National Research Priorities for Luxembourg in 2020 and beyond
Background and process

In its multi-annual contract with the Government, the FNR has been mandated to review the National Research Priorities for Luxembourg in close cooperation with the Ministry of Higher Education and Research (MESR) during 2018 and 2019. This follows a recommendation made by the OECD in its 2016 report on the Luxembourg innovation system.

The Luxembourg research system has experienced intense and steady development over the past 20 years. At present, the Luxembourg public research environment is in a fairly different situation compared to when the first research priorities were defined in the framework of the Foresight Exercise in 2006–2007. Much of what had been proposed then has been implemented, and capacities and strengths have been developed during the last decade. However, some domains developed better than others, justifying a revision of the research priorities.

As a small country, Luxembourg cannot allow for a broad diversification of its research system and has to make strategic choices in order to attain critical mass. Following the OECD recommendations, the revised National Research Priorities are based on the following criteria:

- Current strengths and identification of new areas and emerging topics
- Relevance in an international context
- Relevance for the country: societal and economic challenges

The revision of the National Research Priorities was conducted in a multistage process, with strong involvement of the national and international research community, of public and private stakeholders, as well as of ministries. Concertation with the MESR took place during the whole process.

The aim is to ensure a good balance between reinforcing current strengths and developing capacities for emergent areas, where Luxembourg researchers can have a head start. It is also important to maintain the right balance between fundamental and applied research in order to guarantee long-term adaptability to current and future socio-economic needs. Overall, the FNR fosters research with impact; while research addresses socio-economic challenges, not all of these challenges can be solved by research alone.

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 societal, ecological and economic development of the country. These areas are not considered as being distinct and independent from each other, but as areas that mutually influence each other, so that the sub-themes that define each area can also have ramifications into other areas. The implementation of the research strategy will therefore put a particular emphasis on interdisciplinary projects, which take into account that each of the four broad research priority areas will benefit from results and projects situated in one or more of the other areas. The four chosen research priority areas should guarantee that beyond a development of its GDP, Luxembourg can warrant for a continuous and sustainable development in the well-being of its population, including notably health, environmental and educational factors.

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Industrial and Service Transformation

- Integrative materials science and technology
  - Multiscale modelling in materials science and physics
  - Materials discovery through machine reinforced learning
  - Fundamental phenomena defining materials function and devices
  - Interface-dominated materials
  - Advanced manufacturing: multifunctional, multiclass, and multiscale materials, and their implementation
  - Physics of active and living matter
  - Materials life cycle
  - Scientific instrumentation and characterization

- Trusted data-driven economy and critical systems
  - Security and cybersecurity, reliability and trust
  - Cyber-physical systems

- Future computer and communication systems

- Autonomous and intelligent systems and robotics for earth and space

- Space telecommunications, earth observation and space resources
  - Resources in space
  - Remote sensing and combination with multiscale data

- Fintech/RegTech and transformative applications of distributed ledger technologies

- Fundamental tools and data-driven modelling and simulation

Personalised Healthcare

- Complex biomedical systems – data and models
  - Effective collection and deconvolution of complex biomedical data
  - Multi-scale and mechanistic models

- Precision medicine, including environmental, lifestyle and socio-economic factors
  - Innovative molecular disease models
  - Common mechanisms between diseases – mechanism-based stratification
  - Environmental, lifestyle, and socio-economic impact on mechanisms of diseases

- Understanding, preventing, and treating the health-disease transition
  - Longitudinal dynamics of diseases
  - Multifactorial intervention strategies
  - Innovative clinical trials

- Data-driven healthcare
  - Trusted digital health systems
  - Health informatics and implementation in the healthcare system
### Sustainable and Responsible Development

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Industrial and Service Transformation
01. Industrial and Service Transformation

"The upcoming digitalisation will imply fundamental changes for industry and service providers that are active in Luxembourg. The country has the ambition to become a knowledge-driven data economy actively seeking to diversify its economic activities taking up the latest technological developments and providing high value added. The research carried out in this area should provide the scientific basis for such a development. It encompasses research in the industrial fields in which Luxembourg wants to consolidate and further develop its assets, for example in material science, space industry, or in the field of automation and robotics. Data modelling and simulation are seen as a key enabling technology in this area. It also includes new communication and computer systems and the associated challenges regarding cybersecurity needed for a trusted data driven economy in an ever more connected world. Furthermore, this research seeks to bring new perspectives to Luxembourg’s most important economic sectors, like the financial industry, through the development of key technologies in the fintech/regtech area or in the field of distributed ledger technologies."

Integrative 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.

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.

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.

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.

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.

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. The topic of integrating compositionally graded polymeric materials into a recycling or reuse scheme should also be addressed.

This subdiscipline should be viewed as an integrative part of theme "Integrative 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.

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 biological 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-mobility, and synchronisation.

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

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 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.

Scientific instrumentation and characterization

Luxembourg has strong expertise in scientific instrumentation (for instance for the characterisation of advanced materials), which has been acquired over the years. Throughout several disciplines, for example materials and physics, ICT, environmental sciences and biotechnology, materials characterisation know-how will be of high relevance. It requires close collaboration and interaction with researchers from all those domains. Scientific instrumentation and characterisation cover the full range of science, from fundamental research to applications.
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.

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 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.

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, and systems, also taking into account the energy efficiency of computing and datacenters.
Space telecommunications, earth observation and space resources

Resources in space

This area focuses on technologies for the exploration and utilisation of space resources. It includes the subdiscipline 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.

Interdisciplinarity and collaboration with other space actors is a prerequisite for research in this theme.

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.

Fintech/RegTech and transformative applications of distributed ledger technologies

A highly interdisciplinary research area focuses on systems that enable distributed ledger technologies 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), as well as other use cases in logistics, public sector, the data driven economy etc.

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

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 areas such as engineering, life sciences, physics, as well as the social sciences.

A key novel topical area is the assimilation of hypothesis-driven mathematical models in complex systems vs. purely data-driven machine learning (ML) algorithms (differentiation of causality vs. correlation). In other words, the transition from Small Data (hypothesis-driven) to Big Data (ML paradigm). Other relevant topical areas are the quantification of uncertainties and risks in complex systems and multi-scale/reduced-order modelling (reducing complexity while maintaining information content).
Personalised Healthcare
02. Personalised Healthcare

"Health is considered to be a key indicator of well-being and Luxembourg has the ambition to provide excellent healthcare to its population and to be a frontrunner in the implementation of the latest health technologies. Especially in the field of personalised data-driven digital medicine, Luxembourg wants to be among the leading countries in the world. Luxembourg therefore needs biomedical research that will ultimately be beneficial to the patient. Following this logic, translational medicine will play an important role in the medical research carried out in Luxembourg. The perspective on health will nevertheless not be limited to a purely biological or medical perspective, but will include socio-economic and behavioural aspects considered in a longitudinal perspective throughout the lifespan, which should permit an emphasis on disease prevention and behavioral changes."

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.

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.

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.

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.
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 theme “Complex 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 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.

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 systems – data and models” as well as with “Digital health” to create a strong foundation for computation-based understanding of disease mechanisms and stratification of patient groups for more effective care.

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 chemicals (POP, endocrine disruptors, phytosanitary products …) and pollution (air, noise …).

Understanding, preventing, and treating the health-disease transition

While theme “Mechanisms of disease” 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 disease 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.

Longitudinal dynamics of disease

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.
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, 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.

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.

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

Data-driven healthcare

Trusted digital health systems

As health data is inherently of high value and extremely personal, ensuring the confidentiality and security of data and storage systems means building trust in digital solutions for healthcare. In the near future, the quantity of patient data will increase exponentially with the inclusion of more and more molecular data, including genome sequencing. Thus, the overall amount of sensitive information will increase, along with the risk of data breaches. The advent of GDPR as well as public pressure has created a need for further research into cybersecurity.

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.

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 health economics and inequality) are crucial.
Sustainable and Responsible Development
03. Sustainable and Responsible Development

"Luxembourg fully subscribes to the sustainable development goals of the United Nations and will contribute through its research activities to a sustainable development from an ecological, economic and societal perspective. In the ecological field, a focus will be on research in the context of a transition to sustainability and climate change. Luxembourg has the ambition to become a model country for the efficient use of a renewable energy mix through a smart energy management that includes energy-efficient smart buildings, which are connected to smart grids, also enabling a smart mobility. It will develop technologies to continuously monitor the effects of climate change on ecological systems and biodiversity and use this monitoring in order to model future scenarios allowing for the country’s best adaptation to a changing environment (e.g. in view of agricultural and forestry activities, but also in prevention of extreme events or water availability).

Economically, Luxembourg will innovate through research on new sustainable economic instruments and models, especially in the areas of green finance and circular and sharing economy.

A socially sustainable development is particularly important for a very diverse and multilingual country as Luxembourg, and therefore research on different aspects of social cohesion, like the social consequences of migration and labour market developments, but also questions of cultural identities and nationhood will be included in this research area.

Finally, the upcoming digitalisation raises the question how all these new developments and disruptive technologies can be implemented in a responsible way. In this context, questions about regulations for a responsible and privacy-respecting use of data, as well as ethical questions around data use and disruptive technologies such as artificial intelligence will be in the focus of Luxembourg’s research efforts. They will make a major contribution to the provision of the regulatory/legal framework needed for a smart knowledge-driven economy and society."

Climate change: energy efficiency and smart energy management; resilient eco- and agrosystems

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.

Resilient water systems

Climate change directly impacts water resources in terms of both water quality and water quantity. 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 summer time 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. There is a pressing need for research in this area, against the backdrop of climate change, land-use change, and population growth. 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.

Environmental monitoring

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.

**Transition towards sustainability: energy efficiency**

The reduction of primary energy consumption and ultimately the reduction in CO2 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, and services. 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. 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.

**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 comprises, for example, research on land use, biodiversity loss, housing, transport, air quality, noise, energy and water supply and consumption, waste reuse, rainwater harvesting and management, smart buildings, and recreation. Furthermore, it shall investigate innovative strategies for coupling and integrating these elements with a broad societal view.

In view of increasing urbanisation, cities need to be planned differently in order to allow liveable systems and to provide resilience towards climate change. 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.

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 to foster “climate positive lifestyles” (e.g. cross-border mobility, social hydrology, urban metabolism, etc.).

**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 house-hold 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 solutions for smart energy systems.
Social: migration and social cohesion / cultural identities, cultural heritage and nationhood

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 transformation. Research in this subdiscipline addresses a range of inequalities.

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

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 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 labour market dynamics, and identify the impact of these policies on the various markets (labour, housing, finance) and their normative foundations (non-discrimination, equal opportunities, intergenerational equity).

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 important contributing factors to 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.

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.

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 right-wing populist tendencies 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.

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.

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.

Ethics and sustainability

Present-day scientific discoveries and technological developments raise significant 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. 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.

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

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. As markets become more digitalised thanks to the huge increase in data available, the benefits of and the need for careful regulation take on ever greater importance.

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 benefitting 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 and other businesses. 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.
21st Century Education
“Education is another major cornerstone for the well-being of a society, as it forms the basis for employment, societal participation and ultimately for our democratic functioning. It is foreseeable that education will undergo major changes throughout the 21st century, for different reasons.

Educational systems are currently educating for unknown professional environments, as the upcoming digitalisation will dramatically increase the speed of creation of new job profiles, while existing job profiles might disappear. The fast pace of technological developments therefore implies the need to better monitor the skills gap existing between need and supply and to train the population for new, but highly dynamic digital skills.

Digital tools and technologies thus become on the one hand the content of new training programmes and they are at the same time used to deliver these new contents. In terms of key competencies, transversal skills such as problem solving and communication skills are more and more valued, as they form a skillset that is needed in order to cope with these fast-paced developments and changes.

Lifelong Learning changes from a model that historically implied the update of existing skills to a model in which completely new skillsets have to be acquired in short periods of time, in order to cope with the more fundamental changes in career paths that we will see in the future. These new educational challenges are added to the already existing ones of providing a high-quality, inequality-avoiding initial training to a very heterogeneous and multilingual school population.

Luxembourg will therefore invest in educational research, in order to develop innovative, digitally enhanced learning environments that will be beneficial to a diverse and multilingual school population and thus contribute to equal educational opportunities. Luxembourg also has the ambition to be among the frontrunners in the field of adult education and develop the needed research programmes in order to be well prepared for the upcoming major trends of upskilling and reskilling in the workforce.”

Innovative digitally enhanced learning and assessment environments

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 and teachers’ education 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.

Digital learning and human-machine interaction

Various modes of machine learning and the shaping of human-machine interfaces leave room for a range of solutions that can benefit different groups differently. Digital devices targeted to specific learning groups may be a tool for achieving this effectively and efficiently, not only for migrant populations. The use of artificial intelligence as well as machine learning methods could help to predict socio-economic variables and individual behaviour.
The topic of inclusive and exclusive education is extremely relevant for Luxembourg, given the diverse population who attend its schools. 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 students are offered education that fits their needs and capacities, and that they are supported in their efforts. Of critical importance is the support of the student’s immediate environment, namely their family, parents, school, and teachers. 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 students.

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.

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.

The upcoming 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. 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, 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-/reskilling 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 for upcoming job profiles and associated skills, monitoring skills developments in the workforce, designing and exploring efficient learning environments for up-/reskilling, adapting learning environments to the cognitive and personality profiles of adults coming from different age groups or coping with the uncertainty created by fundamental career path changes.

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