data (ML driven) approaches with a stronger emphasis on transparency, explainability and resilience against misuse. Other relevant topical areas are the quantification of uncertainties and risks in complex systems and multi-scale/reduced-order modelling that reduce complexity without losing informational content, ensuring that outcomes remain robust, ethical and beneficial to society.

1.8. Software engineering

Software engineering is integrated as a new sub-domain in this strategy, with a focus on the development of secure, reliable and sustainable software for critical sectors such as finance, autonomous systems and mobility. It promotes AI-augmented engineering and AI-based engineering sciences, while addressing the challenges posed by AI-based systems, generative AI and agentic systems. Research in the field of sustainable software engineering investigates how to improve energy efficiency, optimise resource use and, as a result, reduce carbon emissions throughout the software lifecycle. The research ensures that scientific results and software systems can be reliably reproduced and validated, thereby promoting transparency and trust in today's complex AI-based environments. This strategy also recognises the key role of open-source software in the digital infrastructure and addresses the associated challenges of assuring the integrity, provenance, and security of third-party software components, and the long-term sustainability of critical open-source components. Software must also contribute to sustainable societal development by incorporating principles of fairness and compliance with regulations such as the GDPR and the European Regulation on Artificial Intelligence. Research examines how quantum and hybrid quantum/classical software systems are designed, implemented and tested in accordance with ethical and socio-technical considerations.

1.8.1. AI-augmented software engineering and software engineering for AI

Artificial intelligence is transforming the way software is engineered, influencing the entire software development life cycle. Strategic investment in AI-driven software engineering is therefore essential to improve productivity and to build secure and dependable systems at scale. It covers AI support for requirements and design, code generation and refactoring, testing, verification, and operational monitoring, maintenance, deployment, supported by rigorous evaluation and integration into engineering workflows.

Conversely, software engineering provides the principles, methodologies, and tooling necessary to develop trustworthy AI solutions, ensuring transparency, robustness, fairness, and the mitigation of bias in AI models.

1.8.2. Methods and frameworks for hybrid software systems

This priority targets the software engineering foundations needed to design, integrate, and provide evidence of trustworthiness for software-intensive systems that combine heterogeneous components, execution platforms, and operational contexts—typically spanning cloud, edge, embedded, and cyber-physical systems. It emphasizes robust approaches for architecture and co-design (i.e., software–hardware–communication, including networking), model-based and multi-paradigm software engineering, and interoperability mechanisms that enable dependable composition of legacy and novel components, including autonomous and adaptive functions, mixed-criticality, and distributed real-time systems.

It also strengthens continuous validation across deployment and operation through DevOps practices, runtime monitoring and verification, resilience and recovery patterns, and software engineering workflows supported by digital twins and simulation.

In addition, it encompasses the software engineering challenges of hybrid computing stacks—such as accelerators and hybrid quantum/classical workflows—by advancing programming abstractions, program analysis, toolchains, testing and verification methods, and system-level performance and reliability engineering needed to translate advanced computation into trustworthy operational systems.

1.8.3. Open-source software ecosystem

Open-source software is a cornerstone of modern software engineering and a critical pillar of today's IT ecosystem. Several domains of nationwide interest (e.g., Cybersecurity) can strongly benefit from open-source tools. Notably, this includes critical sectors but is not limited to them. By fostering open collaboration and encouraging active contributions, open-source communities accelerate innovation while strengthening the security, reliability, and long-term sustainability of software systems.

Being ubiquitous and often integrated into critical systems, open-source software components require strict inspection. This calls for efficient and innovative methods to address key challenges such as the growing number of dependencies (i.e., the software supply chain), the presence of latent vulnerabilities, the rapid and continuous evolution of codebases and third-party libraries and the long-term sustainability of the projects themselves.

1.8.4. Responsible software engineering

Today's software systems must do more than function correctly; they need to create societal value and avoid causing harm. Research in this area proposes new technologies and methods to ensure software behaves in an ethical, fair, transparent and accountable manner throughout its lifecycle, follows secure-, privacy-, and sustainable-by-design best practices, complies with legal regulations at all levels (e.g. GDPR and the EU AI Act, etc.) and remains accessible and inclusive for all users.

Continuous assurance of responsible behaviour through rigorous testing, monitoring and auditing of software components, and the modernisation of legacy systems to help them meet these responsible engineering requirements are also key aspects of this challenge.

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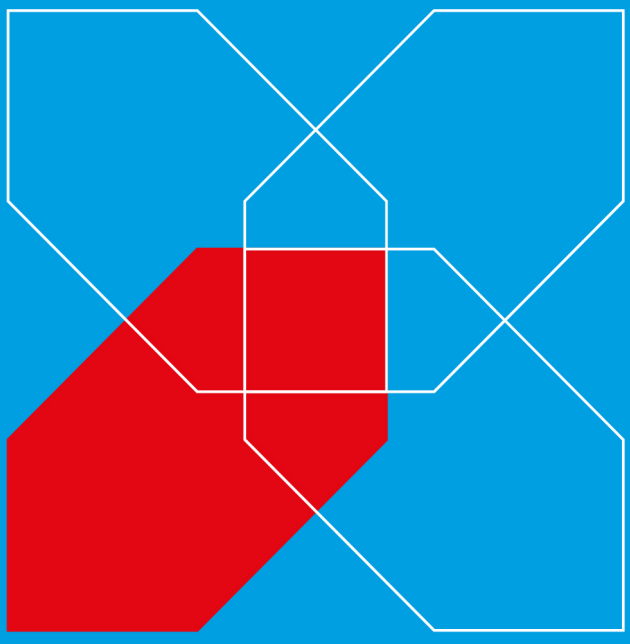
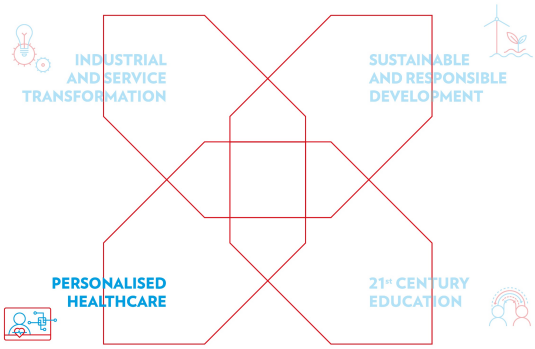
PERSONALISED HEALTHCARE



2. PERSONALISED HEALTHCARE

Luxembourg's ambition is to become a leading international hub for data-driven personalised digital medicine. To this end, genomics, advanced data analytics and artificial intelligence will be leveraged to transform medicine from a "one-size-fits-all" approach towards precision prevention, diagnosis and treatment. To realise this vision, robust biomedical and translational research are needed to drive innovation towards a more effective and sustainable healthcare system with direct and measurable patient impact.



One of Luxembourg's ambitions is to establish a secure, interoperable and ethically governed national genomic data platform that can be leveraged for both research and clinical applications. Luxembourg takes a holistic view on health, recognising that biological factors interact with behaviour, environment and socio-economic determinants. Research will explore how these drivers interact with biology and genetics to affect health and translate into tailored prevention, early interventions and/or behavioural changes.

Luxembourg will also look beyond biomedical research by embracing collaboration with social sciences, environmental sciences, public health and health economics to improve our understanding of disease and population-level health. Research questions will include understanding the impacts of chemical exposures and pollution on health, as well as assessing the cost-effectiveness, equity and sustainability of personalised health interventions.

Luxembourg will continue to expand and develop methods to evaluate the performance of health systems. Research will examine how financing, delivery and regulation affect equity, quality and efficiency. Innovative clinical trial design coupled with novel causal inference methods will ensure research can be translated into tangible patient benefit.

ICT and biomedical researchers will work closely together to develop digital health tools and AI-based analytics to support clinical needs and define best practices to enable the secure secondary use of health data for research and innovation. In pursuing efforts to improve individual health, Luxembourg acknowledges the importance of the societal, economic, legal and regulatory issues surrounding digital health data.

2.1. Complex biomedical systems – data and models

This theme covers systems biology from a practical perspective. The focus here is on utilising high-dimensional data and models to understand complex biological systems, from both top-down and bottom-up perspectives. The creation and refinement of models and the use of data of increased dimensionality will lead to mechanistic as well as therapeutic insights that could help to better stratify patients and develop individualised treatments. This theme should build bridges between the acquisition of Big Data and its use for developing novel insights into health and disease.

2.1.1. Effective collection and deconvolution of complex biomedical data

This subdiscipline comprises top-down research on biological systems and the collection of data to uncover insights relevant for disease profiling through nuanced systems-level information. It encompasses the traditional "omics" analyses (genomics, transcriptomics, proteomics, and metabolomics), as well as other approaches that generate complex high-dimensional data sets useful to biomedical researchers.

Interdisciplinary exchanges should be fostered with researchers in other areas interested in the investigation and exploitation of complex systems, especially with regard to integration of different forms of complex data sets. Biomedical researchers could collaborate with specialists in Materials Science and Physics, Information and Communication Technologies, as well as Social Sciences.

2.1.2. Multi-scale and mechanistic models

This subdiscipline covers bottom-up approaches to understanding complex biological systems, utilising existing and new data to investigate their self-organisation and emergent properties. High-quality models allow increased predictive power regarding drug targets and effects, disease impacts on cellular mechanisms, and other topics that can help to understand differences within and between healthy and diseased individuals, enabling the core of precision medicine.

Interdisciplinary studies in this field should attempt to tie together Physics and Materials Science with Biomedicine. These fields use the same sorts of analysis and modelling methods, and the latter can be merged effectively to increase the impact of these fields, and possibly others as well, depending on the research project.

2.2. Precision medicine, including environmental, lifestyle and socio-economic factors

This theme focuses on understanding the details of disease processes, finding better methods to stratify affected patients, and developing new and more targeted treatments to prevent or reverse disease. These mechanisms are influenced by both internal and external factors, and thus this is generally a broad area of research.

The focus lies on topics that can be used to enable precision medicine, either identifying mechanisms which are similar between different diseases (thus unveiling similar therapeutic targets) or understanding the individual, social, and environmental context of disease incidence and progression.

2.2.1. Innovative molecular disease models

Molecular models are the foundation of modern biomedicine. They represent the actual phenotypes which are being studied in order to uncover insight into health and disease. The most traditional model, the immortalised cell line, is widely acknowledged to have many shortcomings which limit translation to human diseases.

This subdiscipline aims to foster the development and use of more innovative models, including disease-specific animal models, induced pluripotent stem cell models, as well as patient-derived cell models. These studies should be able to provide researchers with models that reflect actual patient phenotypes, an important aspect of precision medicine.

This subdiscipline complements the theme "Complex biomedical systems – data and models", serving both as a resource for high-throughput analyses and as validation for computational models. Advances in the field allow high-throughput profiling techniques (omics analyses, as described in "Effective collection and deconvolution of

complex biomedical data") to be applied to these models. This will create large data sets that can be mined to gain new insights into disease mechanisms on a more personalised level.

2.2.2. Common mechanisms between diseases – mechanism-based stratification

The goal of this subdiscipline is to enable precision medicine through identifying multidimensional disease-related mechanisms and utilising systems medicine techniques. Precision medicine and better high-dimensional patient stratification are huge topics in both applied basic and clinical research, as they will directly impact clinical diagnosis and care of patients.

This subdiscipline focuses on molecular biology, where the aim is to use specialised disease models (e.g. from "Innovative molecular disease models") to understand how diseases arise and progress, as well as to determine whether these mechanisms are conserved between different diseases. Identifying such common mechanisms will make it possible to better stratify patients and to treat them with therapies specifically targeting these mechanisms. This should provide a more accurate and more powerful defence against disease progression.

This research area can be linked with the mechanistic modelling research area "Complex biomedical systems – data and models" as well as with "Data-driven healthcare" to create a strong foundation for computation-based understanding of disease mechanisms and stratification of patient groups for more effective care.

2.2.3. Environmental, lifestyle, and socio-economic impact on mechanisms of diseases

There is a strong incipient global trend towards understanding how non-molecular factors play a role in both the emergence and progression of disease. This is a rising topic in the field of biomedicine, as it is now understood that the complexities of interactions between hosts and their environment have a huge impact on human health. Understanding these interactions can help to enable precision medicine through linking non-molecular with molecular data, forming an individualised holistic understanding of disease onset and progression.

This research area is heavily focused on public health and social sciences. It can include digital aspects (e.g. social networks, Internet use, and digital psychology) as well as more traditional ones (e.g. effects of pollution, nutrition, and gut health; access to healthcare, or ethnic, age, economic and socio-cultural disparities and inequalities).

To this end, links to other domains, specifically Social and Environmental Sciences, Public Health, and Health Economics, can help to push forward the deeper understanding of disease occurrence and progression. This area is open to researchers not traditionally associated with the biomedical field, as their inclusion will both accelerate the growth of the field and enforce interdisciplinary collaboration between the biomedical and other domains, including the monitoring of exposition to and pollution. It should explicitly consider the role of socio-economic and environmental factors.

2.3. Understanding, preventing, and treating the health-disease transition

While the theme "Environmental, lifestyle, and socio-economic impact on mechanisms of diseases" focuses on specific aspects of individual diseases, this theme focuses on how diseases arise and develop over time, in order to identify critical changes as ideal therapeutic intervention points. This improved understanding of health and diseases is required to foster innovative and individualised interventions, including preventive medicine approaches, and can lead to societal impact at both policy and economic levels. This theme includes observation-

and intervention-based research, and should develop the means to directly translate research into patient impact through novel and advanced clinical trials.

In addition, the theme comprises policy-oriented evaluation of health system performance—how financing, purchasing and delivery arrangements affect equity, quality and efficiency.

2.3.1. Longitudinal dynamics of diseases

Primarily observation-based, this subdiscipline aims at identifying decision-making effects and transitional state tipping points in health and disease. These tipping points can be molecular or can be triggered by other means, in particular lifestyle-environment interactions. Identifying these transition states can be made through tracking and gathering patient data, including through digital means such as innovative biological sensors and other data-acquisition processes.

Research in this area should foster preventive medicine and research on risk markers, leading to early flagging of pre-disease states in at-risk individuals and to identification of the corresponding prevention methods. In addition, a deep phenotyping approach on biobanked patient samples would provide an added advantage to research in this area.

This research area has potent links to Social Science and Humanities research, to Public Health, and Health Economics, similarly to "Environmental, lifestyle, and socio-economic impact on mechanisms of disease". Collaboration between researchers in these domains should lead to improved prevention techniques as well as improved adherence, thereby reducing disease prevalence.

2.3.2. Multifactorial intervention strategies

Research in this subdiscipline is focused on designing and testing interventions that are not molecular in nature, for example through lifestyle and digital means. The goal is to improve health through innovative, participatory, and personalised intervention strategies, resulting in health-associated impacts through interdisciplinary research.

Studies in this subdiscipline can take advantage of the unique selling points of Luxembourg: its small population; a close network of patients, scientists, and clinicians; tight organisational networks, etc. This will promote quick uptake by the larger society. Integration of the various data types arising from research in other themes and subdisciplines should allow for relatively rapid timelines for research and development of novel interventions.

This subdiscipline is heavily connected to individuals and societies in order to understand, design, and test interventions that have a true impact on overall societal health. The opportunity for interdisciplinary research focuses on public health aspects, epidemiology, health economics and other research areas where understanding individuals and their motivations is key. In this way, interventions can be designed to positively impact individual and societal health over the long term.

2.3.3. Innovative clinical trials

This subdiscipline centres on taking the current state of the art in clinical trials and refining their design and implementation through innovative means such as digital tools, smart wearables and sensors, electronic medical record analytics, and other precision medicine approaches. These clinical trials are informed by other research in the biomedical domain and should focus on bringing value to patients and/ or to society.

To that end, studies should take the innovative research output in Luxembourg and apply it in a way that positively impacts people's health.

2.4. Data-driven healthcare

2.4.1. Trusted digital health systems

This topic calls for highly interdisciplinary research approaches linking ICT and biomedical experts, in order to foster understanding of the needs from both sides, as well as to ensure that solutions are fit for purpose in biomedicine while enabling secure secondary use of data for monitoring health system performance, cost-effectiveness and quality of care.

Health data is highly valuable and deeply personal. Protecting its confidentiality and security is essential to build trust in digital healthcare solutions. In the coming years, patient data will grow rapidly, especially with molecular data such as genome sequencing. This increase in sensitive information raises the risk of breaches, making strong cybersecurity and privacy-preserving technologies a priority. Regulations like GDPR and public concerns further highlight the need for secure systems and innovative approaches.

To address these challenges, research must bring together ICT and biomedical experts to ensure solutions meet real healthcare needs. Health informatics plays a key role by improving how data is collected, stored, and processed for both patients and clinicians. Understanding the structure and requirements of health data, including harmonization and integration, is critical to use this data effectively for better prevention, diagnosis, and treatment.

2.4.2. Health informatics and implementation in the healthcare system

Health informatics aims at improving the acquisition, storage, and processing of health data from both patient and clinician perspectives, which is necessary to create any sort of value from health data. This field is essential, especially as personal health data assumes a more primary role in research and clinical treatment. The aim of this research is to apply a deep understanding of the structure and requirements of health data, including aspects of harmonisation and integration, in order to facilitate the creation, storage, and use of this data towards improving prevention, diagnosis, and management of disease.

Improving individual health is the main expected impact, but it does not depend solely on data. One must also take into consideration the social, economic, legal, and regulatory aspects of digital health to properly implement the use of digital health data in Luxembourg's healthcare system. This area is driven by excellent interdisciplinary research, namely links with the social sciences and humanities. Specifically, legal and regulatory research (for understanding how digital health changes current regulation), psychology (for understanding how individuals and society are affected by digital health), and economics (for understanding value-for-money and distributional effects) are crucial. Research should also assess health system performance—access, quality, efficiency, equity and financial protection—using linked routine data and patient-reported outcomes to inform governance and resource allocation.

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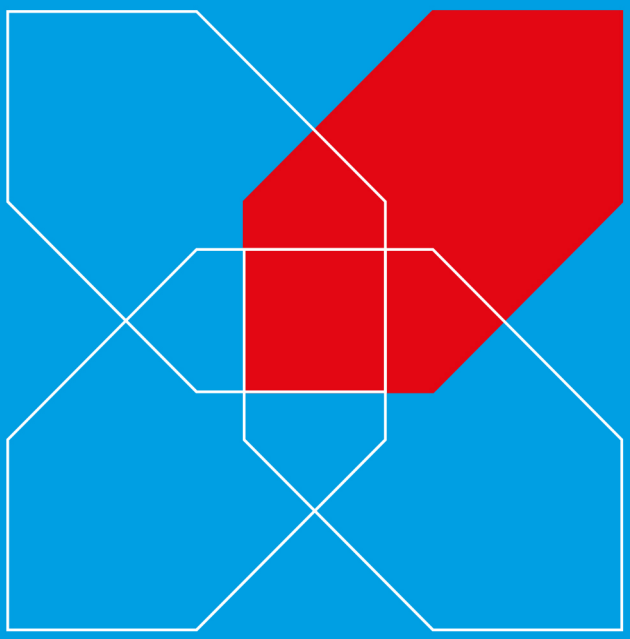
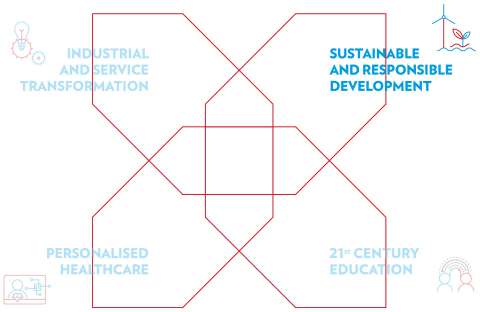
SUSTAINABLE AND RESPONSIBLE DEVELOPMENT



3. SUSTAINABLE AND RESPONSIBLE DEVELOPMENT



Luxembourg embraces the United Nations 2030 Agenda and aligns its research agenda with the Sustainable Development Goals defined therein. Luxembourg prioritises research projects in four areas covering all aspects of sustainability: the ecological, societal and economic pillars as well as the regulatory framework.

Digital technologies play an important role in accelerating ecological transition efforts. Areas such as AI, big data and intelligent systems already enable many applications related to monitoring in real-time, optimisation of resources, predictive maintenance or the development of smart grids and networks, intelligent mobility or precision farming. Digitalisation must also be accompanied by ethical governance frameworks that consider privacy protection and social fairness.

Luxembourg views sustainability as a global responsibility and will work on an international level to make progress in climate mitigation and adaptation, biodiversity and sustainable finance. This includes researching green transition topics such as energy efficiency and renewable energies as well as supporting research on technologies contributing to the carbon-neutrality goal. Innovative solutions for smart energy management as well as circular construction and sustainable urban planning will help Luxembourg build a climate-resilient infrastructure.

Research in food systems and ecosystems will focus on sustainable agriculture and food production, protection and restoration of biodiversity and carbon storage as well as adaptation to climate change, underpinned by research in ecological sciences, precision agriculture and circular bioeconomic models.

Social sustainability is also an essential pillar of sustainability. Topics such as migration, social cohesion and cultural identity as well as the social impact of climate change and labour-market transformations will be addressed by Luxembourgish research. Innovation will also be researched in terms of sustainable finance and bioeconomic business models to enable Luxembourg to continue growing responsibly.

Digitalisation also requires resilient legal and ethical frameworks. Luxembourg will focus its research efforts on topics such as data governance, artificial intelligence and quantum technologies as well as cybersecurity-by-design and enabling regulation to drive sustainable, democratic and data-centric development.

3.1. Ecological development: resilient eco- and agrosystems / energy efficiency and smart energy management

Research in the area “Sustainable and Responsible Development” should not only address regional needs but strive to contribute to achieving the UN’s Sustainable Development Goals (SDGs). The focus is global challenges posed by climate change and energy supply. Due to its size and specificities, Luxembourg offers the possibility for integrated research activities stretching from fundamental process-based studies to country-based studies.

3.1.1. Resilient water systems

Climate change directly impacts water resources in terms of both water quality and water quantity. Watershed management is becoming increasingly relevant for human health and safety – requiring long-term data on non-linear relations between climatic and human-driven forcings. Climate change is projected to lead to major changes in water availability across Europe and also Luxembourg with increasing water scarcity and droughts. Main changes are increasing risks of floods and flash floods during summertime and low water flow in rivers and higher pressure on groundwater recharge. Adaptations in urban drainage and drinking water management are also subject to climate change mitigation scenarios for a resilient infrastructure. This subdiscipline focuses on the investigation and prediction of hydrological responses to extreme weather events at a range of different scales. However, (extreme) statistics of environmental variables are often uncertain, as they may extrapolate multiple times beyond the length of (too short and/or incomplete) instrumental records. Pressing engineering requirements call for expanding environmental chronologies into pre-instrumental times – as a prerequisite developing and applying an innovative physical and eco-hydrological modelling framework to assess the past, present, and future co-evolution of river systems, landscape features and ecosystems. There is an urgent need for research in this area, against the backdrop of climate change, land-use change, and population growth. Further, a focus on mitigation strategies including nature-based solutions, water reuse strategies and changes in governance practices must be made, leading to full-scale demonstration of their efficiency and impact on the society. Research here contributes to a better understanding of the impact of future weather events on the quantity and quality of water in relation to the water supply for domestic and/or industrial use.

Future challenges lie in the non-stationarity, which stretches over the entire investigation chain from prediction and modelling to management of water cycles. An integrated approach all along the investigation chain, including aspects of water quality and water resource management, should be sought.

3.1.2. Environmental monitoring and environmental impact on public health

This subdiscipline focuses on environmental monitoring that is necessary to identify the extent of environmental impact induced by the demographic and economic development, climate change and to derive the necessary adaptation and mitigation measures as well as to verify the effectiveness of already implemented measures in all areas, e.g. agriculture, forestry, urban planning, biodiversity and nature conservation. Research in this field will generate meaningful environmental monitoring data on biodiversity, habitat structures, as well as material and energy flows at the ecosystem level. Research activities contribute to a better understanding and/or elucidation of underlying mechanisms.

Furthermore, the theme addresses the critical knowledge, skills, and technological advancements required to confront the unprecedented environmental threats that directly endanger human health on a global scale. Research in this area should promote advanced surveillance and monitoring of hazardous environmental factors through innovative tools such as real-time sensors, satellite and remote sensing technologies, and big data analytics. These approaches enable timely risk assessment, early warning, and effective mitigation of environmental health issues. Combined with adaptive mitigation strategies—including nature-based solutions and sustainable infrastructure—they form key pillars for strengthening emergency preparedness and response.

3.1.3. Sustainable and resilient agriculture and food systems

This subdiscipline contributes to the development of innovative and impactful solutions for a long-term resilience and sustainability of ecological and agricultural systems.

Research should focus on landscape-scale strategies that strengthen the adaptive capacity of agroecosystems for the production of food, fodder and energy.

Further, research activities should seek solutions that contribute to climate change mitigation and adaptation, sustainable land use and management as well as biodiversity conservation. It is intended to increase nature and climate friendly farming whilst supporting economically viable agri-food systems. These highly interdisciplinary topics require approaches ranging from lab-based trials, field studies, remote sensing, development of web-based applications, biophysical assessments, up to socio-environmental system modelling.

3.1.4. Transition towards sustainability: energy efficiency

The reduction of primary energy consumption and ultimately the reduction in CO_2 emissions is one of the main political targets nationally and worldwide. Energy efficiency research covers a broad spectrum of topics in identifying the potential offered by technologies, processes, designs, services and consumption behaviour changes. It can be applied in various contexts, for example in the construction environment to reduce energy consumption in new and existing buildings, in integrated planning and design of cities, in the transportation sector, as well as in industrial production and recycling processes, including industrial decarbonization. Research on buildings should also integrate the issue of health/environment (building materials, indoor pollution) and circular economy. Furthermore, research could advance in the topics of energy demand scenarios and of impact assessment of policy interventions and regulations.

Overall, the topic is highly interdisciplinary and links to economic as well as to policy-making and regulatory considerations.

3.1.5. Sustainable urban development and smart cities

Research in this area is focused on developing novel methods and approaches for integrating new knowledge and planning in order to achieve sustainable urban development. It encompasses the topics of smart cities and sustainable energy systems development, and extends to autonomy, connectivity, electrification, and shared mobility to support low-carbon, accessible, and climate-neutral cities. It comprises, for example, research on land use, housing, transport, energy and water supply and consumption, waste reuse, smart buildings, and recreation.

In view of increasing urbanisation, cities need to be planned differently in order to allow liveable systems. The various challenges that put pressure on the development require interdisciplinary, integrative approaches in research, involving the combination of a range of complementary expertise from different disciplines. Highly connected autonomous systems are key enabler for sustainability. Research should address the concept of interoperable and AI-enabled Local Digital Twins (LDT). This will enable connected Local Digital Twins in cities across EU in a common European Digital Infrastructure consortium and thus should be aligned with existing EU initiatives for smart city applications (e.g. the EU LDT Toolbox, the Data Space for Smart Communities (DS4SSCC), and the LDT Citiverse EDIC).

A number of social issues and behaviours have a direct link to climate change, and all forms of resource management require an integrated approach between research, technological development, and the buy-in of society (e.g. cross-border mobility, social hydrology, urban metabolism, etc.).

3.1.6. Smart energy systems

To become more climate friendly, fossil fuels will be replaced by electricity produced from renewable energies. The integration of decentralised renewables (like PV) with heat pumps, electromobility and battery storage requires increasingly intelligent applications based on IT-technologies. Such solutions will be needed on a

household level, for instance to manage the self-consumption of PV-based electricity coupled with a battery storage, but also on a system level to coordinate the different players in the system. For the latter, close interaction is needed with the operators of distribution and transmission grids to organise the exchange of electricity while respecting requirements regarding efficiency and reliability, also known as smart grid solutions. Research in this area will focus on the development of the technical and IT-solutions for smart energy systems.

3.2. Economic and industrial development: green and sustainable finance / circular economy / innovation and productivity

3.2.1. Industrial biotechnology / from waste to product

This theme addresses research on sustainable, climate-resilient, and competitive biotechnologies. It builds on nature-based solutions, biotechnology, and biomanufacturing, with the dual aim of contributing to European research and innovation leadership and supporting the diversification of Luxembourg's economy. Research in this area will help reduce dependency on fossil resources, mitigate climate change, contribute to circular economy, and secure resilient supply chains in food, chemicals, and materials.

Microorganisms, plants, and fungi form the basis for a wide range of industrial biotechnologies. Their activities enable the transformation of wastewater, gaseous emissions, biowaste streams, and untreated chemical waste such as plastics into new resources, opening new opportunities for applications across multiple industrial sectors.

Biotechnology also offers the possibility to develop alternative protein production systems, thereby contributing to food security, reducing environmental impact compared to animal-based production and current agricultural practice, and improving human health. This responds directly to pressing global challenges in sustainable food systems.

Using innovative methods and approaches, including advanced AI tools, research activities range from the study of fundamental biological production processes, including isolation and characterisation of relevant bio-based compounds to understanding, controlling, and optimising large-scale production. Furthermore, activities cover the valorisation of the outputs for additional industrial production. Life-Cycle Assessment methods will form an important contribution to these research activities.

3.2.2. Sustainable behaviours

Socially sustainable development is of particular importance to a diverse and multilingual country such as Luxembourg, where society is becoming culturally more diverse and facing rising levels of relative poverty and housing affordability issues. Research therefore needs to address various aspects of social cohesion, including the social consequences of labour market developments, wealth inequality, cross-border labour migration, cultural identities and nationhood.

The exploration of transformation processes can lead citizens and individuals, institutions, companies – and society as a whole – to adopt sustainable and responsible behaviours. Research will look into factors that are driving society to embrace change, from individual behaviours to institutional and governmental decisions as well as the evolution of social norms and their influence on individual and institutional decision-making. This highly interdisciplinary topic is anchored under the umbrella of both social sciences and natural sciences and is directly connected to societal transformation. Research should focus on transformation processes in order to address the country's pressing needs in urban development, transportation, land-use and -management, as well as its effects on biodiversity, environmental impacts and eco-system services.

Special attention will be given to the topic of green and sustainable finance, which is considered as the financial sector's contribution to the creation of a more sustainable global economy.

The highly interdisciplinary topic requires close collaboration among various research domains, and intersectoral exchange with the finance-sector. The expertise required to deliver on the topic comprises substantial competence in systems and network analysis, in social behavioural analysis, in management and organisation, as well as skills in finance, economic and environmental sciences.

3.2.3. Innovation, productivity and long-term transformations

Aligning science, education, innovation, and real-world actors ensures that productivity gains translate into higher innovation, competitiveness, and social well-being, supporting long-term economic transformation that is inclusive and sustainable.

Cross-cutting challenges linked to digitalisation, the green transition, demographic change, increasing spatial constraints, and growing geopolitical tensions are also driving profound transformations in production processes, business organisation, and wider societal structures. Addressing these challenges requires Luxembourg to maximise the efficient allocation of its resources, including capital, public infrastructure, land, and human capital. Rising housing costs and mounting pressures across markets increasingly influence mobility decisions, discouraging skilled workers and capital from relocating to or remaining in the country. This constrains firms' ability to establish or expand and limits the free flow of capital. Research in this area provides insights into labour market dynamics, capital flows, the supply of skills, and interactions between labour, housing, land, and financial markets, including the geopolitical implications of policy and investment choices. These insights support policies that foster a flexible, adaptive, and attractive environment for people and firms alike.

Research in this area explores key drivers such as shifts in power, technological competition, resource scarcity, and institutional fragmentation, and analyses how these translate into societal risks and opportunities. This includes examining the economic, social, and spatial impacts of conflict on population displacement, capital flows, financial instability, labour markets, and long-term development trajectories, as well as conditions for effective post-conflict reconstruction. In parallel, research on resource allocation is crucial to assess trade-offs between defence spending, social investment, and long-term growth.

3.3. Societal development: migration and social cohesion / cultural identities, cultural heritage and nationhood

Social, demographic and technological changes are reshaping Luxembourg's society and exacerbating issues related to inequality, inclusion and belonging. Research in this area examines the social, economic and cultural conditions that underpin social cohesion. Topics covered include inequalities, labour market dynamics, migration and integration, cultural identities, and the role of history and culture in sustaining inclusive, democratic societies.

3.3.1. Social cohesion and inequalities

A good living environment promotes prosperity, health, and well-being and is a prerequisite for social cohesion. It is a major challenge to achieve a comprehensive understanding of the relationships between the multiple environmental, urban, and social drivers involved, especially in view of the ongoing digital, technological and social transformations. Research in this subdiscipline addresses a range of inequalities.

Income and wealth distribution, including poverty and affluence in their extremes, demographic change, are long-standing issues, also in Luxembourg. There are intensive debates about recent changes in the distribution of

monetary and non-monetary resources across households, their impacts in a multi-dimensional domain, and possible consequences for social cohesion. One important aspect here is the impact of digitalisation on gratification chances and accumulation of wealth.

Housing and its environment are highly relevant for quality of life and perceived well-being. Both are shaped by urbanisation and, in the case of Luxembourg, by complex urban and regional development as well as by the shift towards a digital society.

The question of intergenerational fairness is increasingly relevant in ageing societies with demographic changes in family patterns and lifestyles. Pension systems, bequest, and the accountability of entitlements across borders, play a predominant role in this respect.

Additional social inequalities in health, provision of healthcare, and healthy behaviours are increasingly topics for social science research.

3.3.2. Societal transformation and labour market dynamics

Demographic changes, technological innovations, and international competition place economic and labour issues at the heart of the most critical societal challenges of our times. Research needs to help better understand labour market dynamics, the role of labour market institutions, the drivers of job destruction and creation, the development of new forms and ways of organising work, the evolution of required skills, and the role of professional relations in international labour markets affected by digital and technological transformation.

Increasing cross-border interdependencies and labour market dynamics at the level of the EU as a supranational federation – as well as other international exchange relationships – make the exchange of goods and services, the flow of money and of persons, financial instability, and the allocation of human resources more flexible. At the same time, these interactions require regulations that serve the needs of individuals and of collective actors.

Further population dynamics, including demographic and social changes, economic growth in a globalised world, and the challenges of maintaining well-functioning political, infrastructural, and social institutions, and of ensuring social sustainability, will challenge European societies on several dimensions – most notably with respect to living standards as well as social, economic, and spatial cohesion. The labour market will have to rely on a growing population of cross-border workers excluded from the country's political and democratic processes.

In addition, increasingly public engagement becomes crucial in identifying and actively intervening in societal challenges, such as inequalities in different types of capital (human, financial, social, spatial) caused by the (digital) transformation of societies. New instruments and approaches are needed to explore the multiple facets as well as to establish a platform for the co-creation of knowledge between the public, private sectors, and citizens/individuals on topics such as education, spatial planning, employment, and economic, social, health, and fiscal policies. Adequate research should help formulate new policies for a better management of market dynamics and identify the impact and effectiveness of these policies on the various markets (labour, housing, finance) and their normative foundations (non-discrimination, equal opportunities, intergenerational equity).

3.3.3. Household finance and risk management

With the reduction in state old-age provision, the increasing importance of defined contribution pension schemes, and demographic changes (e.g. increase in parental age, ageing population), household financial decisions have become a key factor in the well-being of individuals and societies. The growing complexity of financial investment products and of intermarket dependencies makes the diversification of assets particularly challenging. Research can help in better understanding the difficulties faced by households and in developing mechanisms to support

them in financial decision-making. For any modern society, it is of fundamental importance to further develop and improve skills and knowledge to enable individuals (financial literacy) or organisations (risk management) to undertake informed and correct financial decisions.

This subdiscipline needs to develop its cross-disciplinary character and to foster collaborations between theorists and empiricists as well as between economists, financial economists, psychologists, and lawyers.

3.3.4. Migration and integration

Immigrants must cope with multiple identities and solidarities. Legal regulations and integration measures are crucial for successfully managing competing feelings of belonging and for improving people's life chances in the country of destination at the level of legal citizenship, social and political participation, social integration in the educational systems and labour market, and cultural identity.

The negotiation of nationhood includes cultural and legal definitions of what is required for inclusion, and of what leads to exclusion.

3.3.5. Cultural identities and nationhood

Cultural identities and nationhood are especially challenging for Luxembourg, a small country in the heart of Europe. It has always confronted issues of multi-ethnicity and multilingualism; especially as nearly half of the population do not hold Luxembourg citizenship.

The experience of similarities and borders is an old theme in European history. It has become extraordinarily virulent again, in particular with the strengthening of populist tendencies, the increasing geopolitical tensions and a general trend towards globalisation. Europeans are now dealing with a continent which faces many challenges hitherto unknown to such an extent. The development of awareness of the problems of ethnic diversity is just as necessary in the 21st century as the assessment of one's own national and cultural identity and of its international and national relevance.

The field of cultural identity and nationhood calls for transnational and interdisciplinary research approaches.

3.3.6. Contemporary history, memories studies and public history

The relationship between culture, history, and memory has emerged in a global context as a key issue of interdisciplinary research, thus bringing together the humanities, social studies, and the natural sciences in a unique way. Memory studies is an emerging field that aims to employ memory as a tool for remembering the past. The purpose of the complementary new field of public history is to develop historical practices among the public and to discuss the results in meaningful and inspiring ways during critical debates.

Research in the humanities must not remain in the ivory tower but must also be taught to the broader society. Transnational and interdisciplinary cooperation is important and indispensable; in particular, it makes sense to combine digital history and public history.

3.3.7. Digital humanities

The widely used term "digital humanities" covers a field of research at the interface between cultural and computer sciences. Current global trends show that research and work in the humanities will not be possible in the future without digital approaches.

The Internet and digital media will become primary sources and require competencies in the field of Computer Science. Critical reflection on how the use of new digital tools, research infrastructures, and data sets changes or

impacts the way we think – digital hermeneutics – is the missing link between digital technologies and the humanities.

The massive digitalisation of cultural heritage and its online accessibility demand new forms, formats, and methodologies. New strategies need to be developed for integrating public engagement with history and historical scholarship.

3.4. Responsible development: regulations and ethics for a data-driven society

The rapid digitalisation of society and the increasing use of data- and AI-driven systems are reshaping markets, governance and societies. This creates new opportunities, but also significant legal, ethical and security challenges. This area of research examines how regulatory and ethical frameworks can foster innovation, protect fundamental rights, ensure market integrity and support the development of resilient, trustworthy and sustainable digital societies.

3.4.1. Regulation and supervision of the data-driven economy

Competitive markets can spur innovation, encourage efficiency, and lower prices for consumers. However, markets are also often complex and, when left fully to their own devices, may not achieve the best outcomes. The rapid technological changes raise the question of how disruptive technologies and new developments can be implemented in a responsible manner. Key priorities include the responsible and privacy-respecting use of data, the establishment of clear regulatory and legal frameworks, and the integration of ethics, data protection and cybersecurity "by design." At the same time, building geopolitical resilience through sovereign capacities and adopting open-source models will reduce dependencies and reinforce Europe's strategic autonomy. By embedding these principles, Luxembourg's research will help shape an innovation model that strengthens democracy, safeguards public trust and lays the foundations for a smart, sustainable and knowledge-driven economy and society.

More research is thus needed on the impact of existing regulations, governance standards, and practices on the markets. This is essential to improve the existing regulation and governance and direct its evolution in such a way that market development is stimulated rather than hampered.

The broadening scope of regulations at the national, EU, and international level justifies a more detailed examination of their effects, intentional or not. Regulations can lead to more efficient and fair markets, thus benefiting society, but can also hinder markets (for instance by imposing costs and impede innovation and technological progress) if they are not carefully formulated or enforced.

Luxembourg provides the ideal setting for developing leading research on judicial protection. It has the potential to pioneer reforms of the judiciary to meet the challenges presented by the proliferation of multi-layered regulatory and enforcement systems, in which administrative and criminal tools often compete or collide.

Exchange of goods and services, flows of money, financial stability, and allocation of human resources are becoming more flexible – but at the same time more vulnerable – because of increasing cross-border interdependencies at the EU level and other international exchange relationships. There is therefore an increasing need for further research into cross-border European supervision of financial flows along with development of credible and effective responses, both repressive and preventive, to financial crime.

The data-driven economy will be of key importance, not least because safe and reliable information and communication technologies are indispensable for the finance sector, the real economy and society at large. It is

of prime importance to address the concerns of cybercrime and cybersecurity. Luxembourg has all the ingredients required to develop high-quality interdisciplinary legal research at the interface of IT and cybercrime.

3.4.2. Ethics and sustainability

Present-day scientific discoveries and technological developments raise significant ethical and philosophical questions regarding the use of newly generated knowledge and its impact, intended and unintended, on society and humanity as a whole. In particular, the social and ethical issues arising as a consequence of the ongoing digital and biomedical revolutions need to be addressed in an interdisciplinary approach that ensures accessibility and non-discrimination are embedded by design across digital and biomedical innovation. Topics of relevance are privacy, autonomy, security, human dignity, justice, and balance of power, to name but a few.

As our species is confronted with unprecedented global challenges such as climate change, loss of biodiversity, and depletion of natural resources, the issue of sustainability is of paramount concern and relevance for all research areas. Hence, all researchers are encouraged to consider sustainability questions in their research activities. Especially, questions of ethics, values, and attitudes need to be addressed, as well as best ways to improve environmental education and public engagement.

Ethical issues and sustainability are of fundamental relevance and require adequate answers from the research community. While they should not be considered as a research priority on their own, tackling them in a cross-cutting manner will help in raising awareness of their importance.

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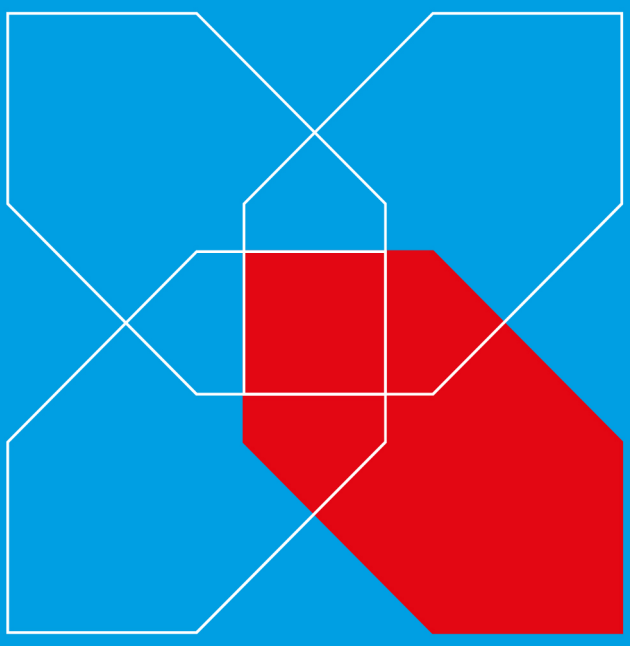
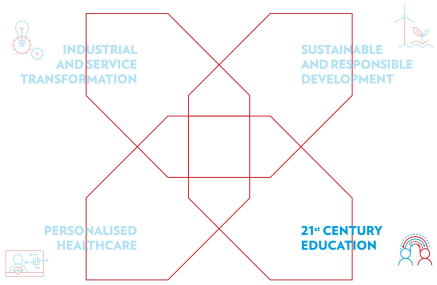
21ST CENTURY EDUCATION



4. 21st CENTURY EDUCATION

Education and training are critical components of societal health. They determine employment prospects, civic engagement and economic competitiveness. The accelerated digitalisation of the 21st century is already disrupting existing job profiles. Upskilling and reskilling the current and future Luxembourgish workforce will be paramount. Anticipating skills needs and adapting education and training provision accordingly will require regular monitoring and flexible policymaking.



The phenomenon of technology-assisted learning has become an academic discipline in itself at the intersection of pedagogy, psychology, computer science and digital innovation. Breakthroughs in artificial intelligence, the Internet of Things, virtual reality, extended reality and connectivity are enabling new methods for more personalised learning experiences at scale. However, they also prompt ethical questions, have been implemented at inconsistent rates and could potentially exacerbate the digital divide.

In addition to transversal skills such as analytical thinking, creativity, digital literacy, adaptability, resilience and cross-cultural skills, future employees will require mastery of skills that are currently only possessed by a minority of the workforce. The concept of lifelong learning is also rapidly evolving to mean less 'updating' of existing skills and more quickly learning new skills as career paths change. Many of these considerations are directly linked to the continued drive for Luxembourg to provide equitable and high-quality education for all citizens, despite rapid demographic shifts and a multilingual population.

Special consideration should be given to approaches that consider linguistic and cultural diversity as a strength. Educational technology has the potential to remove language barriers to provide all learners with equal access to educational resources, as well as to create personalised learning journeys based on the learner's mother tongue and language competency needs.

The applications of AI in education go even further, with algorithms providing personalised content and recommendations to learners, automating instructions for teachers, providing learners with instant feedback, and powering intelligent tutoring systems. Other examples include language translation tools, immersive virtual simulations, and improved formative assessment techniques.

The future of work will undoubtedly involve more automation and therefore continuous skills development. The Grand Duchy strives to become a frontrunner in adult education through the development of research initiatives and platforms to assess skill gaps in the workforce and to provide recommendations for specific upskilling and retraining initiatives. Being seen as internationally innovative and competitive in this area of adult education is also an essential element for talent attraction and retention.

4.1. Innovative digitally enhanced learning and assessment environments

4.1.1. Efficient learning environments

Given its diverse population of learners, a challenge for Luxembourg is to provide a constructive and efficient learning environment, as well as to contribute to a fair educational assessment for diverse learners, in particular with respect to the goal of ensuring more equal opportunities in education. Educational assessment concerns the collection of evidence about an individual's learning, which can be used to adapt teaching as well as the education of teachers and trainers and to plan further steps in learning. Evidence about learning is crucial as it indicates whether there has been improvement (or not) in an individual's learning progress and processes. Understanding of fairness in educational assessment has evolved with developments in learning theory and measurement, and it has increasingly been recognised as a necessary factor for inclusivity in education.

Educators and other professionals in the field can use such evidence to formulate goals and provide individuals with feedback about their learning.

4.1.2. Digital learning and human-machine interaction

Various modes of machine learning and the design of human-machine interactions allow a range of solutions that can benefit groups differently. Digital devices targeted to specific learning groups may be a tool for achieving this effectively and efficiently. Research is needed on what type of digital tools are effective for whom and how human-machine interactions and interfaces need to be designed to be effective. Artificial intelligence and machine learning can be used to analyse large amounts of data in order to anticipate trends in the economy and society, as well as to forecast how individuals or groups might behave. Further, generative AI can also help to enhance accessibility with real-time translation and language support, immersive simulations for experiential learning, and formative assessment.

4.2. Learning in a multilingual and diverse society

The multilingual situation in the Luxembourg school system as well as the increasing number of migrants pose a challenge to the education system and the aim of equality in educational achievement. Multilingual education typically refers to "first-language-first" education: schooling begins in the mother tongue and transitions to additional languages. Typically, multilingual education programmes are situated in countries where speakers of minority languages, i.e. non-dominant languages, tend to be disadvantaged in the mainstream education system.

There are increasing calls to provide first-language-first education to children of immigrant parents. This provides a unique opportunity to study the effects of multilingual education and to provide evidence-based suggestions for effective approaches. Here is the potential for Luxembourg to become an internationally visible actor in the field of innovative early intervention studies and assessments, with a focus on heterogeneous multilingual populations.

4.3. Equality of educational opportunity

The topic of inclusive and exclusive education is extremely relevant for Luxembourg, given the diverse population who attend its schools and need to access life-long learning. This theme provides a unique opportunity to add to the existing research efforts on inclusive education in all its aspects. The driving principle behind inclusive education is that all learners are offered education that fits their needs and capacities, and that they are supported

in their efforts. This includes learners with disabilities and special educational needs. Research should strengthen early need identification, and support transitions from school to work as well as from work to life-long learning. Of critical importance is the support of the learners' immediate environment, namely their family, parents, school, teachers and trainers. Beyond formal schooling, inclusive education also encompasses among others vocational training, second-chance programs for school dropouts and lifelong learning opportunities, ensuring that individuals of all ages and backgrounds can participate fully in skill development and society. Specific challenges arise when exogenous circumstances cannot be further equalized, when inclusive education reaches its limits and exclusive (i.e. special) education is needed for certain learners.

An increasing demand for inclusive practices and a growing awareness of the rights of parents and students have changed perceptions of special educational needs in the community in general, and in education in particular.

These research topics are essential for gaining the knowledge necessary to face educational challenges in the foreseeable future, and to extend current developments in the field.

4.4. Adult education, up/re-skilling and lifelong learning

The growing digitalization will mean fundamental changes for the labour market as a large number of new job profiles will emerge and existing job profiles will disappear. With the rapid growth of AI and data-driven technologies, it is essential to develop a skilled workforce capable of applying AI and data-driven solutions across sectors.

The process of creation and disappearance of job profiles will furthermore be much accelerated compared to the labour market developments observed in the past. This will imply completely new challenges for the field of adult education and training on and off the job, as the known concept of lifelong learning as a process of updating already existing skills over the lifespan has to be replaced by a model for which the acquisition of completely new skill sets and fundamental changes in people's job description will be crucial. This challenge will be further aggravated by short timeframes within which these up/re-skilling operations will probably have to occur. For these reasons, there is currently an urgent need for research in this highly dynamic area. Research questions might include the development of foresight models and platforms for upcoming job profiles and associated skills, monitoring skills gaps and future skill needs in the workforce, designing and exploring efficient learning and training environments for up/re-skilling.