Common Strategy Paper 2016 - 2025

LIH, LISER, LIST and the University of Luxembourg

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Foreword

The performance contracts 2014-2017 between the Luxembourgish government and the University of Luxembourg (UL), the Luxembourg Institute of Science and Technology (LIST), the Luxembourg Institute of Health (LIH) and the Luxembourg Institute of Socio-Economic Research (LISER) foresee a strategic concertation between the four public research institutions in four explicitly mentioned domains:

- Materials Science
- Sustainability
- Information technology and high-performance computing
- Biomedicine

We, representing the four research institutions, see this strategic concertation as part of our common strategic goal – to propel Luxembourg towards becoming one of the top countries on the international map of research in materials, sustainability, ICT/HPC and biomedicine. The recent success of the UL in the 2016 THE international rankings could be regarded as one indicator that Luxembourg is already on a very promising path. Overall, UL is #178 in the global ranking of research universities and #14 among the young universities (younger than 50 years) worldwide. In addition, it also achieved #58 in the worldwide ranking of Computer Science research. This success is in part due to the current collaborations between UL, LISER, LIH and LIST. Further international successes can be expected by realizing the joint strategies in this paper, with the best interest of the whole country and not of one single institution in mind.

Strategic concertation in these selected domains adds to recently initiated joint activities which have contributed to a strengthening of the joint research potential as well as the international reputation for research in Luxembourg:

- Joint doctoral programs in the framework of the new PRIDE scheme of the National Research Fund (FNR)
- A Memorandum of Understanding concerning the future collaboration in doctoral education that has been signed between UL and the three public research institutes plus the MPI for Comparative Law in November 2016
- Recent announcements of joint professorships and nomination of honorary professorships between UL and the three public research institutes (LISER, LIH and LIST).
- Creation of a joint Brussels Liaison Officer to facilitate access for researchers in Luxembourg to European funding opportunities.
- Assisting the FNR in the formation of a Luxembourgish Agency on Research Integrity (LARI).

Moving forward, there is a need to further build on the current joint activities of the 3LIU consortium. Throughout the preparation of this document, it was clear that members of the consortium should work together and share resources where possible, in order to optimize resource allocation and reduce spending that can be used for other purposes. In addition, there is an increased desire and necessity for cross-fertilization of ideas between research fields, which the consortium can focus by taking advantage of the research diversity in its members. It is the view of the consortium that joining forces wherever and whenever possible will help to maximize the efficiency of research in Luxembourg in order to achieve its joint strategic vision and maximize the value impact of research for society.

The main focus of this joint strategy document are twofold:

- The identification of a mission and vision for the future of each of the four research domains, as well as the strategic goals and investments needed to realise them.
- Highlighting the common themes and strategic initiatives needed to maintain and improve collaboration between the four research institutions in Luxembourg, with the goal of creating a unified world-class research landscape in the country.

The present document details the concerted strategy that has been developed as a joint effort of all four partners. In each of the four domains a preamble describes the specific challenges for Luxembourg, followed by the mission and the vision of the joint strategic initiative. An outline of already existing common activities is given, as well as a list of actions and investments needed as part of the joint strategic plan. Finally, we outline the expected outcomes after 10 years.

An earlier version of this document had been compiled in early 2016 under the responsibility of Hilmar Schneider, former CEO of LISER, in his capacity as acting chairman of the 3LIU Working Group that comprises the CEOs of the public research institutes and the President of UL. The final version of this paper has been drafted under the responsibility of Rainer Klump, President of UL and acting chairman of the Working Group, and Sean Sapcariu, PhD, staff member of the Strategy and Planning Office of UL and liaison to the 3LIU Working Group. Special thanks go to the responsible persons within UL and the three public research institutes that have prepared the facts, the plans and the visions on which this joint strategic concertation could be elaborated.

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Materials Science

Preamble – Materials Research and Technology as a national priority

Europe. The research and development of *advanced materials* with increased performance and functionality is a major driver of innovation. According to the Research and Innovation department of the European Commission, it is estimated that "*70% of all new product-innovation is based on materials with new / improved properties* "[1].

It is important to emphasize the **transversal and enabling character of Materials Research**. Materials research, whatever the focus, relies on a foundation of shared knowledge and infrastructures, namely in the synthesis of materials, their physical and chemical characterization, their physical performances and their theoretical understanding. As a consequence of this, Materials Research is generally considered as "enabling", meaning that foundational knowledge in one of the above activities can diffuse into different fields of research and sectors. As an example, the very same nano-materials, only slightly tuned to each purpose, can be used for various applications, e.g. in sensors, in actuators, in coatings, or in nano-composites.

Luxembourg. A large part of Luxembourg's manufacturing industry is closely tied to innovations in materials research. Several companies have extensive R&D operations, ranging from automotive suppliers to aerospace, metallurgy, electronics or construction[2]. Recognizing the importance of the sector for Luxembourg, the first Cluster of Luxinnovation was established on Materials & Process Technologies.

As a mirror of this, the FNR has identified *New Materials and Surfaces* as a research priority for Luxembourg and half of the R&D projects supported by the Ministry of Economy are in the field of materials. The materials and process sector is regarded as one of the main drivers of competitiveness and diversification in Luxembourg. Advanced materials are accordingly part of Luxembourg's smart specialization strategy.

Public R&D in Luxembourg. In line with this strategy, public R&D in Materials Research has significantly increased over the past years. The major divisions focusing on materials today combine about 240+ people: 150 in the Department *Materials Research and Technology (MRT)* at the Luxembourg Institute of Science and Technology (LIST) and 90 people in the research unit (RU) *Physics and Materials Science (PhyMS)* at the University of Luxembourg (UL).

The strategic plan of MRT and PhyMS aims at a significant growth to about 350 people by 2020. A major driver for this growth rate is the success in acquiring external funds. As an illustration, MRT and PhyMS have acquired in 2016 together a new revenue stream of

[1] http://ec.europa.eu/research/industrial_technologies/promotional-material_en.html
[2] To name just a few: Goodyear, Arc. Mittal, Delphi, Dupont, Eurocomposites, IEE, Carlex, Guardian …

about 24 Mio€ from both competitive and industrial projects. The high concentration of excellent researchers provides a solid basis for the future development of physics and materials science in Luxembourg: Today, MRT and PhyMS host together 3 ERC consolidator grant holders, 2 PEARL grant holders and 6 ATTRACT Fellows.

Stimulated by their successful past and on-going joint activities, MRT and PhyMS wish to push their interaction further, and leverage the current dynamism towards a sustainable long-term collaboration framework, to the benefit of both institutions.

Mission

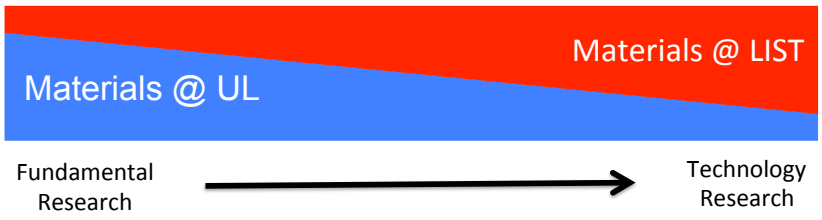
Together MRT and PhyMS form a research hub that combines the intellectual pleasure of fundamental understanding with technology development. This hub will be of strong benefit for industry in Luxembourg and surrounding countries, by developing novel materials and high-value products and will attract some of the world's best researchers in physics and materials science to Luxembourg.

Vision

A high concentration of internationally leading researchers, together with high-quality education and PhD programs and world-class infrastructures will make Luxembourg a Centre of Excellence in Materials Research and Technology. The joint activity in materials science will further strengthen the international standing of UL (currently placed 178 in the world-wide THE ranking) and it will push forward UL to appear in the subject ranking "physical sciences" of THE.

Current activities – A springboard for the future

The research activities of MRT and PhyMS have different centers of gravity. MRT has the mission to translate cutting-edge materials research into transferable technology, while the mission of PhyMS is to perform excellent fundamental and applied academic research as well as to educate the future generation of researchers. As illustrated below, the approaches are complementary and form a good basis to stimulate lively collaboration.



The scientific domain of PhyMS is condensed matter physics, with special focus on the

physics of materials. Current activities range from fundamental questions of nanoscale interaction and self-organisation, to applied topics with a long-term perspective, such as next-generation electromagnetic materials, solar cells, and new materials for articles of daily use. MRT focuses on two main research areas: *Nanomaterials and Nanotechnology* (multifunctional ferroic materials, transparent electronics, nano-enabled medicine and cosmetics) and *Composite Materials* (Bio-based and functional composites, adhesion and interface engineering).

MRT and PhyMS have recently shown how this scope of activities can be the springboard for their federation around specific topics: The joint FNR-PRIDE project MASSENA groups 24 PIs of PhyMS and MRT around a single field: "Materials for Sensors and Energy Harvesting". Also, MRT and PhyMS have jointly established a National Contact Point for Large Scale Research Facilities.

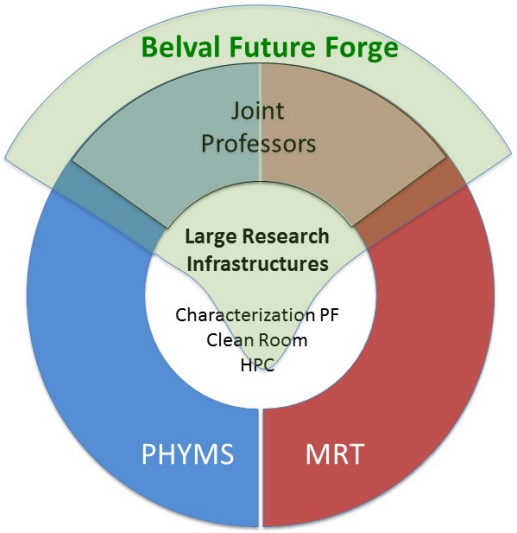
The interaction of MRT and PhyMS is characterized by steady communication and exchange, mutual respect and an agreement to interact synergistically. Testimonies of the collaborative spirit are a joint article on "Materials Science in Luxembourg" in the prestigious journal *Nature Materials*, underlining the shared ambition to establish Luxembourg as an internationally recognized center for materials research, the establishment of a common MRT-PhyMS programme "Physics and materials science" in the Doctoral School of Science and Engineering DSSE. MRT also participates in the steering committee of PhyMS and in UL lecturing, and most senior MRT researchers have UL doctoral supervision rights. Finally, the mutual trust finds its expression in the reciprocal participation in recruitment committees.

Joint strategic plan – The Belval Future Forge

Building on the existing activities and using the symbolic character of the steel production site at Belval, we give our joint strategy the working title "the Belval Future Forge". It aims at creating novel advanced materials that will shape the future of materials industry in Luxembourg and abroad.

The Belval Future Forge will rely on the two pillars of academic research at PhyMS and technology research at MRT. It will span the full range from basic research on materials properties to the study of process technologies, the fabrication of prototypes and, finally, where appropriate, pilot lines. The Belval Future Forge will be an incubator and hub for innovation for the materials related industry of the Greater Region. We envisage a truly joint action of UL and LIST.

The Belval Future Forge will not only strengthen existing collaboration, but will open new possibilities and enable new topics. The strategy foresees strengthening the collaboration by locating PhyMS and MRT in the same building and opening new possibilities by providing new large infrastructures, which also require new personnel. We intend to hire these new positions in a truly collaborative manner as joint appointments. Although the Belval Future Forge concentrates on the collaboration between PhyMS and MRT, it is our intention and wish to extend this collaboration to other partners, like LCSB, SNT, colleagues from RUES @ UL and also the ERIN department @ LIST.



A first focus will be to federate LIST's and UL's recognized and considerable expertise in the field of ***materials and technology for sensors and energy harvesting***. The topic is based both on existing industrial activities in Luxembourg and future-oriented initiatives for the establishment of new fields of activity. It arises from over two years of constructive discussions, which have found their first expression in the FNR-PRIDE project MASSENA, regrouping 24 PIs (!) from MRT and PhyMS. The objective is to acquire and use broad knowledge of coupling/sensing and energy conversion phenomena with an aim of discovering new general concepts, materials and devices, clearing the way for both understanding and applications. Our research lines will cover core competencies as well as new activities with higher risk at the forefront of science and technology, running up to laboratory proof of concept. This topic is predisposed to be leveraged in the framework of an FNR funded NCER, providing further means to the Belval Future Forge.

A second focus lies in the field of ***soft matter, namely innovative polymer-based composites***. The industrial composite materials sector presents a particular strength for Luxembourg with companies with a large R&D portfolio such as Delphi, DuPont, Euro-Composites, e-Xstream, Goodyear to mention only a few. In particular, this sector is currently being developed in the area of sustainability, including an improved durability and the use of alternative materials such as bio-derived polymers and natural fibers. Based on this, the Ministry of Economy, twelve companies, LIST and UL have established the National Composite Center (NCC-L). The objective is to combine high-quality research/technology and education training, hand-in-hand with industry, strengthening therefore Public Private Partnership (PPP). The Belval Future Forge will enhance the collaboration between MRT and PhyMS in this field.

Finally, we envisage further initiatives, with a perspective on additive manufacturing (3D-Printing), in particular new exciting fields such as ***Nano Additive Manufacturing***.

Necessary strategic investments

- *Buildings*

The geographical separation of MRT and PhyMS remains an obstacle for efficient and in-depth interaction and collaboration. As a matter of fact, the currently available space both at PhyMs and MRT does not allow further development. Also, shared/close buildings are an absolute perquisite for the efficient use of world-class infrastructure. The Belval Future Forge will need new and adequate laboratory space. This space should at best be located in a ***common building*** used by MRT and PhyMS that is large enough to host the current activities plus the growth ambitions within the Belval Future Forge. An adequate solution would be to host PhyMS and MRT together in the Aile-Nord/Aile-Sud building.

- *Experimental infrastructure*

Materials science belongs to those scientific topics that rely heavily on expensive world-class infrastructure to be internationally competitive. The cost of competitive equipment ranges from several 100 k€ to several M€. It is thus of great importance to have a scientific- and cost-efficient use of facilities, which is internationally done on shared platforms (or Large Research Infrastructures – LRI - in the EC language) that bundle scientific, technological and financial efforts. We propose to pool existing and new characterization techniques in a LRI and to share a large clean room environment for sample synthesis and nano-fabrication. On a concrete level, we envisage to invest in

- nano-imaging: in particular high-resolution transmission-electron microscopy (HR-TEM), atom probe tomography or super-resolution optical microscopy
- advanced spectroscopy: a range of modern synchrotron based spectroscopies, together with the relevant local laboratory equipment.

- *Computing* (HPC).

The experimental activities need support through theory and simulation. Both PhyMS and LIST pursue computationally costly activities in electronic-structure and molecular-dynamics calculations. If significant HPC infrastructure will be created as part of the national HPC centre, the Belval Future Forge will profit from this equipment.

- *Joint Recruitments*.

We believe that joint positions are key for collaboration; here again the international benchmark is clear. The honorary professorships for Jens Kreisel and Philippe Dubois are a good starting point, but are seen only as a beginning. We propose three joint professorships to leverage the topics described above. These professorships are expected to be strong ambassadors of the collaboration of both institutions. For each professor, investments in relevant equipment and infrastructure are needed in order to make the positions attractive to the targeted world-leading scientists.

Conclusion and Expected Outcomes

The Belval Future Forge will provide the framework for PhyMS and MRT to strengthen and jointly develop the activities in Materials Science in Luxembourg. The activities range from curiosity-driven fundamental research via applied research on novel materials to technology transfer. The strategy towards a successful center comprises four key issues:

1. It provides a necessary substantial upgrade towards world-class infrastructure (common buildings, cutting-edge experimental equipment, clean room, modern computing facilities);
2. It will strengthen the ties between UL and LIST through a road map towards top international recognition that is founded on joint activities, ranging from common equipment platforms to joint professorships.
3. It will expand the expertise and activity range in Luxembourg materials science through three new professorships in key-areas of nano-imaging, spectroscopy, and nano-additive manufacturing. We will hire persons complementary to existing faculty, with world-class research tracks.
4. The new location can comprise a partnership office and be a strong partner for the materials related industry in Luxembourg. It will thus cater to the diversification of Luxembourgish value creation.

Sustainability

Preamble

The vision: Luxembourg develops a world-leading society model capable of serving present and future generations whilst balancing diverging interests and using limited resources.

The mission: Establish Luxembourg as a *Centre of Excellence in Research on Sustainable Development* where all fields of science, all researchers, stakeholders and users cooperate to embrace synergistically a future-oriented process of changing socio-economic practice and technological innovation.

Research initiatives will ensure that research outcomes present actionable knowledge and innovative products and services that have direct traction in the economy, government and civil society. *The overarching goal is the transformation of human-environment interactions towards improved sustainability.*

Background – The global challenges In view of accelerating global changes along multiple and interdependent spheres of society, economy, technology and environment, challenges of sustainability[3] are growing ever more complex and are ever more difficult to act upon.

In September 2015 the United Nations adopted the Agenda 2030 on sustainable development, a process in which the EU and Luxembourg then holding the presidency over the EU Council, played a leading role. Even though the Agenda 2030 is not legally binding, over 180 signatory governments have committed to take ownership and establish national frameworks for the achievement of the 17 Goals by 2030. In Luxembourg, the Higher Council for Sustainable Development[4] was mandated by government to develop a line of work on the implementation of these goals in Luxembourg. In international comparisons, countries that are pro-actively developing effective strategies to analyze and act on sustainability challenges are considered more likely to achieve a sustainable balance between enhancing environmental quality, well-being and equity, and wealth creation in the long-term. Consequently, the recent OECD review of Luxembourg's innovation policy[5] recommends to strengthen the links between national strategies for research investments and for economic diversification, social well-being, and sustainability goals'. This is also largely in-line with new strategic research opportunities

[3] Sustainability is a term originally derived from ecology where it stands for longevity and diversity of living systems.

[4] http://www.csdd.public.lu

[5] http://www.oecd.org/sti/inno/Luxembourg-Innovation-Review.pdf

opening up under the forthcoming EU Horizon 2020 research calls, in particular in research on the 'grand societal challenges'.

Challenge 1 – Recent spatially fragmented and socially divisive urban growth patterns challenge increasingly environmental and socio-economic sustainability

Properly steered urban growth has the potential to drive wealth creation, social equity and socio-economic inclusion. The very sharp dynamic of urban growth (Luxembourg is the fastest growing country in Europe with regard to relative demographic increase) raises crucial challenges that have to be tackled with a sustainable spatial planning strategy, both at the national and cross-border scale. How can we develop a multidimensional planning of urban development which allows to answer to the needs for more housing, more economic zones, but more environmental protection as well? How to ensure that our society is not becoming more and more divided, socially as well as spatially, in a context of strong increase of housing prices?

Challenge 2 – Upcoming demographic mutations require creative policies, robust and sustainable socio-economic practice and technological innovation

Population ageing and increasing migration flows on the one hand, changes in the structure of employment, job insecurity and increasing automation of jobs on the other hand put the sustainability of traditional western Welfare State institutions under threat. In a context when spending increase and sources of financing become more uncertain, can existing institutions and social protection mechanisms be sustained without merely shifting the burden of the costs to future generations? Taking up the challenge will require innovative approaches to social policy design, and accurate understanding of the magnitude and implications of population change on labour markets, on the demand for health care, on the recourse to social protection, and on social interactions. Critically, it will also require preparing a change from Welfare State institutions primarily designed for isolated nation states to Welfare State mechanisms adapted to a globalized world in which people, capital, goods and jobs move more and more freely.

The compositional shift from younger to older age groups also raises the question of how a decreasing working-age population will be able to sustainably support pension insurance and welfare systems. Policy makers around the world view "sustaining economic growth under conditions of population ageing by far as the most pressing global policy challenge for the next fifty years" (Hasselhorn and Apt, 2015: 12).

Challenge 3 – The complexity of human-environment interactions is increasing and continuously changing

Traditional fields of 'normal' science can only play a limited role in resolving the growingly complex problems involving human-environment interactions, and need to be accompanied by more varied forms of knowledge generation through cross-cutting, inter-disciplinary and trans-disciplinary research and practice.

Challenge 4 – Without ownership there will be no sustainability

Contemporary debates on sustainability are putting a strong emphasis on civil society agents and public participation processes, as steps towards the "co-production" of knowledge by various professionals, intermediaries and lay actors.

Current Activities

The research community includes internationally leading experts in salient disciplinary fields, and has excellent connections to a strong international network of leading experts for transformative sustainability science. At present, research in disciplinary fields prevails, but there are some recent successful initiatives to build up inter- and trans-disciplinary research.

Existing collaborative institutionalized instruments:

- joint RDI projects and PhD supervision;
- contribution to the student education at UL (for instance ERIN/LIST contributes about 400 lessons/academic year, LISER with about 113 lessons/academic year, LIH with about 100 lessons/academic year).
- collaborative effort to establishing the 'Certificate in Sustainability and Social Innovation', a unique study programme that is open to students at all levels and to professionals, and which draws on perspectives from natural and social sciences and practice, with contributions from all UL faculties as well as from ERIN/LIST.

On a series of topics, successful and mutually reinforcing collaborations between Luxembourg public research organizations exist. Amongst these existing collaborations relating to sustainability, the following must be further extended and consolidated to form starting points for our 3LIU sustainability strategy:

1. **LIST-ERIN, UL-FSTC RUES and UL-FLSHASE-ECCS** have gained a PRIDE Doctoral Training Unit on understanding Environmental Change with UL-FSTC RUES and have developed a project to develop citizen science for social learning and anticipating potential challenges at the food water energy nexus (Convention to be signed) with UL-FLSHASE-ECCS. This emerged from five years of joint development and implementation of the Certificate in Sustainability and Social Innovation a unique study programme that is open to students at all levels and to professionals, and which draws on perspectives from natural and social sciences and practice, with contributions from all UL faculties as well as from ERIN/LIST.

2. **LISER, the UL FLSHASE, and the UL-FEDF-CREA** have joined efforts to start a PRIDE Doctoral Training Unit on 'Migration, Inequality and Labour Markets' a domain which is at the core of social sustainability issues. It will bring together 12 PhD students. Three joint professors between LISER and the UL are also integrated in the DTU initiative—two with UL-FDEF and one with UL-FLSHASE--- with the first positions starting early 2017.

3. **LIH-Department on Population Health and the UL-FLSHASE-INSIDE Institute on Health and Behaviour conduct joint research on** health costs and the sustainability of public expenditures on health care and prevention for sustainable public finance.

4. **LISER, LIST and the UL FLSHASE-IPSE Institute on Geography and Spatial Planning** have collaborated for over a decade in the area of sustainable mobility and mobility planning. A joint Chair on Urban Planning is starting early 2017.

5. **LISER and LIST** have collaborated during recent years on several research projects about sustainable mobility like Zac eMovin (electromobility in activities areas) and CONNECTING (Consequential Life Cycle Assessment of multi-modal mobility policies).

The complementarity of expertise between LIH, LISER, LIST, and the UL offers much room for expanded and more in-depth collaboration to tackle sustainability-related challenges, in particular in the development of projects to address complex problems at the interface where society meets environment.

The research strategy

Responding to new worldwide challenges posed by the sustainability perspective will require new social, economic and environmental policy thinking, which will need to be backed up and supported by new research initiatives. In the words of the OECD, "responding to new challenges means we have to adopt more ambitious frameworks, design more effective tools, and propose more precise policies that will take account of the complex and multidimensional nature of the challenges" (OECD Insights, "Debate the Issues: New Approaches to Economic Challenges", http://www.oecd-ilibrary.org/economics/debate-the-issues-new-approaches-to-economic-challenges_9789264264687-en).

The objectives are to:

- Provide the government with data and analyses necessary to address the societal challenges of its governmental program[6];
- Contribute to the socio-economic development and diversification of Luxembourg building on existing institutions and policy instruments (such as the Ecoinnovation cluster[7] and Luxembourg's smart specialisation strategy[8]);
- Establish new approaches for collaboration across science, policy and civil society for concerted action based on a better understanding of the dynamics and complex social-technological-ecological systems we live in;[9]
- Contribute to the fostering of the social and solidarity economy (as contained in the Luxembourg Declaration signed in December 2015);
- Reflect on the political and societal framework conditions under which sustainability can or should be pursued;
- Accordingly develop appropriate means of communication and decision-making,

It is suggested to (i) build on existing core competences, (ii) extend and consolidate existing areas of collaborations and identify new strategic collaboration fields and (iii) position our areas of excellence within society and in the globalized world.

6 http://www.gouvernement.lu/3322796/Programme-gouvernemental.pdf
7 http://www.ecoinnovationcluster.lu/
8 http://www.horizon2020.lu/content/download/19067/178306/file/Luxembourg Strategy for Smart Specialisation Oct 2014-3.pdf
9 e.g. https://www.umweltbundesamt.de/publikationen/umweltpolitik-fuer-die-transformation-fit-machen

It is useful to think of sustainability as the three interrelated spheres of environmental sustainability, social sustainability and economic sustainability, which needs to be studied and understood both separately and in their complex relationships. The following themes offer relevant, ambitious and competitively promising potential for common RDI activities and strategic investments:

- The threat for the sustainability of public finances, especially in the domains of health care and pensions, is reinforced by the increase in long term unemployment which has also raised concerns about a potential atrophy of skills in Europe, whereas our economies need to both develop new high value-added activities and be more respectful of the environment. In order to maintain our standard of living and our jobs, research must be conducted to develop and evaluate efficient socioeconomic policies targeted at both workers and employers. Delaying retirement and increasing the participation of older workers to the labour market are potential solutions which need to be carefully designed by public authorities.

- Employers can also play an important role in the domain of sustainability through initiatives of Corporate Social Responsibility (CSR). While firms may take these initiatives on a voluntary basis, public authorities should help firms to integrate social and environmental concerns into their business operations. For this promotion of responsible behavior to be efficient and take into account stakeholders' interests, more research is needed to understand (1) how CSR can go hand in hand with both sustainable firm growth and social performance, and (2) which policies can promote it in an efficient way while still taking into account stakeholders' interests. Finally, firms' strategies with respect to the environment can have an impact on households' behavior in terms of adoption of new cultural and social practices through isomorphic change.

- Research at the nexus of central social problems such as inequality, poverty and well-being, on the one hand, and education, health and welfare services, on the other.

- Research on long-term, lifetime inequalities and on the transmission of both human and financial capital across generations and their impact on equality of opportunity, and research that determines the potential roles of social policies in this transmission

- Further research on the measurement of 'inclusive and sustainable growth' is needed to understand how is prosperity is shared, to monitor progress adequately, to help set measurable targets and to examine evolutions towards those targets, both internationally and in particular countries and regions

- Research on the sustainability of the welfare state needs to understand and foresee demographic trends and labour market evolutions to identify future costs and financing of existing institutions, but also propose innovative alternative mechanisms-

--within but also across nation states---more apt to face the economic and demographic changes in a globalized world

- As far as labour force participation is concerned, continuous training and educational programs must better reach vulnerable groups such as the young and older workers. Also, it is of crucial importance to identify the areas of emerging employment and the skills which will be necessary in these areas in the future. Indeed, recent and future advancements in ICT's will reshape labour markets and induce reallocations of skills needed by workers. Movements of digitalization, human/intelligent machine interface, big data analytics, advances in robotics, automation will displace, destroy and create new jobs and new tasks.

- New dynamic micro-simulation models that incorporate richer behavioural mechanisms at the individual and household-level and policy options are needed to forecast future developments, test alternative policy proposals and evaluate their impact on the distribution of welfare and long-term inequalities

- Novel approaches to conceptualizing, tracking change in and modelling complex dynamic social-ecological-technological systems.

- Transition studies, including cross-border region studies: Luxembourg and the Greater Region provide a unique and challenging lab for studying the impact of cross-border differentials on regional socio-economic convergence, residential and daily mobility, spatial development and environmental dynamics.

- Scenario processing for a more methodological understanding of accelerating global change, including uncertainties and mapping unknowns, associated with back-casting approaches focusing on changing policies and practice (also for mitigation/adaption strategies).

- 'Smart-City' modeling integrating the multi-level dimensions of smart living, smart housing, smart mobility, etc.

- To give the targeted objectives a relevant 'fit' with the complexity of decision making, implementation and communication within society, it seems highly promising to explore and understand the underlying mechanisms of what could be called the "science-policy-civil society triangular interface".

The implementation strategy

Luxembourg research and innovation in the area of sustainability should on one hand build on the strengthening of discipline-based research and on the other hand develop interdisciplinary and transformative research collaborations that draw on natural, engineering, social sciences and humanities. The complementarity between both promises an enriched understanding of the complexity and dynamics of social-ecological-technological systems and an improved repertoire of action for transforming human-environment interactions in Luxembourg.

Capacity building – build on core competences and develop infrastructures

- **Develop research infrastructure to enable internationally top-ranked research**
  Invest in the next generation High Performance Computing (HPC) infrastructure with an associated big data analytics platform,[10] including for the use for citizen science.

- **Develop a research environment that attracts and retains top-ranked scholars**

- **Develop tools to enable the development and prototyping of innovative solutions**
  We aim at developing a GreenTech innovation center for developing and prototyping new technologies (in particular for the bioprocessing of biomass and organic wastes for the production of molecules of industrial interest, as well as for bioenergy), a smart Energy center addressing the challenges facing the management of efficient and secure grids (with demonstrators, testbeds and living labs) as well as testbeds for developing and prototyping new businesses relying on space related assets, and in particular satellite imagery.

- **Develop the legal framework and the technical infrastructure for getting access to and exploiting large-scale matched micro data sources for research**
  Frontier science research is nowadays based on large scale matched micro data records. This requires both:

  (i) an appropriate legal framework that protects privacy and at the same time foster scientific research and
  (ii) an intelligent integrated data archiving system to allow secure and flexible creation of "research data files".

  Such resources are vital if Luxembourg research aims to flourish, have a significant impact on Luxembourg society and to be recognized internationally.

[10] CSC leads the University of Luxembourg High Performance Computing service. The managed resources include several server rooms featuring over 5000 cors, 90 TFlops and 5 Petabytes of storage. The computing capacity should be doubled by end of 2016. One additional petabytes of storage should also be added in Q4 2016.

Increase interdisciplinary collaborations – extend and consolidate existing areas of collaborations and identify new strategic collaboration fields

- **Develop improved institutional structures for collaborations**
  We recommend a strategic investment in order to build up the 3LIU into a functioning platform for collaboration, with an empowering governance structure enabling efficient decision-making, a dedicated secretariat, a budget drawn from diverse ministries, and working groups on the four strategic topics for collaboration. A 3LIU working group on sustainability could thus develop robust proposals for developing joint research and doctoral programs, jointly hosting visiting researchers, and share existing and build new joint research infrastructures, including for HPC.
  Develop joint Doctoral programs and favor the integration of qualified LIST/LISER/LIH scientists in doctoral schools at UL. Increase PhD enrolment from LIST/LISER/LIH at UL.
  Propose joint professorships in topics related to sustainability, and joint visiting researcher programs.
- **Mutualise and grant privileged access to research infrastructure** (field, laboratories, databases, software, …) with the goal of developing national and internationally visible projects Develop a expertise center for system dynamics modeling.
- **Develop an *Integrated Center for Excellence in Research on Sustainability***
  We want to invest in a collaborative effort to develop a joint virtual knowledge and excellence center for sustainability-related research, whose objective is not only to foster research collaborations and interactions between public research institutions but as well with the private sector and civil society. The to engage in sustainability expertise and practice for easier building of inter- and trans-disciplinary projects and relational mapping of existing research.

Impact – position the areas of excellence within society and in the globalized world

- **Develop platforms to enable the transfer of knowledge and technology to society**
- **Foster the implementation and adoption of innovative solutions in society**
- **Contribute to sustainability awareness within society**
- **Extend and promote Luxembourg's commitment to develop expertise for sustainable societies across the world**

Expected Outcomes and Conclusion

Research, technological innovation and associated changes in social practice will be cornerstones for Luxembourg's transition to a more sustainable society, as well as for differentiating its position in the global economy. Some areas of research consider eco-innovation and improved co-operation between public research and innovative industries and facilitating the commercial exploitation of research results as driving factors for this transition. In other research areas, sustainability is seen as an emergent property from societal conversation that draws on critical research perspectives questioning the meaning of progress and prevailing values sets; science, research, and technological innovation is considered embedded in social practice that is in turn manifested in social structures including institutions, policies, but also in ideas and ideologies. Such research is also interested in lock-ins and blocks to transitions, as well as thinking about unobvious points to leverage for social and technological change.

The vision and recommendations for its implementation presented in this document aim to build a diverse research landscape, in which researchers working on complementary strands can co-exist and collaborate. To foster social and technological change for sustainability investments in improved infra- and institutional structures for collaboration are paramount. Supporting a collaborative effort to build a *Centre for Excellence in Research on Sustainability* also promises creating opportunities in the private sector and for civil society to engage in sustainability transitions. Leveraging the unique position of Luxembourg with building this Centre promises to open up countless exciting new engagement opportunities across disciplines and sectors in policy and practice in our networked world.

Information and Communications Technology

Preamble

The ICT (Information and Communication Technologies) sector is a main pillar of the Luxembourg government's strategy to diversify the economy. A successful ICT RDI (Research, Development, Innovations) strategy will lead to economic growth, job creation, an efficient public sector, and more prosperous citizens, see also Digital Luxembourg strategy recently adopted by the government. Significant public investments in physical ICT infrastructures in Luxembourg (communication networks & connectivity, broadband access networks, data centres, etc.) over the last 15 years have been instrumental in creating a highly attractive business environment for the ICT dependent industry and ensuring broadband access for our citizens. The main public research institutions, the UL and LIST fuel this sector with innovative ideas and people as well as anchoring businesses in Luxembourg through increased RDI investments.

ICT research at the University of Luxembourg is conducted at SnT and CSC with a research focus on Security, Reliability and Trust and partnerships (28 partnerships and excess of 70 MEUR in secured competitive funding since 2009, 3 spin-offs, Computer Science ranked 21st in Europe by THE). ICT research at LIST is conducted at ITIS with a focus on innovation of service with a focus on technology transfer and innovations (2 patents, 184 paying licenses, and 3 spin-offs in the period 2013-2014).

Mission:

Our strategy is to develop scientific excellence in these areas and ensure that research outcomes translate to more competitive services and products through efficient knowledge transfer. We will attract ICT talent around the world and provide internationally competitive PhD research training, fueling this sector with highly skilled individuals. In addition, we will develop tools to systematically bring promising research outcomes and innovations to commercial exploitation creating impact in the country.

Vision:

UL and LIST will work together to establish Luxembourg as a centre of excellence in ICT research and innovations. By creating an internationally competitive environment, we will attract RDI investments in ICT to the country.

Current Activities

The SnT/UL and ITIS/LIST have strengths in different research areas that complement each other with little overlap in terms of research expertise. However, there is existing collaboration in specific areas covering several activities.

- **Research projects -** There are joint research projects within the FNR/CORE programme, ASINE, RationalArchitecture.
- **Education -** The Master's programme in Security Management is conducted jointly by UL and ITIS/LIST, contributions to the Master in Computer Sciences
- **Events and Outreach -** UL and LIST co-organise events and conferences on a regular basis, for example European Data Forum, 2015 and Information Security day

During 2015, ITIS has reaffirmed its difference in terms of areas of expertise with respect to SnT. The topic of Business Informatics (see section 3) has been refined into the role of "IT for Integrating Smartness in organisation". This concerns the role that IT plays in supporting innovative organisations which are dealing with the needs to put in place smart systems to rapidly analyse, predict and manage the needed transformation and adaptation of their operations in a complex, and continuously changing, technical, social environment.

IT for Smart Systems heavily relies on Business Analytics capabilities at the conjunction of three key competences: domain-specific industry knowledge, information processes that take place in ecosystems of industries and consumers, and information technology (including High Performance Computing (HPC)).

A strategy has been defined regarding the deployment of a Business Analytics platform based on the use of an advanced Big Data Analytics infrastructure, taking also profit of the performance of the future HPC (IPCEI project). By doing so, ITIS is aiming at consolidating a centre of competences in Business Analytics similar to the one put in place at NUS in Singapore. The global investment needed for the next 5 years about 12M€, it covers software, hardware and human costs, and it also based an alliance with major IT providers in the domain of business and data analytics. The services offered by this platform will target private, public and research institutions making possible to transform their data into new value proposition. It will also help to augment the visibility of the next generation HPC by embedding processing capabilities with "big" data.

In addition, LISER analyses the way ICT's are adopted by individuals, and the way ICT's affect them in return, in particular in the workplace. ICT's facilitate information and knowledge sharing, strengthen communication inside and outside organizations, which has led to strong increases in firm performance. However, evidence on the impact of ICT's on individuals remains scarce. Researchers at LISER contribute to the understanding

of how technology developments impact individual behavior. The impact of ICT on decision-making, employees' job and life satisfaction are in particular assessed. The approach combines survey and experimental data.

Also, in line with the socioeconomic challenges explained above, older workers are an important target group in the context of sustainability. However, several studies show that older workers are less likely and less qualified to use ICT's. Researchers at LISER study how policy-makers and firms can motivate and help older workers to remain productive and make efficient use of ICT's, especially in human capital intensive sectors.

All members of the 3LIU consortium have lent their support to the Partnership for Advanced Computing in Europe (PRACE - http://www.prace-ri.eu/), a pan-European project providing access to first-class computing resources for European scientists from academia and industry. Participation in this initiative will strengthen international cooperation, increasing the scientific potential and the HPC knowledge transfer in Luxembourg.

Since the initial document was drafted, SnT has refined and aligned its objectives in the government's Digital Lëtzebuerg strategy. The strategic areas (Secure and Compliant Data Management, FinTech, Cyber Security/Resilient Infrastructures, Satellite Systems, Vehicular Software and Sensor Systems, Smart City/Building/Home) are developed with instruments that are aligned to the recommendations provided in the recent OECD report reviewing Luxembourg's Innovation Policy. Specifically, our actions address the following items highlighted in the report: diversification of the economy, bring research actors closer to areas of important economic activity, strengthen PPP collaborations and increase Luxembourg's international focus, especially through a greater participation in European programs.

SnT leverages public base funding with a factor 2.6 (for every euro in base funding, SnT attracts 2.6 euro in competitive funding). The investment in additional base funding required for SnT to execute the strategic plan is 15 M€ for the period 2017-2021 excluding investments in facilities.

Necessary Strategic Improvements

There are several areas where coordination and cooperation between UL and LIST can be improved in the ICT area. UL and LIST will develop complementary research expertise with the goal of minimizing duplication of efforts.

Both institutions combine long term, scientifically excellent research, innovations, technology transfer, and exploitation spanning the entire chain. However, ITIS places an

emphasis on medium term contractual collaborative research, innovations, technology transfer, and business development. SnT/CSC places an emphasis on long-term research, collaborative research, technology transfer, and entrepreneurship. Because of their complementary positioning in terms of Technology Readiness Maturity Levels, UL will join forces with LIST in projects requiring co-contracting or contract research strengthening Luxembourg's offer in this domain. This avoids duplication of efforts since engineering resources may be used across the specialization domains listed above.

SnT and LIST will join forces with the goal of creating a research program in Financial Technologies supporting the digital transformation of the banking and financial industry in the country. With partner support, a public-private partnership model will be pursued to develop an internationally recognized hub for research and innovations in FinTech.

The doctoral training in computer science and computer engineering at UL will be used more systematically by LIST and the supervision of PhD candidates by scientists at LIST will be recognised by UL. Infrastructure investments will be coordinated as well as events and outreach activities.

Actions and Investments Needed

- Encourage joint project acquisition bringing complementary expertise together increasing the competitiveness of the Luxembourg offer.
- Encourage co-contracting arrangements using complementary skills, in particular in terms of the different foci with regards to TRL (http://en.wikipedia.org/wiki/Technology_readiness_level).
- Integrate LIST scientists in the computer science and computer engineering doctoral school at UL. This specifically includes the need to allow senior researchers from ITIS to be the primary supervisor (HDR/ADR/Habil) for PhD students that will obtain their degree from UniLux.
- Ensure PhD supervision rights for qualified LIST scientists at UL and increase PhD candidate enrolment from LIST at UL.
- Strengthen joint educational offers at the Masters level building on the MSSI programme. Consider the creation of other joint Professional programmes
- Create structured support for events and outreach bringing the joint capacity of UL and LIST together in the ICT domain.
- ITIS and SnT are located in Belval and Kirchberg. The institutions collaborate to investigate joint locations for fostering collaboration and allow the hosting of events at both sites.
- The Luxembourg HPC initiative is not considered to be ICT specific and investments and strategy for HPC should be coordinated at a higher level.
- Integrate Luxembourg into the PRACE consortium, increasing the credibility of Luxembourg as a major player in a European HPC setting.

Expected Outcomes and Conclusion

The ICT sector is a main pillar of the Luxembourg government's strategy to diversify the economy. This document outlines how our research organizations have aligned strategies to the government's ambitions as described in the Digital Luxembourg strategy. The vision of this digital RDI strategy is economic growth, job creation, an efficient public sector, and more prosperous citizens. The efficient execution requires and additional investment in our organizations of some 27 M€ in the coming five years. This investment should be conditioned on reaching ambitious targets and reviewing achievements regularly.

Biomedicine

Preamble

The vision: Luxembourg shall become a world leader in an information and communication technology (ICT) driven integrative biomedicine in a future biomedical research and health economy.

The mission: Working hand in hand with all stakeholders from researchers to healthcare professionals, from ministries to patient associations to industry, we will create the basis for a future oriented health research and care. Insights will be gained into the mechanisms of diseases by integrating data across all scales and disciplines from environmental data and population data down to data about individual health and molecular interactions. We will provide new strategies and tools for prevention, early diagnosis and effective treatments.

Background - The global challenges A knowledge-driven economy is determining the global development. Luxembourg has to prepare for the corresponding changes projected for the future healthcare environment.

Challenge 1 - The spectrum of diseases will change

With increasing age of the population, the prevalence of chronic diseases and multi-morbidity is growing and leads to a high burden for the healthcare system, the patients and their relatives. There is a need to develop cures and earlier diagnoses based on the better understanding of the disease mechanisms. This understanding will also the recognition of early warning signals before the disease manifestation and will further allow prevention.

Challenge 2 - The characteristics and application of therapies will change

The old concept of "one-drug-fits-all" is no longer valid. Even though a disease may be homogenous in its symptoms, underlying mechanisms can be different and thus different treatment would apply. Therefore, in many cases, treatment of patients can be improved by personalising the approach to therapy. This brings with it a need for carefully studying complex interactions.

We need to better understand the causes of disease to be able to find novel cures. This is particularly true for chronic diseases based on a complex interaction of genes and environment, including pollutants, nutrition, life style and social context. We need to employ a holistic systems-based approach to untangle the mechanisms of diseases from these complex networks.

Challenge 3 - The basis of diagnostics will change

Advanced imaging and the introduction of molecular technologies into healthcare will provide a vast amount of data, complemented by health and disease parameters, information on life style and environmental influences collected over the lifetime of a person. The deluge of data of different type and origin need to be transformed into knowledge to provide solid predictions. Decision support systems will be needed for reliable treatment recommendations based on improved diagnostics.

Challenge 4 - The engagement from patients will change

Patients will be more participatory and interested in their health, and will want to have ownership of their health data. It is imperative to take patient needs seriously and to include patients actively in the diagnostic and decision process. Therefore, we consider outreach to and integration of the general public as essential elements of a biomedical research strategy.

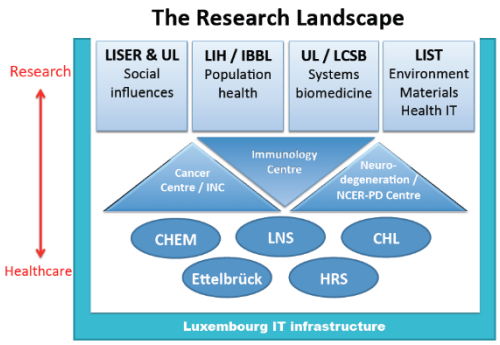
Challenge 5 - The economy of health will change

While therapies are progressively being developed for progressively smaller and more targeted patient groups, diagnostics for selecting the right therapy for the right patients will achieve a larger market share. The biggest increase is foreseen in consumer health: the public will look for individualised health consultations. This will result in a growing demand in preventive nutrition, portable health and environmental monitors as well as mobile devices for a health-oriented lifestyle management.

Besides this, investments in health and the design of health financing policies should take into account the interaction between health and the economy. Indeed, health conditions (mortality, morbidity, disability) depend not just on standards of living, but on the actual performance of health systems themselves. Research institutions, healthcare providers and systems must work hand in hand with industry to address these new opportunities for Luxembourg.

Current activities at the various institutions

Biomedical research



The Luxembourg Institute of Health (LIH) and the University of Luxembourg (UL), including the Luxembourg Centre for Systems Biomedicine (LCSB), drive the biomedical research from complementary methodologies. In a "downwards", patient and population centred approach, LIH drives public health and clinical research with special emphasis on epidemiology and interaction of genes and environmental factors. The LCSB and the University Life Sciences Research Unit (LSRU) at the Faculty of Science Technology and Communication at the UL follow an "upwards" approach, where the mechanisms of health and disease are derived from a reconstruction of a systems level based on molecular profiles gained from individual patients, animal models and *in vitro* cells and organs. The main disease foci are cancer, neurodegeneration and allergy. Chronic inflammation and changes in metabolism will be studied as cross-sectional subjects that are relevant in all these diseases. These foci are also supported by research on cancer and neuropathology in the Laboratoire National de Santé (LNS).

Clinical research takes place mostly at the Centre Hospitalier du Luxembourg (CHL). Activities like the National Centre of Excellence in Research (NCER) for Parkinson Disease funded by the Fonds National de la Recherche (FNR) and the National Cancer Institute (NCI) aim also at a wider integration of hospitals in the research. Due to structural constraints, however, clinical research at the hospitals is still limited.

State of the art infrastructure is an important element in biomedical research. The Integrated BioBank of Luxembourg (IBBL) offers access to a wide collection of premium biospecimens for research based on a stringent accredited quality system, and is now connected with the European translational medicine infrastructure EATRIS. The Luxembourgish European bioinformatics infrastructure ELIXIR Node will host a public database of translational medicine datasets. In addition, the Clinical and Epidemiological Investigation Center (CIEC) at the LIH gives guidance and support in the conduct of clinical trials.

Other relevant research fields

The Luxembourg Institute for Socio-Economic Research (LISER) and the Faculty of Human Sciences (FLSHASE) of the UL complement the biomedical research activities. They investigate socio-economic and health profiles as well as the role of psychosocial stress in the development of disorders.

The environment plays an important role in an integrative approach to biomedicine to understand influences of nutrition and exposure. The Luxembourg Institute of Science and Technology (LIST) is working in the field of environmental research and monitoring. LIST also engages in material research, which is relevant for the development of miniaturised sensors for environmental and health purposes and microfluidics devices for laboratory experiments.

Information and communication technologies (ICT) research, development and infrastructure are vital for the realisation of the biomedicine vision. Both, the LIST and the UL engage in this field spanning from dedicated software solutions to advanced computing approaches for "big data" requirements and high performance computing. Particularly the security research at the Interdisciplinary Centre for Security, Reliability and Trust (SnT) of the UL is important, as an information driven biomedicine must ensure a high-level data protection and privacy for the patients in research and healthcare.

Future Strategy

The research strategy

Luxembourg's research institutions will achieve their strategic goals through a strongly interdisciplinary and collaborative approach: where usually disciplines remain in their own domains, we will create a joint biomedical research realm. A key success factor for the integration of disciplines are the strong IT capabilities and infrastructure in Luxembourg.

Building up "integrative biomedicine" in Luxembourg

- ***Integration of data for better knowledge***

LIH, IBBL, UL (LSRU, LCSB), LISER, and LIST together with the hospitals and LNS will contribute to a comprehensive coverage of all impacts on people's health. For this, a multitude of data concerning a person needs to be considered, from the social, lifestyle and environmental influences to healthcare data and molecular profiling of the individual. Personalised cell models derived from patients' tissues will provide additional data. A systems-oriented approach of electronic health records should be implemented among the above partners for a better data interoperability and ultimately for a better personalized healthcare.

Data needs to be gathered on an individual level so that no information is lost by integration of heterogeneous subjects. We will develop a personalised epidemiology: a population-based approach with in-depth monitoring and phenotyping of individuals. A complementary approach is achieved through profiling of *in vitro* models based on single cells and organs-on-chip where also interventions can be tested.

We will face the technological and cultural challenges to integrate this kaleidoscope of data. Through interpreting the data from individual people in the context of population data, experimental data from advanced biological models and prior knowledge from literature we will derive a better understanding of diseases.

LISER and LIH will collaborate to combine medical with social and economic data to understand the underlying mechanisms of the impact of changing socio-economic and demographic trends on the determinants and evolution of public health. This information can then be used to develop tailor-made patient treatment and further improve health care provision.

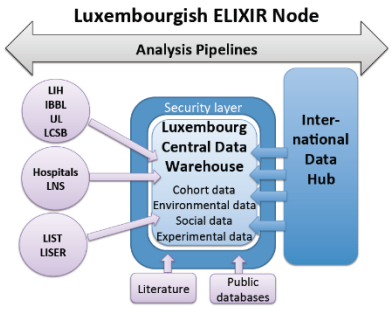
- ***Integration of disciplines for more innovation***

The necessary integration of disciplines needs to go beyond medicine, biology, environment and social sciences. Personalised health and exposure monitoring as well as the observation of advanced cell models require knowledge in miniaturisation and nanostructures to develop microfluidics and sensors as well as mobile solutions for continuous measuring. LIST and LIH will play an important role for these developments as environmental causes are linked to several non-communicable diseases, but the underlying mechanisms are not necessarily well understood. This will create innovation in the technology sector and create applications relevant for drug testing.

Data analysis and data security involve mathematical and IT skills. We will work with the Faculty of Science and Technology on better ways to integrate and interpret the data, and with SnT on novel concepts of data protection to ensure highest possible privacy for people participating in our research. We aim to make Luxembourg a leading country in hosting secure medical data.

Meeting the "big data" challenge with ICT enabled innovation

- ***Smart and secure databases to create an international data hub in Luxembourg***



On the national level, a central data management system will be provided that integrates data from the different disciplines of all research stakeholders via a data warehouse that also includes public and literature data and includes analysis pipelines for user-friendly data interpretation. The data warehouse serves also as data hub for international data. The data abundance and integration poses new challenges for ethics and data protection that will be met with advanced security layers and forward-thinking solutions. This environment will create innovative business opportunities around data hosting and data management in health on a global scale.

- ***Data analysis and interpretation to create knowledge***

Smart algorithms are needed for handling and interpreting large amounts of data. We will work with the FSTC and LIST to employ artificial intelligence for health related data analysis. The development and utilisation of smart hardware suitable for the requirements of biomedicine will accelerate the computing capabilities. Mathematical modelling will be used to describe disease

mechanisms, predict potential intervention targets and provide decision-making tools for medicine. These tools will lead to innovation in the area of diagnostics and therapies.

- ***Decision support systems to allow a better healthcare***

The amount of data in healthcare and the fast increasing medical knowledge will soon make it impossible for the individual physicians to decide on the right therapy for their patients. We will engage in decision support systems for clinicians that integrate the wealth of data and guide to personalised therapies based on the state of the art. In addition, also health apps for mobile devices to be used by the general public are envisaged to aim at a better prevention. Together with Agence e-Santé, we will develop an electronic healthcare infrastructure integrating decision support. Interfaces to mobile devices and research applications will be provide the necessary set-up to pursue the research strategy of comprehensive data integration. The implementation of an electronic healthcare environment with decision support systems will create innovation in health management.

The implementation strategy

Our approach focuses on existing competences and we have identified actions to achieve the vision.

Capacity building – creating the basis for success

- ***Bridging groups and translational medicine centres to integrate the stakeholders***

Innovation is stimulated by close interaction of researchers with a different background. The creation of bridging groups between the research institutions is therefore a central element in our strategy. Of particular importance is the integration of the research institutions with the hospitals and the LNS to create translational medicine centres. Within these centres biomedical research and healthcare will enhance each other. With activities like the National Centre of Excellence in Research (NCER) for Parkinson Disease funded by the Fonds National de la Recherche (FNR) and the National Cancer Institute first steps are already made to bring research closer to the healthcare system.

- ***Training to create innovative researchers***

We will make teaching of IT literacy a vital element in all disciplines around biomedicine. We will develop interdisciplinary curricula for the future research workforce from basic research to clinician scientist in order to achieve innovative mind-sets and interdisciplinary skills. Joint doctoral schools across disciplines are one example for the implementation.

- ***Infrastructure to enable high-class research***

Strategically chosen research infrastructure gives a competitive advantage and creates an attractive work place. Investments will be targeted to areas where they provide uniqueness and enable international leadership of Luxembourg within data-driven integrative biomedicine.

- ***Industry to bring research results into the market***

To enable fast growth in biomedicine industry, we will target companies at the intersection of health and already existing sectors such e.g. IT, communication, materials, nutrition or logistics. We will build on present companies and encourage them to enter the health and biomedicine market for opening up new business sectors, for instance by creating joint spin-offs with research institutions. Potential candidates are e.g. SES Astra, Skype, iTunes and Vodaphone for mobile and health applications. In the diagnostic market, private diagnostics companies such as Laboratoires Réunis and KetterThill have already recognised the potential of new markets around consumer health and are seeking collaboration. We will build on this interest to foster public-private

partnerships. All efforts will be made to use national technological platforms in order to accelerate R&D transfer to both healthcare providers and industry. Lux innovation will help promoting Luxembourg biomedicine research actors' visibility at the EU level.

Positioning in a global world

The unique profile of integrative biomedicine research based on a strong IT approach will allow Luxembourg to gain international leadership in health research and will contribute to the country's competitiveness. As an international data hub, Luxembourg will attract visiting scientists and engage the best minds, ideas and resources worldwide to complement the research portfolio and interpret data in a global context.

Special attention will be given to the partnerships in the Greater Region for achieving local critical mass. Partnerships with hospitals are pivotal for a wider access to patients. Proximity is also important for building a sustainable industrial landscape. Ultimately, cross border healthcare services will be extended towards global services for the private health market.

Recommending pivotal governmental support

We are committed to collaborate on the national research strategy in biomedicine, but we depend on support of the government to achieve the goal of international leadership.

- ***Support attractive infrastructure***

A national roadmap for funding strategic large-scale infrastructure should be developed and the means for medium-size infrastructure and its continuity need to be foreseen in the budgets of the institutions. This includes buildings with up-to-date basic equipment, advanced data centres and a high performance / high content computing aimed at smart application driven computing, as well as suitable facilities for animal experiments, sequencing, and clinical trials. Joining forces when possible will also maximize efficiency.

- ***Fund bridging programmes***

Bridging programmes at the intersection of disciplines of research organisations will unite outstanding scientists around related research topics. NCER-PD was the first example of biomedical research reaching out to the clinic and the research strategic plan within the Plan Cancer is the next bridging programme. Further centres should develop along the above defined disease focus areas and become integrated with healthcare, sustainably uniting the worlds of research and healthcare. In addition, the support of bridging groups or centres to other disciplines is essential for fostering the innovative interaction of technological, environmental and social research with biomedicine.

- ***Establish a research culture in the health care system***

Stronger clinical research and wider openness to innovation in medicine should be implemented in the healthcare system. There is a need for clinician-scientist positions, which would allow clinicians to work both in research and healthcare. Within the upcoming instrument "réseau de compétences" a true integration of research and healthcare should be encouraged and supported. Integrative biomedicine requires also a timely implementation of structured electronic patient records and their interfaces with research.

- ***Discuss the opportunity of a medical school***

A research and IT oriented medical curriculum in the university with special focus on the priority disease domains would create additional clinical research competences and train physicians that are IT literate and ready for personalised medicine. The opportunity and the cost-effectiveness of

a medical school, either stand-alone or in collaboration with European partners, should therefore be critically discussed in the light of the national research strategy in biomedicine.

- ***Develop a research friendly legal and organisational environment***

Integrative biomedicine requires a fast decision-taking and a planning security to succeed in a fast changing, competitive world. Equally relevant is a legal framework suited for research (e.g. a more flexible labour law, healthcare laws open for research). An appropriate data privacy legislation and a pro-active support for ethical discussions will be of paramount importance for data integration across all stakeholders in an integrative biomedicine, which finds acceptance in the population. This is key to maximize the research efforts of the country.

Conclusion

Based on existing competences in the country, we will develop an international uniqueness through a comprehensive cross-sector collaboration at the national level that unites the various stakeholders within research, healthcare, related industries and the general public based on a data and IT driven integration of knowledge. All LIs and parts of the University involved with biomedical research should ideally be located in a single campus, hosting a clinical center, in order to stimulate integrative research environment. Thereby, we will make biomedical research in Luxembourg an internationally leading show case, which attracts excellent scientists and educates a forward thinking workforce, leading to economic growth, improved health for the population, and a sustainable healthcare and welfare system.

Summary and Conclusion

Throughout the four cooperative strategies laid down above, there are common themes that we believe to be necessary investments for the continuing collaboration between the 3LIU consortium. They should therefore be discussed in the context of the next Four-Year Plans of each institution. These investments can be subdivided into two domains:

Concrete infrastructure for enabling world-class research:

- **High Performance Computing (HPC):** HPC technology is central to both the digitalization strategy of Luxembourg as well as modern "Big Data" research. Promoting and extending our HPC capabilities is necessary to compete in a modern research environment. Membership of Luxembourg within PRACE is a first step that should be followed by multiple initiatives that are open for all 3LIU within the IPCEI framework.

- **Equipment Fund:** Cutting edge research requires access to (and replacement of) cutting edge equipment, and funding must be allocated to purchase new technology as necessary. If an equipment fund were created at the FNR that should evaluate proposals and potentials for synergies the 3LIU would be ready for the implementation of a co-funding scheme.

- **National Centres of Excellent Research (NCER):** Centres of collaborative research between the 3LIU as the ones proposed in both Materials and in Sustainability (and already existing in Biomedicine) shall remain a major area of competitive funding by FNR. It should be supported by a competitive funding scheme that combines already existing schemes in a package related to a particular and collaborative research question.

- **Identification of National Technological Platforms of Excellence:** To avoid wasting of resources, technological platforms should be identified which are of value to the entire Luxembourgish research landscape. Shared used of expensive equipment and other resources should be promoted whenever possible to optimize resource allocation and maximize value impact of research for society.

- **Unification of Research On-Campus**: All LIs and University involved with biomedical research should ideally be located in a single campus, hosting a clinical centre, in order to stimulate integrative research environment. Also in all the other areas of strategic cooperation the availability of sufficient lab and office space on the new Belval Campus remains a highly critical prerequisite.

Attracting world-class researchers to Luxembourg:

- **Visiting Scientist Program:** In order to promote the new Belval Research and Innovation Campus as well as Luxembourg as a European hub, the 3LIU would like to set up infrastructure for a Visiting Scientist Program of high international standing (office space, guest house facilities). A small number (not more than four per year) of "3LIU Fellows" invited by the University and at least one other research institute, should stay in Luxembourg for at least 6 months and contribute to joint research activities, joint doctoral programs, teaching and public outreach.

- **Joint Professorships:** Shared professorships between the University and the Institutes would improve knowledge transfer, enable access to shared equipment and resources, and be beneficial for the overall research reputation of Luxembourg. The existing program at the University should be continued and expanded. Administrative regulations for top recruitments should be harmonized across the institutions.

- **Matched Partner Position for Strategic Recruitments:** To enable world-class recruitments for the 3LIU, a yearly structural position (CDD for 5 years) should be made available for spouses of candidates in strategic positions in one of the Luxembourgish institutions where possible.

- **Joint Doctoral Programs**: Doctoral programs are vital both for the career development of future researchers and the success of research projects. Having joint programs between the University and the Luxembourgish institutes increase the attractiveness of Luxembourg as a place to obtain a PhD degree. The PRIDE scheme of FNR should thus be continued and be expanded.

Process improvement between institutions in 3LIU consortium:

- **Joint innovative knowledge-transfer mechanisms**: To optimize the value impact of research for society, the 3LIU should be enabled to develop joint knowledge transfer programs utilising a variety of creative tools and instruments.

- **Harmonization of Administrative Rules and Procedures**: Joint activities of the 3LIU in all areas are often hampered by a misalignment of bureaucratic procedures. As the University is planning a major revision of its administrative framework over the next years it would make sense to incentivize a joint initiative of all institutions to harmonize their rules and procedures in key areas. This should also include a harmonization of working conditions, including salary grids, as well as of VAT related rules. In addition, a common legal framework and technical infrastructure for getting access to and exploiting micro-data for research should be discussed.

- **Branding our Unique Selling Points** for a stronger Luxembourg research recognition and outside visibility, as for example by the joint Brussels Liaison Officer and a Belval branding initiative.

The strategy and related strategic investments outlined in this document would provide a solid basis for improving the collaborative research efforts of all four research institutions in the 3LIU consortium, especially within the strategic research areas important for the development of a world-class research landscape in Luxembourg. In the coming years, the members of the 3LIU consortium will think about appropriate ways to push the consortium in a sustainable and long-term direction, allowing for even more collaborative actions and activities leading to a unified top-level research reputation for Luxembourg on an international stage.

Annexes

Table 1. Overview on Organizations and Sustainability-related Themes

Institute	Research domain	Core themes on sustainability
LIH	The Department of Population Health conducts research on Epidemiology and public health in Luxembourg. The department hosts population-based studies, health economics, clinical trials and disease registries, primarily on cardio-metabolic conditions, cancer and neurodegenerative disease. The Departments of Infection and Immunity and Department of Oncology have together with UL, obtained extensive biological and technical expertise related to analyses of the human genome and proteome (multi-omics approaches). The expertise gained from basic research and population registries will be used for the advent/development of systems biomedicine	**Research on health costs and the sustainability of public expenditures on health care and prevention**, based on understanding the prevalence, incidence and distribution of health risks and diseases will be key for sustainable public finance. The Departments have obtained PRIDE support for the development of next generation scientists within the fields of immunology and cancer. Therefore, LIH has made the first baseline steps in order to sustain a future knowledge base that will eventually benefit the Luxembourg population within the fields of cancer and infection and immunity.
LISER	LISER conducts research in the field of social and economic policy, including the spatial dimension. This comprises topics like poverty, inequality, education, social inclusion, employment, health, housing, mobility, and regional convergence. The aim is to improve the understanding of causal relationships and to provide evidence for the impact of institutional settings and policy options on outcomes.	***Micro-simulation-based research on social policy and Welfare State:*** **Research on Welfare State l sustainability** requires understanding and anticipating costs and sources of financing in the long-run, in all key dimensions of the welfare State (pensions, health care, social protection), to foster robustness against demographic challenges and structural changes of the economy. *Social disparities and inequality research:* **Research on social sustainability** also requires monitoring and understanding the evolution of the distribution of well-being across the population, examining social disparities and the strength and patterns of social stratification to prevent concentration of wealth and power and extreme inequalities to lead to conflict, social tensions and poorly functioning democracies *Monitoring instruments:* Research on sustainability requires international collaboration towards the development and monitoring of a portfolio of indicators of sustainability. The UN Sustainable Development Goals is an important of such initiatives. A complementary measure to address social sustainability challenges is to raise workers' labor force participation and the **sustainability of job positions**. In order to

		assess the nature and quality of jobs over time, the duration of jobs and job transitions are important indicators. **Ecological sustainability** is addressed with regard to (1) mobility practices and its impact on land use, pollution, life standards and time consumption. (The processes of land take and soil sealing are monitored and the results allow to contribute to the policy debate on the urban densities to be promoted in the future national plan for territorial development.) and to (2) the link between corporate social responsibility and environmental innovation.
LIST	The Environmental Research and Innovation (ERIN) department brings together life science, environmental science, and information and communication science and engineers to tackle major environmental challenges. The goal is to implement a smart green vision, striving for scientific excellence in the understanding of complex environmental systems and their interaction with the techno-sphere, in order to accelerate innovation towards the sustainable management of natural resources and the transition towards a circular economy. The activities range from experimental research, environmental model and software development, process control and automation to environmental technologies, all relying on advanced tools for big data analytics, visualization and management.	Integrated water resources management and smart cities Bioresources for bioenergy and renewable biomolecules of industrial interest Energy systems and smart cities Life cycle sustainability analysis and risk assessment; circular economy Precision agriculture Environmental informatics and data analytics
UL-FLSHASE-ECCS	The research unit on 'Education, Cognition, Culture and Society' covers a wide range of research topics, including curriculum and policy studies, teacher education, cognitive development and learning processes, migration, multilingualism and social inequality in school, higher education and life-long learning.	The Institute for Applied Educational Sciences is concerned with **transformative social learning for sustainability**, with particular interests in learning and evaluation of complex problem solving and **future-oriented systems thinking**, and linkages of learning processes across social scales (individual, organizational, and systemic).
UL-FLSHASE-INSIDE	In the 'Integrative Research Unit on Social and Individual Development' (INSIDE), research focuses on social inequalities, health and behaviour, as well as governance, migration and border studies.	The Institute for **Health and behavior** and the Institute for **Social inequalities**, income, and wealth dedicate their research to sustainability issues.
UL-FLSHASE-IPSE	The Research Unit 'Identités. Politiques, Sociétés, Espaces' (IPSE) areas of interest centre on urban and spatial planning and sustainable mobility.	The Institute for Geography and spatial planning conducts research on regional development, **spatial planning, border studies, migration, and on local sustainability transitions, green building, and urban development.**
UL-FSTC-CSC	The Computer Science and Communications research unit (CSC) is active in resource management (smart grids, optimizing the use of energy in data centers, scheduling) using the latest artificial intelligence techniques (decentralized optimization, evolutionary computing, machine	A wide range of CSCs research relate to sustainable computing including projects on green ICT and energy-efficiency. High Performance Computing, including efficient code writing for distributed and parallel platforms.

	learning, etc.). CSC and the UL HPC team also handle and develop key knowledge in efficient software development for high-performance-computing environments.	
UL-FSTC-RUES	RUES is an interdisciplinary group active in environmental research and engineering in geophysics, urban water management, sustainable construction, transport, and energy-efficient buildings. The main focus of research is on measuring the effects of climate change, the development of technological solutions as well as on the sustainable and economical use of all kind of resources.	All sub-groups pursue research lines relating to sustainability: geophysics and climate change, urban water management, sustainable construction and energy efficient buildings, and transport theory, modelling, planning, and management.

Table 2. Overview on Organizations and ICT-related Expertise

SnT/CSC areas of expertise	ITIS areas of expertise	Shared interests
Computer science	Business informatics	Modelling
Communication networks & protocols	Enterprise and Information Systems Engineering	Requirements engineering
Signal processing & automation	Trusted service systems	Data Analytics
Software engineering, security, privacy	Collective decision-making	
Computational sciences	Innovative shared design	

Table 3. Overview and Main Characteristics of the High Performance Computing (HPC) Facility of the University of Luxembourg (UL) – http://hpc.uni.lu

Attribute	Associated Key Metrics
Current* Computing Capacity	4 clusters 98 Management Servers 522 computing nodes, featuring: - 5420 computing cores (CPU) -- **90.199 TFlops** - 120704 accelerators cores (GPU) -- **76.22 TFlops**
Current* Shared Storage Capacity	4 parallel and distributed File Systems (GPFS, Lustre, GlusterFS, NFS) - 1556 disks on total - **4.018 PB** for shared user data - **1.516 PB** for backup
Human Resources	Head: Prof. Pascal Bouvry – Pascal.Bouvry@uni.lu 4 systems administrators, led by Dr. Sebastien Varrette
HPC-related UL Activities	EU COST Actions Membership: - IC1305 NESUS (**Network for Sustainable Ultrascale Computing**) - IC14006 cHiPSet (**High-Performance Modelling and Simulation for Big Data Applications**) ETP4HPC (**European Technology Platform (ETP) for HPC**) Member PRACE (**Partnership for Advanced Computing in Europe**) Member (expected. Feb. 2017) Participation to reference HPC/Cloud scientific conferences Committees
Incoming Milestones	[2017]: new cluster installation in CDC per 2016 RFPs attribution - **107 TFlops** over 2800 computing cores - **1.440 PB** for shared user data [starting 2018]: new Direct-Liquid Cooling (DLC) based HPC Facility deployment in CDC S-02 to target the following capacities: - **3588 TFlops** by 2019 - **17.7 PB** by 2019

**: as of Nov. 2016*