CEBE Research Roadmap Appendix

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CEBE

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Research field 1 – Assessing and measuring environmental sustainability

1. Introduction, vision & mission

1.1. Introduction to the Research field

How can we accurately measure the climate and environmental impact of the entire built environment – both what we build new and what already exists? This research field develops new methods for assessing emissions, environmental impacts and resource use across buildings and infrastructure throughout their full life cycle. The goal is to create precise, dynamic methods and models that support decision making for all types of interventions in the built environment and help the sector meet absolute sustainability targets. Whether through building new, or renovating and transforming what already stands.

1.2. Vision

Enable society to evaluate the environmental performance of the built environment and relate it to absolute environmental sustainability limits through scientifically robust, dynamic, and absolute-target sustainability assessment methods driving decisions aligned with planetary boundaries.

1.3. Mission

Develop scientifically robust, dynamic, and absolute-target-based environmental sustainability assessment methods by advancing the science behind system scoping, temporal modelling, absolute target setting and impact characterization. Deliver tailored decision support tools for buildings, infrastructure, and the wider built environment, enabling researchers, industry, and policymakers to meet emerging environmental targets.

2. State of the field

2.1. Global centers of excellence

Key international centers provide methodological leadership in LCA and absolute sustainability assessment. ETH Zurich stands out for LCA on buildings and materials *(Guillaume Habert)* and for work on life cycle impact assessment (Stefanie Hellweg and Stephan Pfister) and absolute environmental boundaries *(Stephan Pfister)*. The European Commission's Joint Research Centre (JRC) drives EU-wide development of LCA methods and absolute environmental thresholds, supporting consistent application across countries.

University College London (UCL) is a leading actor within absolute sustainability metrics, while the Stockholm Resilience Centre provides the scientific basis for the Planetary Boundary approach. For forward-looking methods, CML at Leiden University remains central to prospective and scenario-based LCA, and the Paul Scherrer Institute (*Romain Sacchi*) advances methodologies, data foundation and tools for prospective LCA.

Collaborating with these centers through joint research, data sharing, and methodological exchange would strengthen Denmark's capacity in advanced LCA, dynamic modelling, and absolute sustainability assessment and ensure alignment with international best practice. In parallel with these academic leaders, engagement with key international stakeholder organizations is also essential for linking methodological advances to real-world implementation. These include the Buildings Performance Institute Europe (BPIE), the UN environmental program (UNEP) Life Cycle Initiative, the International Global Alliance for Buildings and Construction (GlobalABC), and C40 Cities.

2.2. State of the art and DK position in the research field

Life cycle assessment (LCA) of buildings is gaining increasing attention as focus shifts from operational energy to whole life carbon footprint, especially embodied emissions [Röck et al., 2020, Birgisdottir et al., 2017]. While LCA for infrastructure is emerging, it remains less methodologically mature due to long asset lifetimes, complex maintenance cycles, and functional unit definition challenges [Du et al., 2014, Liljenström et al., 2020, Liljenström et al., 2022]. In parallel, life cycle-based building stock modelling is becoming widely recognized as a key tool for supporting climate mitigation policies and long-term planning [Elnour et al., 2025, Röck et al., 2021].

Internationally, research on whole-life carbon assessment is evolving rapidly, with distinct contributions across regions. European research communities - especially in Switzerland, the Netherlands, France, Germany, and the Nordic countries - have been central in developing harmonized datasets, improving uncertainty treatment, and advancing dynamic and scenario-based LCA approaches [Röck, et al. 2020, Priore et al., 2026]. Denmark is among the first European countries to introduce life cycle assessment and greenhouse-gas limit values directly into building regulations for new construction, drawing on a substantial national research foundation [Zimmermann, et al., 2021, Tozan et al., 2024, Lund et al., 2022, Zimmermann et al., 2023]. However, recent studies show that respecting planetary boundaries requires an approximately 80% reduction in new construction activity in Denmark, with the remaining 20% built according to best-practice standards to stay within a safe operating space [Horup et al, 2025]. These findings highlight that far more ambitious measures are needed to achieve national and international climate objectives, including the Paris Agreement's temperature goals, climate neutrality targets, and commitments to restoring degraded ecosystems [Andersen et al., 2020, Horup et al., 2025]. Collectively, these developments reflect a global shift toward deeper integration of temporal dynamics, stock-flow modelling, and long-term scenario analysis in built-environment sustainability assessment.

A major frontier is the integration of absolute environmental sustainability targets, derived from science or policy. Here Danish researchers are front-runners internationally, and several studies have been conducted on Danish case studies. Although such targets are vital for assessing whether the built environment operates within ecological limits, they are not yet fully developed or consistently applied in current assessment frameworks [Andersen et al., 2020, Bullen et al., 2021, Lützkendorf et al., 2014]. Their interdependency across impact categories and the methods for determining compliance remain insufficiently refined [Satola, et al., 2021], limiting their practical use. Absolute environmental boundaries currently employed in absolute environmental sustainability assessment (AESA) include boundaries for our pressure on climate and other elements of the natural environment. Absolute boundaries have also been proposed for natural resources, but they generally lack the maturity required for reliable use in AESA [Dudka et al., 2025, Thomassen, et al., 2024].

The definition and alignment of system boundaries is another persistent challenge. Misaligned or overly narrow boundaries can lead to misleading sustainability conclusions. Recent EU guidance stresses that correct boundary choice must reflect the system scale and decision context - an aspect often neglected in built environment assessments [Bjørn, et al., 2025].

Improved integration of material and energy dynamics is also needed, particularly as circularity, efficient first use, and reuse concepts gain traction [Andersen et al., 2024]. These approaches require better stock and flow mapping and alignment between material flow analysis and LCA. Behavioural and social aspects add further complexity. Rebound effects - where efficiency gains trigger increased consumption - remain underexplored, yet they significantly affect both the actual operational and embodied impacts.

Current methods still rely heavily on static, discrete modelling, which fails to capture time dependent changes, dynamic feedbacks, and potential burden shifting across product systems and environmental impacts. Although dynamic and prospective LCA approaches are developing [Su et al., 2017, Horup et al., 2025, Slavkovik & Stephan, 2025], their adoption is limited by high data demands, uncertainty, and lack of methodological consensus. Data gaps and outdated datasets further constrain accuracy, while industry resistance slows integration of advanced methods due to established practices and skepticism toward change.

Together, these challenges point to the need for more consistent, dynamic, and absolute-target-based sustainability assessment methods. Strengthening system boundary definitions, integrating temporal and material dynamics, accounting for behavioural factors, and providing smart simplifications for practical industry use are essential steps toward more credible and actionable decision-support for the future built environment.

In Denmark, three leading universities collectively provide a uniquely strong foundation for advancing sustainability assessment for the built environment. Aalborg University contributes established expertise in sustainability assessment, LCA modelling, and the development of practical tools widely used in industry and regulation. The University of

Southern Denmark adds specialized capabilities in industrial ecology, dynamic LCA, and material-flow analysis, supported by extensive collaboration with industrial partners. The Technical University of Denmark complements these strengths through its long-standing focus on environmental impact assessment, attributional LCA, and absolute sustainability methodology. Taken together and with a strong dedication to effective collaboration, these institutions form a coherent and mutually reinforcing national research environment that positions Denmark at the forefront of next-generation methods for sustainability assessment in the built environment.

3. How will the research field address the core challenges?

Research field 1 will address the three core challenges addressed in CEBE in the following:

1) *Decoupling construction from environmental harm by shifting to sustainable materials – circular by design, low-carbon, and from renewable or reused sources.*

   Research efforts contribute by establishing methods for allocating science-based environmental budgets to projects, providing the quantitative basis needed to assess whether materials - whether renewable, reused, bio-based, or low-carbon - align with absolute sustainability thresholds. By grounding material choices in environmental budgets, the research field supports other research fields of CEBE and consultancies in advancing the assessment of absolute environmental sustainable and circular material loops while lowering dependence on resource-intensive and emission-heavy options and distinguishing the solutions that have the potential to be sustainable in absolute terms and not just better than the alternatives.

2) *Redesigning infrastructure and coastal defences for resilience to climate extremes – integrating nature-based solutions, enhanced monitoring, predicted climate risks and optimised response strategies.*

   Life cycle assessment, sustainability assessment frameworks, and absolute sustainability approaches ensure that climate-resilient infrastructure is designed without generating unintended environmental burdens. These methods identify environmental hotspots and resource use and help prioritize which existing built-environment assets are most critical to preserve,- rank mitigation options according to their life cycle sustainability performance and support evaluations of the trade-offs between protection investments and potential losses. By integrating these assessments with climate-risk projections and emerging resilience strategies, researchers guide the development of resilient infrastructure and coastal defences that stay within ecological limits.

3) *Breaking systemic inertia in the built environment by driving circular, resource-efficient building design and construction practices – enabled by digital tools, enhanced monitoring for safe life extension and optimised renovation strategies.*

   Advances in temporal and dynamic modelling capture long-term changes in buildings and infrastructure, including degradation, renovation cycles, and reuse opportunities. By representing these trajectories, these models support decision-making that prioritizes safe life extension, strategic renovation, and circular design interventions, enabling reduced environmental pressure and better use of existing assets.

3.1. Global Perspectives

Urbanization is projected to require a doubling of the global building stock by 2050, and since the building sector is already a major driver of climate change, biodiversity loss, and land-use pressures, this rapid growth makes it essential to develop construction practices that stay within planetary boundaries globally. This puts a special focus on emerging economies, where most of the new construction will occur. These regions must expand their built environment while avoiding long-term environmental lock-ins, as their choices today will largely determine the future global carbon trajectory.

The global relevance of RF1 is therefore significant. Many emerging economies currently lack formalized sustainability assessments for buildings, but interest in LCA methodologies adapted to local practices is increasing - recent collaborations with countries such as Thailand illustrate this trend. Although some methodological advancements developed in RF1 may be too advanced for immediate implementation in the most resource-constrained contexts, selected central outputs can be adopted. Uptake of these would enable emerging economies to advance more rapidly toward more sustainable building practices and reach an advanced level early in their transition. RF1 will maintain a strong global perspective from the outset in the development of the assessment methodologies and tools and will actively explore opportunities to collaborate with relevant actors in the Global South and to co-develop joint projects. The realization of these collaborations will depend on securing external funding, and where successful, will support the contextualization of methods and foster knowledge exchange across regions.

For these reasons, CEBE's insights and methods must extend beyond Danish building practices. The outcomes of RF1 can guide the development of materials, construction techniques, and design approaches that respect planetary boundaries - not only for climate, but also for biodiversity, resource use, and chemical emissions - across diverse global contexts.

4. Impact framework

4.1. Intended impact

This research field will establish the assessment foundation for a science-based, circular, low carbon and resilient built environment that operates within planetary boundaries.

It is our ambition that, over time, the research conducted in this field will enable and inspire broader sectoral change, including:

- Absolute sustainability assessment methods covering all relevant environmental impacts being taken up by the different centers of excellence within the built environment.
- LCA methods based on planetary boundary criteria being adopted by building owners and consultants, resulting in a more efficient built environment and reductions in resource use and environmental impact that reach absolute sustainability targets.
- National authorities, municipalities, and certification organizations adopting more rigorous ambition levels aligned with planetary boundaries.
- More consistent assessment and application of circular principles in building and infrastructure projects.
- Future generations of professionals will be up to date with the most advanced knowledge.
- Standardization for LCA and other environmental sustainability assessments of buildings and built environment are based on a planetary boundary approach.

4.2. Contextual conditions

Several societal and sector-wide trends can create favorable conditions for adopting LCA methods based on planetary boundaries:

- **Growing societal and political focus on sustainability**, including introduction of absolute targets for national contributions to climate change in the climate law and pressure to reduce environmental impacts across the building sector. This increases interest in assessment methods that reflect absolute limits.
- **Rising national and international research attention** to integrating planetary boundaries into environmental assessment frameworks as seen in the EU Commission's development of a Guideline for Absolute Environmental Sustainability Assessment [1.24]. This both applies to the other research fields of CEBE (RF2-7) and within international centers of excellence. This creates fertile ground for scientific collaboration and uptake of the project's methods.

- **Industry interest and demand** for clearer sustainability guidance, driven by stricter climate targets, material innovation, and the need to document environmental performance.
- **Certification schemes and regulatory frameworks** are increasingly open to integrating more ambitious sustainability criteria. Their willingness to adopt metrics based on absolute limits is essential for creating broad demand.
- **Consultants and engineering firms** are actively seeking more robust assessment tools to meet client expectations and upcoming policy requirements, making them likely early adopters of new LCA approaches.

Together, these contextual conditions can provide both the *societal momentum* and the *practical pathways* needed for the project's methods to be adopted in practice. To actively leverage these conditions, the programme will undertake a set of targeted activities aimed at supporting uptake, collaboration, and external engagement.

4.3. CEBE impact levers

The research field will generate methods that can be applied widely as an assessment tool to bring the environmental impacts of the built environment within safe operating space of the planetary boundaries. These methods are expected to create impact through multiple pathways:

- **Within CEBE:**

  The methods will be applied across the remaining six research fields (RF2–7) as a common framework for assessing environmental performance. This includes, for example, evaluating how new materials and building components contribute to keeping impacts within planetary boundaries, and how service-life extension of existing assets supports this objective.

- **In industry and practice:**

  The methods are designed for application by consultants, engineers, and developers as part of project assessment and decision-making processes. Over time, they may contribute to the development of industry standards, certification schemes, and regulatory requirements.

To support these impact pathways, CEBE-RF1 will implement a set of targeted and coordinated activities:

- **Internal integration within CEBE:**

  Facilitating workshops and collaborative sessions with other research fields to introduce, test, and refine the methodology across application areas. A dedicated PhD course will be developed and made mandatory for PhD students, postdocs, and tenure-track researchers within CEBE to support implementation across RFs.

- **Stakeholder engagement and advisory board:**

An advisory board will be established with key stakeholders (e.g. consultants, developers, engineering firms, and public authorities). This will ensure continuous dialogue, relevance, and feedback throughout the programme. The advisory board will serve as a platform for workshops, case-based collaborations, and iterative testing of methods in practice.

- **External engagement with industry and regulators:**

Engagement with certification bodies, policymakers, and authorities will support understanding of the methods and explore how planetary boundary–based metrics can be integrated into existing frameworks and future regulatory developments.

- **Demonstration through case studies and pilot applications:**

The methodology will be applied in selected flagship cases, including area developments, new construction, renovation, and transformation projects. Pilot applications and demonstrator projects will illustrate the practical use and value of the methods in real-world decision-making contexts. Collaboration with industry partners will enable testing in environmentally ambitious projects.

- **Capacity building through education:**

The methods will be integrated into teaching activities across partner institutions, including coursework and master's theses, to equip students and early-career professionals with relevant competencies.

- **International collaboration and knowledge exchange:**

The programme will actively participate in international research networks and conferences to position the work within ongoing scientific developments and facilitate knowledge exchange. Collaborations with international partners - including actors in the Global South - will be explored and, where possible, established. Joint research and funding opportunities will be pursued to support co-developed activities.

In line with the overall CEBE programme approach, RF1 will adopt a proactive and iterative strategy for impact, emphasizing early and continuous stakeholder involvement. Engagement will be embedded in the research process through advisory boards, workshops, pilot applications, and co-creation activities to support testing, validation, and refinement of methods in real-world contexts.

Through these coordinated efforts, the programme will translate favourable conditions into concrete pathways for adoption. The scope and depth of some activities - particularly international collaborations and implementation-oriented efforts - will depend on the successful establishment of partnerships and access to external funding.

Overall, RF1 aims to establish planetary boundary–based LCA methods as scientifically robust and practically applicable tools for guiding the transition of the built environment.

4.4. Intended outcomes and main beneficiaries

The research field will deliver scientifically documented methods that are rigorously developed and validated, and that are made accessible through datasets, guidelines, and practical tools that can be used both in research and in practice. These methods are the key outcome, and they will be disseminated through peer reviewed academic publications to ensure transparency, scientific rigor and international recognition. Over time, the results are expected to support the uptake and integration of planetary-boundary-based LCA approaches in consultancy and construction practices, where engineers and practitioners can apply them in real building projects. If additional funding becomes available, the methods may also be incorporated into established LCA software tools used in the built environment, enabling wider and more systematic adoption. RF1 will actively pursue funding opportunities (e.g. Innovation Fund Denmark and other industry-oriented programmes) to enable the integration of the methods into relevant LCA tools. Furthermore, the research field aims to contribute to policy frameworks, standards, and regulatory discussions by providing scientifically robust measurement methods and engaging with policymakers, certification bodies, and standard-setting organizations through targeted workshops, bilateral consultations, and contributions to emerging standards and guideline development processes. A central achievement will also be a clearer and more commonly shared understanding of what constitutes carbon neutral and circular solutions within the built environment, including the development of definitions and criteria that can be consistently applied across research, practice, and policy. Finally, the research field will support education and knowledge transfer, ensuring that younger generations (students, early-career professionals, and future decisionmakers) gain access to the most advanced and up-to-date understanding of building sustainability, preparing them to work with approaches aligned with planetary boundaries.

4.5. Research outputs

The research activities will focus on developing novel methods for measuring the environmental performance measures of the built environment, including both new and existing buildings as well as infrastructure, within the absolute limits. This includes establishing definitions and methodological approaches for assessing what constitutes absolute environmentally sustainable, climate-neutral and circular solutions across different building typologies and material categories. The project will also generate new methods for evaluating the absolute sustainability impacts of buildings, going beyond relative or comparative assessment to determine whether a building's environmental profile fits within its fair share of the Earth's ecological capacity. In addition, the research will explore and test innovative design techniques, construction approaches, and material solutions that enable building projects to be conceived and delivered within planetary boundaries. Important milestones of RF1 are the release of LCA methods to be used by other researchers and by expert practitioners. First version of the planetary boundary LCA method is planned to be used outside RF1 (in RF2-7 and also externally) by the end of year 2 and an updated and improved version will be released every three years. The same applies for methods to evaluate climate neutral building and climate neutral built environment. This is reflected in table with targets of the research field below.

RF1 will develop new methods for integrating the temporal dimension into environmental performance assessments of the built environment. Incorporating dynamics in quantitative sustainability assessments and LCAs for the built environment will enable performance assessments of buildings and constructions that reflect actual or predicted changes occurring in the surrounding society, including factors that influence the environmental performance of buildings and construction systems.

Regarding system boundaries, these have long been recognized as a major limitation of LCA applications in the built environment. Until now, LCA practice has had to balance applicability with methodological complexity, often resulting in quite simplified approaches that lack the ability to capture indirect impacts induced by remote parts of the system. This uncertainty has generally been accepted to maintain practical usability. However, as some strategies for buildings and constructions aligned with the green transition increasingly rely on materials (e.g., biomaterials) with complex, system-boundary-dependent impact profiles, the need to account for these remote impacts is becoming more urgent than ever and the need to address multiple sets of system boundaries has become a practically unresolved priority.

4.6. Research activities

The research field is organised into four closely connected work packages (WPs), each addressing critical methodological gaps in assessing environmental sustainability within the built environment. Together, the WPs develop a comprehensive and integrated framework for evaluating whether buildings and infrastructure operate within absolute environmental limits.

WP1.1 focuses on developing core methodologies for assessing absolute sustainability impacts across biodiversity, resource use, and chemical emissions over the full life cycle of the built environment. This includes advancing characterisation models for resource depletion and ecotoxicity, as well as establishing regionally differentiated system boundaries to better capture spatial variability in environmental impacts.

WP1.2 investigates the implications of system boundary choices in life cycle assessments of the built environment. It systematically compares simplified and expanded system boundaries, demonstrating how these choices influence both relative and absolute sustainability outcomes. The WP further explores how more comprehensive system boundaries can be integrated into LCA practice to strengthen decision support.

WP1.3 develops dynamic assessment methods that account for changes over time, enabling evaluation of long-term environmental impacts without burden shifting across life cycle stages or generations. This includes improved quantification of temporal emissions and modelling of evolving environmental and socio-economic conditions over the long service life of buildings and infrastructure.

WP1.4 establishes absolute environmental performance targets for the built environment, including climate, biodiversity, and resource-related goals. These targets may reflect net-zero, planetary boundary-based or restorative approaches. Building on the methods developed in WP1–WP3, this WP provides guidance for defining, interpreting, and verifying sustainability targets to ensure robust and credible application in research, policy, and practice.

Strong interaction and continuous knowledge exchange across the WPs ensure methodological coherence and integration. Together, the work packages deliver a step change in how environmental performance is assessed, moving from relative comparisons towards scientifically grounded evaluations aligned with planetary boundaries.

The core research activities comprise the development of new methodological frameworks and their integration into practice and education. This includes the development of LCA methods for the built environment that embrace the latest and upcoming advances in quantitative sustainability assessment, thereby increasing the scientific validity and practical usefulness of sustainability evaluations across buildings and infrastructure.

These activities pivot around three interconnected research areas:

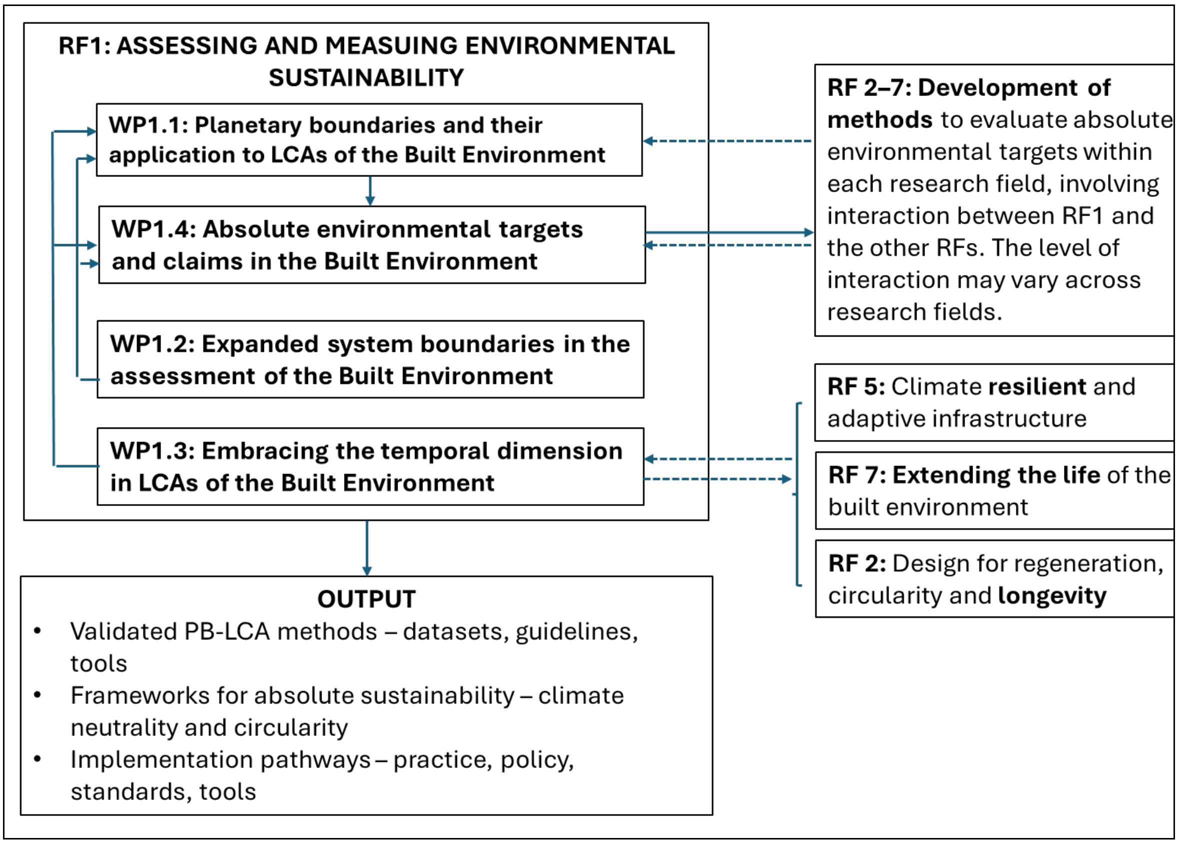
(1) absolute sustainability assessments of the built environment (WP 1 and 4),
(2) dynamic and temporally dependent assessments (WP3), and
(3) system-boundary dependent assessments (WP4), as described in detail above.

Together, these research areas provide a comprehensive foundation for evaluating the environmental performance of buildings within planetary boundaries.

A central strand of the work will establish a novel methodology for assessing the absolute sustainability impacts of buildings on climate impacts, biodiversity, resource use, and ecotoxicity from chemical emissions throughout the life cycle of the built environment. This includes developing characterization models for resources based on their occupation within, and dissipation from, buildings and infrastructure life cycles. Ecotoxicity impacts from chemical releases will be assessed against regionally differentiated environmental boundaries, reflecting the varying carrying capacities of exposed ecosystems.

Further, the project will develop methods for scaling the safe operating space defined by planetary boundaries to the built environment. This will enable assessments of whether both new and existing buildings operate within their fair share of global ecological limits, moving beyond comparative or relative assessments to determine true absolute sustainability performance.

Illustration of RF1 interactions with other RFs



RF1 aims to develop methodologies that can be applied across all research fields for consistent evaluation. This requires interaction between RF1 and the other research fields (as illustrated in the figure above). The extent of this interaction may vary and evolve over time.

All methods developed in RF1 will be made operational for application across the other research fields within CEBE. This enables alternative design options, material choices, and construction strategies to be evaluated consistently in terms of both their relative impacts and their alignment with planetary boundaries.

Through this integration, the methodological advances will support informed decision-making in practice and be embedded in educational activities, ensuring that future professionals engage with state-of-the-art sustainability assessment approaches.

4.7. Research Field specific output, outcome and impact targets

For the research field we have defined the following targets based on the milestones developed in the application, and for which the realization hereof will be evaluated over the course of the programme. The targets are mainly detailed for the first four years and will for the following years be further detailed as part of the mid-term evaluation.

Targets of the research field

Target name & description	Evaluation method	Impact Type	Category	Year
WP1.1: First version of the **Planetary Boundary -LCA methodological foundation for the built environment** with biodiversity impact will be released and ready to be used by RF2-7 and outside CEBE. It will be further developed and updated every three years.	-Publication of journal article/s describing the method	Output	Methodology	2
WP1.4: First version of the **Methodology and framework for climate neutral building** will be released and ready to use outside RF1. The advisory board will support early testing, application, and adoption of the methodology by industry stakeholders."It can support research, building owners, municipalities and regulators for meeting requirements for climate neutral buildings. It will be further developed and updated every three years.	-Publication of journal article/s describing the method	Outcome	Framework, applied by industry and research	2
WP1.4: First version of **Methodology and framework for climate neutral built environment** will be released and ready to use outside RF1. The advisory board will support early testing, application, and adoption of the methodology by industry stakeholders." It can support research, municipalities and regulators for meeting requirements for climate neutral built environment (group of buildings and infrastructure). It will be further developed and updated every three years.	-Publication of journal article/s describing the method	Outcome	Framework, applied by industry and research	2
WP1.2: **Improved C-LCA data and approaches for built environment**. This can support better use of Consequential LCA for assessments within the built environment for evaluating larger system changes.	-Publication of journal article/s describing the method	Output	Methodology	2
Future generations of professionals will be up to date with the most advanced knowledge. Our aim is that our improved LCA methods are included in teaching curricula of the four partner universities of CEBE, and thereby can inspire future generations of professionals to work with more ambitious environmental practices.	Student evaluations. Evaluations of course descriptions. *This should be done yearly from year 2.*	Outcome	Change in teaching curricula	2
WP1.4: First version of the **Methodology and Framework for built environment within planetary boundaries** will be released and ready to use outside RF1. The advisory board will support early testing, application, and adoption of the methodology by industry stakeholders."It can support research, building	-Publication of journal article/s describing the method	Outcome	Framework, applied by industry and research	3

owners, municipalities and regulators for meeting requirements for built environment within planetary boundaries. It will be further developed and updated every three years.				
WP1.1: Methodology to include **resources in absolute sustainability assessment for buildings**. This method is lacking in both assessment related to absolute targets such as Planetary Boundaries and absolute sustainability. The foundation of the framework will be developed in a phd thesis.	-Publication of journal article/s and a phd thesis describing the method	Output	Methodology	3
WP1.1: Methodology to include **use of chemicals and their effects in absolute sustainability assessment for buildings**. Similarly to resources, methodology for evaluation of chemicals and their effects within the built environment is missing, e.g. for Planetary Boundaries.	-Publication of journal article/s describing the method	Output	Methodology	3
LCA methods based on planetary boundary criteria are **adopted by building owners and consultants** in Denmark in their practices resulting in a more efficient build environment including an absolute reduction in resource-use and environmental impact	By documenting in industry surveys, such as "Byggeriets Modenhedsmåling": - a change in the perception of the usefulness of PB criteria and monitoring methods in consultancy; - a change in the perception of the usefulness of PB criteria and monitoring methods in consultancy. *This should be done yearly from year 3.*	Impact	Uptake of new methods in industry	3
Voluntary certification systems have adopted higher ambition levels closer to or aligned with planetary boundaries.	By documenting changes in requirements in certification manuals, such as DGNB, Nordic Ecolabel etc. *This should be done yearly from year 3.*	Impact	Change of practice	3
Municipalities have adopted higher ambition levels closer to or aligned with planetary boundaries.	By documenting changes in requirements through survey among municipalities. *This*	Impact	Change in local requirements /legislation	3

	should be done yearly from year 3.			
WP1.4: Evaluation methods for **circularity** within the built environment. The advisory board will support early testing, application, and adoption of the methodology by industry stakeholders.”	-Publication of journal article/s describing the method	Outcome	Framework, applied by industry and research	4
Absolute sustainability assessment methods covering all relevant environmental impacts **are taken up by the different centers of excellence** for sustainability within the built environment	Citations of CEBE-RF1 methodology used in academic journal papers. *This should be tracked yearly from year 4.*	Impact	Uptake of new methods in academia	4
WP1.3: New/refined dynamic methodology and scenario data for use in updating approaches and models in WP 1 and 4	-Publication of journal article/s describing and testing the method	Output	Methodology	4
WP1.2: Proposal for how expanded system boundaries can be applied for assessing the built environment	-Publication of journal article/s describing the method	Output	New approach	4
WP1.1: Integrated PB-LCA method adding updated biodiversity method, resources, energy and chemicals. This is an update of the methodology from year 2, now including resources, energy and chemicals in the evaluation methodology.	-Publication of journal article/s describing the method	Output	Methodology	5
WP1.3: New dynamic multi-scenario model for aligned MFA and LCA that will improve models within WP 1, 2 and 4	-Publication of journal article/s describing and testing the method	Output	Methodology	7
WP1.1: Extended PB-LCA method adding biomaterial and temporal perspective.	-Publication of journal article/s describing the method	Output	Methodology	8
National authorities have adopted higher ambition levels closer to or aligned with planetary boundaries.	By documenting changes in building regulations	Impact	Change in national legislation	8

5. References

Andersen, C. E., et al. (2020). Assessment of absolute environmental sustainability in the built environment, Building and Environment, Volume 171, 2020, 106633, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2019.106633.

Andersen, S. C., et al. (2024). Environmental impacts of circularity in the built environment: How do system boundaries affect decision support?, Developments in the Built Environment, Vol-ume 18, 2024, 100398, ISSN 2666-1659, https://doi.org/10.1016/j.dibe.2024.100398.

Birgisdottir, H., et al (2017). IEA EBC annex 57 'evaluation of embodied energy and CO2eq for building construction', Energy and Buildings, Volume 154, 2017, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2017.08.030.

Bjørn, A., Paulillo, A., Sanye Mengual, E., De Laurentiis, V., Vea, E., Hauschild, M.Z., and Sala, S. (2025). Guidance for applying absolute environmental sustainability assessment on activities at different scales (beta version). Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2760/7677803, JRC142099.

Bullen, L., et al. (2021). Absolute sustainability of New Zealand office buildings in the con-text of climate targets, Building and Environment, Volume 205, 2021, 108186, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2021.108186.

Du, G., Safi, M., Pettersson, L. et al. Life cycle assessment as a decision support tool for bridge procurement: environmental impact comparison among five bridge designs. Int J Life Cycle Assess 19, 1948–1964 (2014). https://doi.org/10.1007/s11367-014-0797-z

Dudka, K.M., M.Z. Hauschild, and M. Owsianiak. 2025. Evaluating mineral resource boundaries for application in absolute environmental sustainability assessment. Resources, Conservation and Recycling 219(October 2024).

Elnour, M., et al. (2025). Dynamic life cycle assessment of building stocks: a systematic re-view, Renewable and Sustainable Energy Reviews, Volume 218, 2025, 115682, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2025.115682.

Horup, L. et al. (2025). Absolute sustainability assessment of the Danish building sector through prospective LCA, Science of The Total Environment, Volume 966, 2025, 178780 ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2025.178780.

Katarina Slavkovic, André Stephan. 2025. Dynamic life cycle assessment of buildings and building stocks – A review. Renewable and Sustainable Energy Reviews. Volume 212. 115262. ISSN 1364-0321. https://doi.org/10.1016/j.rser.2024.115262.

Liljenström, C. et al. (2020). Life cycle assessment as decision-support in choice of road corri-dor: case study and stakeholder perspectives. International Journal of Sustainable Transporta-tion, 15(9), 678–695. https://doi.org/10.1080/15568318.2020.1788679

Liljenström, C. et al. (2022). Including maintenance in life cycle assessment of road and rail infrastructure—a literature review. Int J Life Cycle Assess 27, 316–341 (2022). https://doi.org/10.1007/s11367-021-02012-x

Lund, A. M. et al (2022). Whole Life Carbon Assessment of Renovation: Possibility of Specifying Limit Values for LCA of Renovation Work. Department of the Built Environment, Aalborg University. BUILD Rapport Vol. 2022 No. 33

Lützkendorf, T. et al.(2014). Net-zero buildings: incorporating embodied impacts. Building Research & Information, 43(1), 62–81. https://doi.org/10.1080/09613218.2014.935575

Paulillo A.. et al (2025) Advancing Absolute Environmental Sustainability Assessment: Introducing the First Technical Guidance and a Call for Feedback, J. Industrial Ecol. 29 (6), 1933-1935, http://doi.org/10.1111/jiec.70113.

Priore, Y. et al (2026). What really matters when benchmarking carbon mitigation measures against carbon budget-aligned targets for buildings?. Energy and Buildings. Volume 350. 2026.116664. ISSN 0378-7788. https://doi.org/10.1016/j.enbuild.2025.116664.

Röck, M., et al. (2020). Embodied GHG emissions of buildings – The hidden challenge for ef-fective climate change mitigation, Applied Energy, Volume 258, 2020, 114107, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2019.114107.

Röck, M. et al (2021). Environmental modelling of building stocks – An integrated review of life cycle-based assessment models to support EU policy making, Renewable and Sustainable En-ergy Reviews, Volume 151, 2021, 111550, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.111550.

Satola, D., et al. (2021). How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC annex 72, Building and Environment, Volume 192, 2021, 107619, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2021.107619.

Su, S., et al. (2017). Dynamic LCA framework for environmental impact assessment of buildings, Energy and Buildings, Volume 149, 2017, Pages 310-320, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2017.05.042.

Thomassen, G., A. Eswaran, S. Van Passel, and J. Dewulf. 2024. A Planetary Boundary for Mineral, Metal, and Fossil Resource Extraction Rates: How Much Primary Materials Can a Circular Economy Extract? Environmental Science and Technology 58(46): 20345–20351.

Tozan, B. et al (2024). A novel approach to establishing bottom-up LCA-based limit values for new construction. Building and Environment, Volume 263, 1 September 2024, 111891. https://doi.org/10.1016/j.buildenv.2024.111891

Zimmermann, R. K. et al. (2021). Whole Life Carbon Assessment of 60 buildings: Possibilities to develop benchmark values for LCA of buildings. Polyteknisk Boghandel og Forlag. BUILD Report No. 2021:12

Zimmermann, R.K., Rasmussen, F.N., Birgisdottir, H. Challenges in benchmarking whole-life GHG emissions from renovation cases: Evidence from 23 real-life cases. Energy and Buildings. Volume 301, 15 December 2023, 113639. https://doi.org/10.1016/j.enbuild.2023.113639

Research field 2 – Design for regeneration, circularity and longevity

1. Introduction, vision & mission

1.1. Introduction to the Research field

Research Field 2 addresses how civil engineering can support the green transition of the built environment through design for regeneration, circularity, and longevity. Many planetary boundaries are overstepped, and the field therefore responds to the need to move beyond merely reducing harm and enable the design of *built environments with environmental load that enables the regenerative properties of the planetary ecosystems to reestablish the safe operating space below the planetary boundaries.* Focus is on cocreating design and construction methods, circular building systems, and long-lasting solutions that remain robust in a changing climate.

1.2. Vision

The vision of Research Field 2 is to establish a new scientific and practical methods and tools for designing buildings with an environmental impact that enables the regenerative properties of the planetary ecosystems to reestablish the safe operating space below the planetary boundaries. The field aims to enable the building industry to design and construct buildings and building systems for repeated circularity, enhance biodiversity, and remain resilient over time and under future climate conditions. This will position Denmark as an international frontrunner in the green transition of the built environment.

1.3. Mission

The mission of Research Field 2 is to develop research-based methods, processes, and solutions for building design, long-lasting and circular building systems, and construction management with a low environmental impact. Through interdisciplinary research, experimental testing, digital design methods, and co-creation with industry and international partners, the field will generate knowledge that can be implemented in practice. In this way, the research field will accelerate the transition toward long-lasting and circular buildings and urban environments with a regenerative environmental impact.

2. State of the field

2.1. Global centers of excellence

Within building design for regeneration (WP 2.1), leading research environments in development of *design methods* with focus on the integration of performance-driven design and simulation into early-stage decision-making includes the Building Technology Program within the Department of Architecture at MIT where methods for integrating environmental performance, energy use, and indoor climate into building design processes is developed, the Architecture and Building Systems group at ETH Zürich where advances building design methods are coupled to energy performance, indoor environmental quality, and system integration. Similar approaches are developed at institutions such as TU Munich, KU Leuven, Chalmers, and Lund where research focuses on simulation-based design, building performance modelling, and the integration of technical systems into architectural design workflows. Research environments on *climate-change ready design of buildings* with emphasis on resilience to overheating, changing climate conditions, and reduced operational energy demand is particularly strong in the U.K. at University of Cambridge, University of Bath, and Loughborough University. There are also several international research environments that are advancing approaches that integrate *ecological processes and living systems into the built environment*. At TU Delft, research within Architectural Engineering has contributed to the development strategies for ecological integration in architecture. The Hub for Biotechnology in the Built Environment (HBBE), a collaboration between Newcastle University and Northumbria University, combines biotechnology, microbiology, and architectural research to develop living materials and bio-integrated building systems. At ETH Zürich, the ALIVE (Advanced Engineering with Living Materials) initiative explores how biological processes can be embedded into engineered materials through the integration of material science, digital fabrication, and synthetic biology. At University College London, the Bio-Integrated Design (BioID) Lab has developed bioreceptive materials and design strategies that enable biological growth on building surfaces

Within design for circularity and longevity (WP 2.2), leading research groups are developing methods and infrastructures to enable the reuse of materials and components in new building systems. At ETH Zürich, the Circular Engineering for Architecture (CEA) group develops digital infrastructures for circular construction, including material passports, digital inventories, and urban mining systems that support designing-from-stock approaches. At EPFL Lausanne, both the Structural Xploration Lab and the Laboratory for Creative Computation are advancing circular structural design and computational fabrication methods, enabling the reuse of load-bearing components in new systems and the adaptive assembly of irregular and heterogeneous materials. At MIT, the Digital Structures group develops computational design and optimisation methods for resource-efficient structural systems, including approaches applicable to reused components in new systems.

Within construction processes for regeneration (WP 2.3), research is increasingly focused on aligning construction practices, logistics, management systems and previous design and subsequent use with circular and regenerative principles. This includes the development of construction workflows with an environmental impact that enables the regenerative properties of the planetary ecosystems to reestablish the safe operating space below the planetary boundaries, new process frameworks and digitally based systems that enable upcycling of materials, material reuse and reduce and transform resource consumption, when it comes to machinery and other production equipment. Internationally, this area is less consolidated, despite long term building production that enables the natural properties of the ecosystems to regenerate do exist in US and Australia but relevant contributions are emerging from research environments working with production for regeneration in e.g. Chalmers and Lund universities, digital construction, robotics, and integrated project delivery, including initiatives at ETH Zürich and MIT that explore automation, digital fabrication, and data-driven construction processes. Compared to advances in building design and development of building systems, these domains are at present less mature, highlighting a need for stronger conceptual connections between construction processes, design decisions, and material cycles drawing on longer term practice experiences. By following the large Chalmers/Lund project, it is possible to learn from their ongoing theoretical development and later create synergies on scientific knowledge production

2.2. State of the art and DK position in the research field

Within building design for regeneration (WP 2.1), the state of the art in engineering method for building design has over the past two decades evolved around the integration of dynamic simulation, parametric modelling, and multi-objective optimisation, enabling designers to evaluate complex trade-offs between energy and comfort in early design stages (Clarke, 2001; Petersen & Svendsen 2010, Attia et al., 2013). Currently, there is ongoing development of approaches and tools that incorporate life-cycle assessment (LCA), material reuse strategies, and resource-aware design into early-stage modelling and decision-making processes (Pomponi & Moncaster, 2017; Soust-Verdaguer et al., 2017; Anand & Amor, 2017; Röck et al., 2020; Eberhardt et al., 2020). Next step in research is to investigate how to integrate a design paradigm into the approaches and tools that make ecological regeneration a driver for design decisions, extending conventional simulation environments with new types of data and evaluation criteria like the ones described in Reed (2007) and Mang & Reed (2012). In this context, design methods and tools are required to operate across disciplines, linking e.g. building physics, material science, ecological modelling, sufficiency and well-being in architectural solutions. It is noted that the uptake of the research outcome in the building design practice seems to rely on whether these new approaches and tools support already well-established design activities in practice (Purup & Petersen 2020a; Purup & Petersen 2020b). This aspect needs to be considered carefully prior to any research activity related to development of new design methods and approaches. In Denmark, research in digital design methods and tools for performance-based building design decisions has already contributed significantly over the last few decades with tools and methods co-created for and with practitioners (Petersen & Svendsen 2008; Petersen & Svendsen 2010; Petersen et al. 2014; Lauridsen & Petersen 2014; Petersen 2017; Purup & Petersen 2017; Petersen et al. 2018; Petersen & Purup 2019; Purup & Petersen 2020; Kamari et al. 2021; Petersen et al. 2021a; Petersen et al. 2021b; Purup & Petersen 2021; Petersen et al. 2022) and a continuation of this research into a paradigm that enables the regenerative properties of the planetary ecosystems to reestablish the safe operating space below the planetary boundaries is imminent. Subsequently, approaches increasingly focus on better ecological outcomes through the integration of living systems, where organisms function as active contributors to building systems and environmental performance. In this context, research has explored how mineral substrates can be engineered to host biological communities, such as algae, mosses, and other surface-adapted organisms, enabling processes including carbon uptake, evaporative cooling, moisture buffering, pollutant capture, and microhabitat formation. The field originates in studies of spontaneous biological colonisation on stone, concrete, and clay substrates, initially framed in terms of durability and biodeterioration (Miller et al., 2012; Ortega-Calvo et al., 1995) and has progressed toward performance-driven material and surface design, where bioreceptivity is treated as a controllable parameter (Cruz & Beckett, 2016), and then expanded through bio-receptive concrete, bio-integrated composites, microbial systems, and engineered living materials (Veeger et al., 2023, 2025; Birch et al., 2021; Crawford et al., 2021, 2022; Chen et al., 2025; Cui et al., 2026; Dranseike et al., 2025). In Denmark, research within bio-integrated and bioreceptive building systems remains emerging but builds on strong national positions in building physics, façade engineering and nature-based urban design. At the same time, Denmark has a strong tradition of collaboration between research institutions, architects, engineers and manufacturers, creating favourable conditions for translating experimental research into demonstrator projects and scalable building applications.

The objective of design for circularity and longevity (WP 2.2) is to enable design of circular and climate-robust building systems with a low environmental impact. The WP is focusing on how building systems (facades, roofs, floors) can be designed as functional assemblies based on reclaimed resources, biobased materials and reusable components. The state of the art has moved from a material-substitution logic towards system-oriented design strategies that enable building systems to remain useful over time. This development emerges from early theories of adaptable and layered building design e.g. by Habraken (1972) and Brand (1994). Within contemporary circular construction research, central strategies include design for disassembly, design for adaptability, design for reuse, modularity, reversible connections, accessible layers, standardised interfaces, and documentation of material and component properties (Crowther, 1999; Durmisevic & Brouwer, 2002; Guy & Ciarimboli, 2008; Durmisevic, 2019). These strategies aim to slow resource loops by extending service life, close loops by enabling future reuse, and narrow loops by reducing material intensity, following the circular economy framework proposed by Bocken et al. (2016). However, as pointed out in a review by Eberhardt et al. (2022), the field on circular design and construction strategies remains fragmented, also in Denmark, with a need for defining decision-support methods that can help designers choose building system strategies according to context and environmental performance. They also highlight that research has predominantly focused on recycling materials, while comparatively less attention has been devoted to the integration of circular principles into complete building systems and their interfaces. Other similar reviews also conclude that practical implementation remains limited due to a lack of quantitative evidence on long-term environmental performance, inconsistent circularity assessment methods, and weak integration into ordinary architectural and engineering workflows (Çetin et al., 2021; Akinade et al., 2020). Newer examples of how researchers are trying to address these issues is the development of methods on how to use reclaimed resources in a way that building systems can be designed to rely on locally available material inventories using computational design and optimisation (Fontaine, 2025; Gattas et al., 2025; Sun et al., 2026; Warmuth et al., 2021). The state of the art in Denmark related to the objective of this WP is very much related to innovation where the a priori application of biobased or recycled building materials, components, and systems are claimed to be sustainable. However, as pointed out by Pomponi & Moncaster (2017), circular design strategies should not be assumed environmentally beneficial a priori, but instead evaluated through whole-life modelling of resource flows, replacement cycles and environmental impacts. Denmark currently occupies a strong international position in research in operationalization of life-cycle assessment (LCA) within building design processes. This position should be utilized to develop circular design principles that address how reclaimed resources, biobased materials and reversible connections can be integrated into complete and climate-robust building systems such as façades, roofs and floor assemblies. Recent advances in digital design, fabrication and robotic construction demonstrate the potential for integrating design and handling reclaimed and non-standard materials with sufficient precision for architectural and structural applications. Studies from research environments at institutions such as ETH Zürich and Massachusetts Institute of Technology show how data-driven fabrication, robotic assembly and computational workflows can expand the applicability of reused timber, irregular geometries and reclaimed components within industrialised fabrication processes (Bruun et al., 2024; Grangeot et al., 2024; Skevaki et al., 2025; Yen & Svilans, 2025; Zanetti et al., 2025).

Within construction processes for regeneration (WP 2.3), there is an emerging focus on aligning construction planning, logistics, production systems and management methods that enable material reuse, reduce waste generation and support adaptive and resource-efficiency. Construction processes across the building life cycle is then enriched with circular and regenerative principles (Koch 2025, Mang and Reed 2012). A central theme is how to develop and formulate more specific concepts for building production systems and construction management approaches *that enables the regenerative properties of the planetary ecosystems to reestablish the safe operating space below the planetary boundaries*. Other themes include digital platforms for material tracking, integration of design and construction data, material passports and urban mining systems, as well as the application of automation and robotics in fabrication and assembly processes (Çetin et al., 2021; De Wolf et al., 2024). In parallel, research on digital infrastructures for circular construction has explored how material inventories, component passports and urban mining databases can support identification, grading and integration of reclaimed materials within design and construction workflows (Çetin et al., 2021; De Wolf et al., 2024). However, the studies emphasise that the field remains underdeveloped in relation to scalable workflows for circular construction. Emerging research environments are beginning to formulate systematic concepts for building production systems and construction management approaches *that enables the regenerative properties of the planetary ecosystems* *to reestablish the safe operating space below the planetary boundaries* (Kifokeris et al., 2025), but the field remains at an early stage with relatively few integrated frameworks spanning the full project lifecycle from design and procurement to future transformation and reuse. Denmark is currently contributing with a limited but growing research environment within construction processes that focus on reducing the environmental impact to a level where the planetary ecosystems can regenerate. The research is focused on changing the fact that research and practice remain fragmented and largely project-based, with limited development of integrated workflows across the construction process (Koch 2025, Kunic et al., 2026; Naboni et al., 2024; Svilans & Thomsen, 2024; Tamke et al., 2025; Thomsen et al., 2025).

3. How the research field will address the core challenges?

The overarching core challenge in research field 2 is how to design buildings and urban environments with a life-cycle environmental impact that enables the regenerative properties of the planetary ecosystems to reestablish the safe operating space below the planetary boundaries.

In relation to design for regeneration, Research Field 2 will address this core challenge by applying scientifically proven efficient research methods for research-industry co-creation (Purup & Petersen 2020a) that leads to practical methods and tools for decision-support in the design process. Special attention in this co-creation process is to enable the assessment of potential design decisions on long-term environmental performance and improved capacity for buildings to adapt to changing conditions. The anticipated end-users of these methods and tools are consulting engineers and architects. In the same way, the research field also contributes to advancing design methods for building systems and construction practices that enable buildings to remain relevant and functional over extended time horizons while responding to environmental and climatic challenges. The anticipated end-users of these methods are consulting engineers, building system developers, construction managers and contractors. In a Danish context, the research field builds on strong existing competencies within life-cycle assessment, energy-efficient building design, and the digitalisation of the building sector.

Danish research and industry actors are characterized by close collaboration and a strong ability to translate research into practice. Research Field 2 extends these strengths by addressing areas that are not yet fully developed, including the systematic reuse of building systems, the application of biogenic and low-impact materials in building systems, and the development of construction processes that support circular material flows. By strengthening these areas, the research field contributes to maintaining and advancing Denmark's position within sustainable buildings, while responding to emerging challenges related to resource scarcity, biodiversity, and climate adaptation.

At the international level, the research field aligns with a growing ambition that the built environment must enable the planetary ecosystems to regenerate back to safe operating space below the planetary boundaries. Research Field 2 positions itself within this development by contributing to ongoing research on circular material use, low-impact construction, and long-term building performance. This creates a strong basis for collaboration with leading international research environments working on bioreceptive materials, circular structural systems, and advanced computational design and fabrication methods. The field is well suited to participate in international research initiatives, particularly within European frameworks that emphasize interdisciplinary collaboration and implementation-oriented research. Through such collaborations, the research field can contribute to advancing both scientific knowledge and practical solutions for the green transition of the built environment.

3.1. Global Perspectives

Building design with a regenerative environmental impact and circular construction address global challenges related to climate change, resource scarcity, and ecosystem degradation, and therefore require a perspective that extends beyond highly industrialised contexts which is the primary focus in RF2.

In developing and emerging economies, rapid urbanisation and increasing construction demand create both constraints and opportunities. Limited access to advanced technologies and formalised systems may restrict the immediate application of digital design tools and automated processes. At the same time, these contexts often rely on locally available materials, low-impact construction methods, and climate-adapted design, which align closely with regenerative and circular principles. This suggests that knowledge exchange in a global perspective should be reciprocal rather than one-directional; while advanced methods developed in industrialised contexts may inform future development, practices from resource-constrained environments can contribute valuable insights into sufficiency, adaptability, and low-resource design.

For this research field, direct implementation of highly digitalised approaches may be limited in the short term in many regions. However, the underlying principles – such as lifecycle thinking, material reuse, and ecological integration – remain broadly applicable and can be adapted to local conditions. In rapidly developing economies, there is also potential to integrate these principles early in new construction, avoiding lock-in to high-impact practices. Overall, the research field has clear global relevance, but its impact depends on the ability to translate methods and concepts across different socio-economic and technological contexts.

To support translation across different socio-economic and technological contexts, RF2 will prioritise the development of methods and workflows that are modular, interoperable and adaptable rather than dependent on specific technologies or industrial conditions. Comparative case studies and international research collaboration will be used to evaluate how regenerative and circular principles can be adjusted to different climatic, material and resource contexts. The research field will further emphasise principles that are transferable across both high- and low-technology settings, including adaptability, material efficiency, passive environmental strategies, local resource utilisation and lifecycle-based decision-making. Through open dissemination of methods, demonstrator documentation and digital workflows, RF2 aims to support international knowledge exchange and enable adaptation of research results within both industrialised and resource-constrained construction contexts.

4. Impact framework

4.1. Intended impact

A widespread adoption of knowledge-based design and construction practices that enable the building industry to develop built environments supporting the regeneration of local and planetary ecosystems. This implies a shift toward much lower environmental impact through integrated design, material use, and construction processes. RF2 contributes to this transition by co-creating new methods for designing and constructing buildings with a regenerative environmental impact using circular and robust building systems. The RF generates knowledge and tools that enable designers, engineers and manufacturers to integrate reclaimed resources, biobased materials, living systems and lifecycle-based environmental assessment into coordinated design and construction workflows suitable for long-term adaptation, reuse and climate resilience.

4.2. Contextual conditions

The current Danish research environment in this research field is well positioned to generate new research results that will lead to the intended impact in a building industry that shows increasing readiness to adopt new approaches, driven by climate targets, regulatory pressure, and a growing focus on resource efficiency.

However, key barriers remain: Workflows are fragmented across disciplines and project phases, limiting the implementation of circular and regenerative strategies during the building design and construction process. There is also a lack of standardised methods for assessing reused building systems, creating uncertainty for industry actors. Technical challenges related to quality variability, performance prediction, and scalability further constrain implementation. Opportunities for impact lie in developing coherent design methods and process frameworks that enable knowledge-based decision-making. RF2 addresses these gaps through collaboration between researchers, architects, engineers, contractors and manufacturers to develop and test integrated methods for design of buildings with a regenerative environmental impact, circular building systems and resource-efficient construction processes. This includes the integration of lifecycle-based assessment methods in the decision process, workflows for integrating reclaimed and biobased resources into building systems, and optimized construction processes. Through iterative development with industry partners and application in demonstrator contexts, the field aims to support the transition from isolated innovations toward systematic implementation of practices within ordinary building projects.

4.3. CEBE impact levers

Transferring research outputs into practice requires a structured approach that connects knowledge generation with implementation across the building lifecycle. Within RF2, this is addressed through an iterative research and innovation approach in which researchers, architects, engineers, manufacturers, contractors and other industry actors are involved throughout the development process. Research results are not developed as isolated academic outputs, but through continuous testing, evaluation and refinement in collaboration with practice partners. A central mechanism is therefore the co-development of design methods, assessment approaches and construction workflows through workshops, design studies, demonstrator projects and evaluation activities carried out together with industry stakeholders.

A key process within RF2 is the translation of research into applicable methods, tools and validated workflows that can be integrated into existing design and construction practices. This includes the development and testing of design guidelines for circular building systems, design-integrated lifecycle-based performance assessment methods and resource-aware decision-making. Demonstrator activities and pilot-scale implementation studies will be used to evaluate technical feasibility, environmental performance and practical integration into ordinary project workflows. Through these activities, RF2 aims to identify both technical and organisational barriers related to implementation across design, procurement, fabrication, assembly and future disassembly processes. To support integration into existing industry practices, RF2 will collaborate with industry partners and digital specialists on the development of interoperable digital workflows and data structures that can connect environmental assessment, material inventories and design information across project phases. The research field will further engage with ongoing developments within standards, certification systems and regulatory frameworks related to circularity, reuse and lifecycle assessment in the Danish building sector. This includes dialogue with industry organisations, authorities and standardisation environments to ensure that research outputs are aligned with emerging regulatory and professional requirements.

Capacity building and dissemination constitute an additional impact lever within RF2. The research field will integrate research results into higher education activities, professional training, workshops and industry-oriented dissemination formats targeting architects, engineers, contractors, manufacturers and public-sector actors. By involving stakeholders across the value chain from the early stages of the research process, RF2 aims to strengthen implementation potential and support shared learning between academia and practice. Successful implementation depends on coordinated involvement across the sector. RF2 therefore involves stakeholders representing design practice, engineering, manufacturing, construction, material supply and building operation, as well as public and regulatory actors relevant to implementation and standardisation. Through continuous interaction between research, education and industry practice, the research field seeks to support the transition from fragmented pilot activities toward more systematic implementation of regenerative and circular approaches in ordinary building projects and construction workflows.

4.4. Intended outcomes and main beneficiaries

The intended outcomes focus on integrating regenerative solutions and circular principles into digitally supported design and construction methods and workflows, enabling a shift toward knowledge-based and system-oriented practices across the building lifecycle. Rather than developing entirely new software platforms, the research field focuses on extending and connecting existing digital design and construction environments with methods and data structures that support decision-making for regeneration, circularity and longevity.

For WP2.1: Design for regeneration, the intended outcome is the integration of design principles that lead to regenerative environmental impact into early-stage architectural and engineering workflows through computational design methods, simulation environments and parametric modelling approaches. This includes integration with commonly used BIM and simulation environments for daylight, thermal conditions, moisture, biodiversity, and lifecycle assessment, enabling environmental processes and ecosystem interactions to inform early-stage building and site design decisions. The outcome supports architects, engineers and clients in designing buildings and urban elements as active contributors to ecological performance rather than merely reducing negative impacts.

For WP2.2: Design for circularity and longevity, the intended outcome is the development of digitally supported methods for designing circular and adaptable building systems, including façades, roof systems, floor assemblies and interior layers based on reusable and disassemblable materials and components. The work focuses on extending BIM-based workflows and lifecycle assessment tools with methods for evaluating adaptability, disassembly potential, component reuse and long-term resource value. Moreover, it is explored how design can integrate with computational fabrication, automation and robotics. This enables architects, engineers, contractors and manufacturers to integrate secondary and biobased resources into coordinated building systems and supports lifecycle-based decision-making across design, construction and future transformation scenarios. Main beneficiaries include design professionals, manufacturers, contractors and building owners through improved resource efficiency, reduced environmental impact and increased long-term adaptability.

For WP2.3: Construction processes for regeneration, the intended outcome is the integration of regenerative and circular principles into digital construction planning, logistics and production workflows. This includes methods for coordination and integration, material tracking, digital material inventories, reuse documentation, construction sequencing and data-supported coordination between design, fabrication, assembly and future disassembly processes. The work further explores how WP2.2 works on design integration with computational fabrication, automation and robotics can support handling and integration of reclaimed and non-standard materials within industrialised construction workflows. These outcomes support contractors, manufacturers and project managers in implementing more resource-efficient and adaptable construction processes while reducing waste generation and improving traceability of material resources across the project lifecycle.

Across all work packages, the overall intended outcome is the development and adoption of interoperable, digitally supported workflows that enable the building sector to implement circular principles within ordinary design, construction and management practices. The research field thereby supports coordinated collaboration across stakeholders including architects, engineers, contractors, manufacturers, clients and public authorities, helping move the sector from isolated pilot projects toward scalable and systematic implementation.

4.5. Research outputs

The research field will deliver methods, digital workflows, assessment approaches and demonstrator-based knowledge that support the implementation of regenerative solutions and circular principles across building design and construction practices. Initial outputs focus on developing integrated design and assessment methods that can be embedded within existing digital workflows, followed by testing and refinement through case studies and demonstrator projects involving industry partners.

For WP2.1: Design for regeneration, the primary outputs are computational design methods, environmental assessment workflows and design principles that enable regenerative environmental performance to inform early-stage architectural and engineering decisions. This includes methods for integrating ecosystem-related parameters such as biodiversity potential, microclimatic effects and lifecycle-related environmental impacts into BIM-based and parametric design environments. Additional outputs include demonstrator cases and evaluation frameworks for building and site design under Danish climatic and regulatory conditions.

For WP2.2: Design for circularity and longevity, the primary outputs are design methods and digitally supported workflows for circular and adaptable building systems, including façades, roof assemblies, floor systems and interior layers designed for disassembly, reuse and long-term adaptability. The work delivers methods for evaluating reuse potential, disassembly strategies, lifecycle scenarios and integration of reclaimed and biobased resources within BIM- and LCA-based workflows. Additional outputs include prototype system concepts, assessment methods and demonstrator studies documenting environmental and practical implementation potentials.

For WP2.3: Construction processes for regeneration, the primary outputs are methods and process frameworks for integrating regenerative solutions and circular principles into construction planning, logistics and production workflows. This includes approaches for coordination and integration across building processes

4.6. Research activities

The research activities are structured across three interconnected work packages combining computational modelling, experimental studies, case-based investigations and industry collaboration to develop and validate regenerative solutions and circular design and construction approaches.

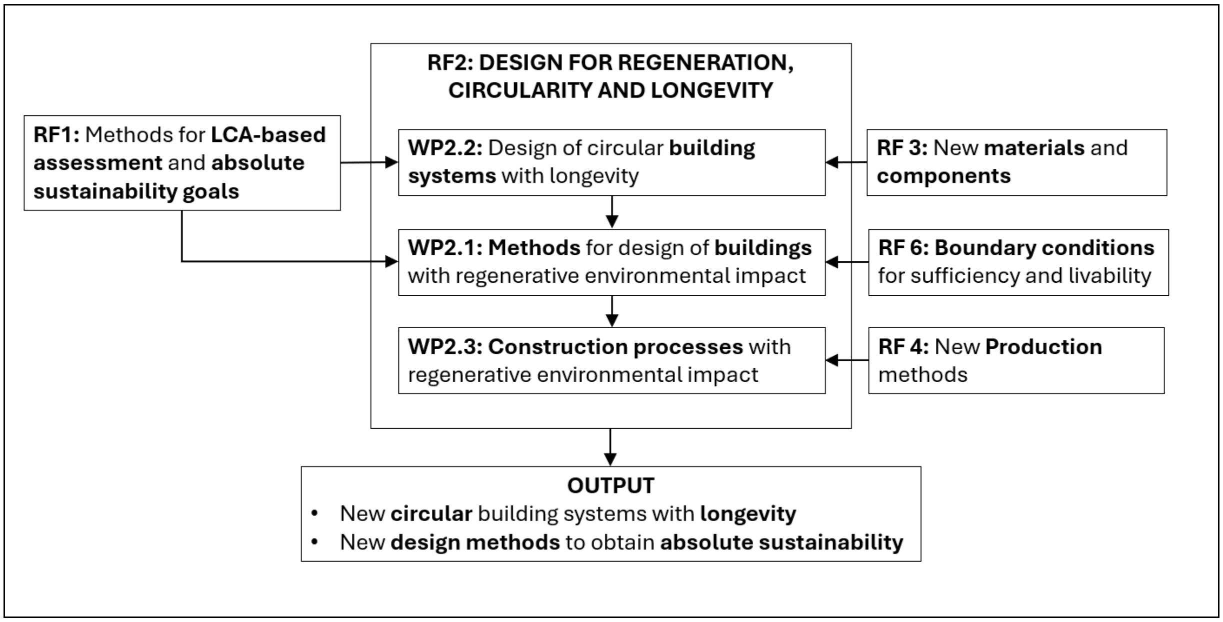
For WP2.1: Design for regeneration, activities include the development and testing of design methodologies through simulation studies, parametric modelling and environmental performance analysis across building and neighbourhood scales. Research activities involve investigation of climate-responsive and climate-change-ready building design strategies, modelling of thermal and moisture-related performance, and integration of biodiversity-, water- and ecosystem-related parameters into digital design workflows. The work further includes comparative case studies and demonstrator-based evaluations of design principles for regeneration under Danish climatic conditions.

For WP2.2: Design for circularity and longevity, activities include development and evaluation of circular building system concepts through lifecycle modelling, material flow analysis and BIM-supported design studies. Research activities involve analysis of reversible connections, adaptability strategies and reuse scenarios for building systems such as façades, roof systems and floor structures. The work further includes prototype development, assessment of reclaimed and biobased resource integration, and testing of methods for disassembly, reuse and long-term lifecycle performance in collaboration with industry partners.

For WP2.3: Construction processes for regeneration, activities focus on analysing and developing construction workflows that support regenerative solutions and circular practices across planning, logistics, fabrication and assembly processes. This includes studies of digital material tracking, reuse documentation and lifecycle-oriented construction sequencing, as well as investigations into how computational fabrication, automation and robotics can support handling of reclaimed and non-standard materials. Activities further include development and testing of integrated digital workflows connecting design, fabrication, construction and future disassembly processes through demonstrator projects and interdisciplinary collaboration with industry stakeholders.

Across all work packages, research activities include iterative co-development with architects, engineers, contractors, manufacturers and other sector stakeholders through workshops, pilot projects, evaluation activities and dissemination processes aimed at supporting implementation and validation in practice. The figure below shows where RF2 is mainly interconnected with research activities in other research fields in the CEBE programme.

Illustration of RF2 interactions with other RFs



4.7. Research Field specific output, outcome and impact targets

For the research field we have defined the following targets for which the realization hereof will be evaluated over the course of the programme.

Targets of the research field

Target name & description	Evaluation method	Impact Type	Category	Years
BIM- and simulation-integrated design workflow for early-stage ecosystem performance assessment in buildings and sites (WP2.1)	Integration and testing in at least two BIM/simulation environments in collaboration with architectural and engineering partners through pilot design cases	Output	New method / digital workflow	5
Climate-adaptive thermal design method for buildings under future climate scenarios	Validation through simulation studies and application in 1–2 real building cases with engineering consultancy partners	Output	New method	4
Climate- and biodiversity-responsive design guidelines for neighbourhood planning	Publication and demonstration through comparative neighbourhood-scale case studies with municipal and planning stakeholders	Output	New concept / design approach	5

BIM-LCA workflow for design, disassembly assessment and fabrication planning of circular façade, roof and floor systems (WP2.2)	Prototype workflow tested with manufacturers, engineers and contractors through pilot projects	Output	New tool / new workflow	4
BIM-supported method for grading, documentation and integration of reclaimed building systems in engineering workflows	Validation through pilot implementation with engineering and material supplier partners using reclaimed-material datasets	Output	New method	5
Demonstration project implementing circular building systems based on reclaimed and biobased building systems	Realised pilot project with documented environmental, technical and assembly performance in collaboration with contractors and manufacturers	Outcome	Demonstrated in practice	7
Adoption of lifecycle-based circular building systems design methods in engineering practice	Documented application by at least one engineering consultancy or manufacturer in commercial project workflows	Outcome	Applied by industry	7
Data-supported construction planning, coordination and integration and material tracking workflow for circular construction processes (WP2.3)	Prototype construction management system tested in pilot construction project with contractor and digital platform partners	Output	New tool / new process framework	5
Pilot implementation of construction workflows integrating reuse documentation, material tracking and lifecycle-based process coordination and integration	Documented implementation in 1–2 construction projects with contractors and project management partners	Outcome	Applied in construction practice	8
Contribution to national or international standards, guidelines or certification approaches for circular construction	Inclusion of methods or workflows in guideline documents, standardisation activities or certification frameworks involving industry and regulatory actors	Outcome	Applied in regulation / standardisation	9
Adoption of interoperable and circular design-construction workflows across multiple industry actors and projects	Evidence through implementation across several projects involving architects, engineers, contractors and manufacturers	Impact	Change of industry practice	10

5. References

Akinade, O. O., et al. (2020). Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). Resources, Conservation and Recycling.

Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings. Renewable and Sustainable Energy Reviews, 67, 408–416.

Attia, S., Hensen, J. L. M., Beltrán, L., & De Herde, A. (2013). Selection criteria for building performance simulation tools: Contrasting architects' and engineers' needs. Journal of Building Performance Simulation, 5(3), 155–169.

Birch, E., Bridgens, B., Zhang, M., & Dade-Robertson, M. (2021). Bacterial Spore-Based Hygromorphs: A Novel Active Material with Potential for Architectural Applications. Sustainability, 13(7).

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33(5), 308–320.

Brand, S. (1994). How Buildings Learn: What Happens After They're Built. Viking Press.

Bruun, E. P. G., Besler, E., Adriaenssens, S., & Parascho, S. (2024). Scaffold-free cooperative robotic disassembly and reuse of a timber structure in ZeroWaste. Constr. Robotics., 8(2), 20.

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular Digital Built Environment: An Emerging Framework. Sustainability, 13(11).

Chen, X., Zhang, Z., & Angst, U. (2025). Accelerating CO2 sequestration in cementitious materials using carbonic anhydrase: Experimental insights into performance and mechanisms. Carbon Capture Science & Technology, 17, 100511.

Clarke, J. A. (2001). Energy simulation in building design. Butterworth-Heinemann.

Crawford, A., In-na, P., Caldwell, G., Bridgens, B., & Armstrong, R. (2021). Photosynthetic textile biocomposites: Using laboratory testing and digital fabrication to develop flexible living building materials. Science and Engineering of Composite Materials, 28, 223–236.

Crawford, A., In-na, P., Caldwell, G., Armstrong, R., & Bridgens, B. (2022). Clay 3D printing as a bio-design research tool: Development of photosynthetic living building components. Architectural Science Review, 65(3), 185–195.

Crowther, P. (1999). Design for disassembly to recover embodied energy. Proceedings of the 16th Annual Conference on Passive and Low Energy Architecture.

Cruz, M., & Beckett, R. (2016). Bioreceptive design: A novel approach to biodigital materiality. Architectural Research Quarterly, 20, 51–64.

Cui, Y., Tibbitt, M. W., Lu, T. K., & Tang, T.-C. (2026). Design principles for adaptive and evolving engineered living materials. Current Opinion in Biotechnology 97, 103397.

De Wolf, C., Çetin, S., & Bocken, N.. (2024). A Circular Built Environment in the Digital Age.

Dranseike, D., et al. (2025). Dual carbon sequestration with photosynthetic living materials. Nature Communications, 16(1), 3832.

Durmisevic, E. (2019). Circular economy in construction: Design strategies.

Durmisevic, E., & Brouwer, J. (2002). Design aspects of decomposable building structures.

Eberhardt, L. C. M., et al. (2020). Circular construction: Current state and future perspectives. Journal of Cleaner Production, 263, 121537.

Eberhardt, L. C. M., Birkved, M., & Birgisdottir, H. (2022). Building design and construction strategies for a circular economy. Architectural Engineering and Design Management, 18(2),

Fontaine, A. (2025). Stock-constrained design of pseudo-standard walls from studs off-cuts.

Gattas, J. M., Ottenhaus, L.-M., Liu, H., & Xie, Y. M. (2025). Design and optimisation of timber-framed structures using a stock of reclaimed elements. Automation in Construction, 180.

Grangeot, M., Wang, Q., Beyer, K., Fivet, C., & Parascho, S. (2024). Rising from rubble—Leveraging existing construction tools for upcycling concrete waste into slender walls.

Guy, B., & Ciarimboli, N. (2008). Design for Disassembly in the Built Environment: A Guide to Closed-Loop Design and Building.

Habraken, N. J. (1972). Supports: An Alternative to Mass Housing.

Kamari, A., Jensen, S. R., Petersen, S., & Kirkegaard, P. H. (2021). Sustainability key performance indicators' assessment and visualization aimed at architects in early renovation design processes. Nordic Journal of Architectural Research, 2, 41–80.

Kifokeris, D., Troje, T., Aulin, R., & Linderoth, H. (2025). Revitalising Building Production Through Regeneration: A Positional Paper. Proceedings of the 41st Annual ARCOM Conference.

Koch, C. (2025). Reviewing "Regenerative Building" contributions to learn from the past and set directions for the future. Proceedings of the Creative Construction Conference.

Kunic, A., Angeletti, D., Nabi, J., & Naboni, R. (2026). Stock- and Stress-Informed Design and Fabrication of Load-Bearing Systems from Reclaimed Timber. Structures.

Lauridsen, P. K. B., & Petersen, S. (2014). Integrating indoor climate, daylight and energy simulations in parametric models and performance-based design.

Mang, P., & Reed, B. (2012). Designing from place: A regenerative framework and methodology. Building Research & Information, 40(1), 23–38.

Miller, A. Z., et al. (2012). Bioreceptivity of building stones: A review. Science of The Total Environment, 426, 1–12.

Naboni, R., Kunic, A., Jensen, C., & Sander, S. (2024). Re-VoxLam Truss. Topology optimisation and reclaimed voxel lamination of horizontal wood structures.

Ortega-Calvo, J. J., Ariño, X., Hernandez-Marine, M., & Saiz-Jimenez, C. (1995). Factors affecting the weathering and colonization of monuments by phototrophic microorganisms. Science of The Total Environment, 167(1), 329–341.

Petersen, S. (2017). Combined Daylight and Thermal Calculation Tool for Annual Energy Performance Simulation of Rooms with Advanced Daylight-Controlled Lighting Systems.

Petersen, S., & Purup, P. B. (2019). Building Performance Simulation Supporting Typical Design Activities: The Case of 'Reference Pictures'.

Petersen, S., & Svendsen, S. (2008). Method for integrated design of low energy buildings with high quality indoor environment.

Petersen, S., & Svendsen, S. (2010). Method and simulation program for informed decisions in the early stages of building design. Energy and Buildings, 42(7), 1113–1119.

Petersen, S., Bøving, A., Nielsen, C., & Purup, P. B. (2018). Integration of Thermal Simulations in REVIT for Decision Support and National Building Code Compliance.

Petersen, S., Bryder, J., Levinsen, K., & Strunge, J. (2014). Method for integrating simulation-based support in the building design process.

Petersen, S., Danielsen, M. S. K., & Klavsen, P. (2021). Building performance simulation supporting typical design activities: The case of 'Organising 2D layout'.

Petersen, S., Momme, A. J., & Hviid, C. A. (2014). A simple tool to evaluate the effect of the urban canyon on daylight level and energy demand in the early stages of building design. Solar Energy, 108, 61–68.

Petersen, S., Mortensen, V. H., & Kiholm, E. (2022). Archetype EnergyPlus Models for Verifying the Thermal Performance of Danish Office Buildings.

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. Journal of Cleaner Production, 143, 710–718.

Purup, P. B., & Petersen, S. (2017). Rapid Simulation of Various Types of HVAC Systems in the Early Design Stage. Energy Procedia, 122, 469–474.

Purup, P. B., & Petersen, S. (2020a). Requirement analysis for building performance simulation tools conformed to fit design practice. Automation in Construction, 116, 103226.

Purup, P. B., & Petersen, S. (2020b). Research framework for development of building performance simulation tools for early design stages. Automation in Construction, 109, 102966.

Purup, P. B., & Petersen, S. (2020c). Building Performance Simulation Supporting Typical Design Activities: The Case of 'Volume Massing'.

Purup, P. B., & Petersen, S. (2021). Characteristic traits of visualizations for decision-making in the early stages of building design. Journal of Building Performance Simulation, 14, 403–419.

Reed, B. (2007). Shifting from "sustainability" to regeneration. Build. Res. & Inf. 35, 674-80.

Röck, M., et al. (2020). Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Applied Energy, 258, 114107.

Skevaki, E., Duong, E., Yang, H.-B., & Parascho, S. (2025). Truss from trash: A human–robot framework for adaptive timber assembly on the construction floor. Construct. Robot., 10(1), 2.

Soust-Verdaguer, B., Llatas, C., & García-Martínez, A. (2017). Critical review of BIM-based LCA methods to support the design process. Journal of Cleaner Production, 172, 2231–2245.

Sun, Q., Reisach, D., Langenberg, S., & Dillenburger, B. (2026). Computational Design Methods for geometry-driven upcycling of found objects in construction. Automation in Construction, 183, 106803.

Svilans, T., & Thomsen, M. (2024). Drawing a blank – design modelling composite timber elements. Architectural Intelligence, 3.

Tamke, M., Svilans, T., Huber, J. A. J., Wuyts, W., & Thomsen, M. (2025). Non-Destructive Assessment of Reclaimed Timber Elements Using CT Scanning: Methods and Computational Modelling Framework.

Thomsen, M., Nielsen, S. D., Svilans, T., Choo, E. P., & Tamke, M. (2025). Design for adaptation—Adopting adaption for timber construction at three scale.

Veeger, M., Nabbe, A., Jonkers, H., & Ottelé, M. (2023). Bioreceptive concrete: State of the art and potential benefits. Heron, 68, 47–76.

Veeger, M., Veenendaal, E. M., Limpens, J., Ottelé, M., & Jonkers, H. M. (2025). Moss species for bioreceptive concrete: A survey of epilithic urban moss communities and their dynamics. Ecological Engineering, 212, 107502.

Warmuth, J., Brütting, J., & Fivet, C. (2021). Computational tool for stock-constrained design of structures.

Yen, Y.-W., & Svilans, T. (2025). A Digital Framework for Robotic Processing of Reclaimed Timber. World Conference on Timber Engineering 2025, 3494–3503.

Zanetti, E., Witt, V., Fuentes Quijano, J., & Dörstelmann, M. (2025). Digital Upcycling: Transforming Waste Wood for Circular Construction through Digital Strategies.

Research field 3 – Low carbon and robust construction materials

1. Introduction, vision & mission

1.1. Introduction to the Research Field

Today's most widely used construction materials have vast environmental impacts, highlighting the need for sustainable alternatives. Balancing urgency and demand for sustainable materials is a massive challenge. The research strategy has two tracks. A short-term strategy (5 years) for significantly improving the environmental impact of known materials based on reuse and redesign without compromising performance. And, a long-term strategy (5-10 years) providing science-based tools to develop and document new low-carbon, resource-efficient, and robust materials.

1.2. Vision

We will accelerate the adoption of alternative, sustainable, and robust construction materials and components as a new normal through research, *i.e.*, from science-based development to implementation, to meet the urgency of documenting low-carbon construction materials for the building industry.

1.3. Mission

We will generate the fundamental knowledge required to understand, predict, and engineer the performance of sustainable construction materials through rigorous scientific inquiry at the intersection of experimental investigation and physics-based computational modeling. By anchoring every step of material development, *i.e.,* from microstructure to structural component, in validated models and stringent physical principles, we will equip the building industry with the science-based evidence needed to replace carbon-intensive materials with durable, safe, and resource-efficient alternatives that operate within planetary boundaries.

2. State of the field

Terminology in this document: **Reuse of components** is the direct incorporation with minimal reprocessing of structural elements from one building (to be demolished) to another (new or transformed). **Upgraded materials** cover materials of today but with significantly improved environmental footprint (lower CO_2 emissions, CO_2 sequestration, and use of recycled raw materials rather than natural ones), without compromising performance (mechanical and durability). **New materials** are those under development that are not on the market today and are intended to replace today's carbon-intensive materials (mainly concrete) in specific high-volume applications. **Alternative material** is a collective term for reused, upgraded, and new materials. **Components** are assemblies or subsystems at an intermediate scale between materials and structural systems, composed of one or more materials and configured to fulfil a defined structural function. Together, these alternative materials and their application at the component level are the foundation for the paradigm shift needed to support the CEBE vision: "A science-based circular, low-carbon and resilient built environment within planetary boundaries".

2.1. Global centers of excellence

The global centers of excellence are largely connected to the WP. Thus, they are dealt with separately.

WP3.1 New theoretical foundation linking key characteristics and properties

Research toward unified structure–property frameworks for cement-based materials is concentrated in several complementary groups, including the *MIT Concrete Sustainability Hub, the Concrete Microlab at Delft University of Technology, durability modelling groups at University College London, the quasibrittle mechanics school at Northwestern University, and the international collaboration Innovandi - Global Cement and Concrete Research Network*. These groups collectively aim to link material structure (from nanoscale hydrates and pore networks to mesoscale aggregate structures) to macroscopic mechanical performance and long-term durability. MIT focuses on nanomechanics and poromechanics to connect nanoscale C-S-H structure with macroscopic properties such as strength and creep. Delft's Concrete Microlab develops mesoscale lattice and discrete models to simulate cracking, healing, and transport-fracture interactions. Research at UCL emphasizes microstructure-informed transport modelling for durability and service-life prediction. Northwestern University provides theoretical foundations for quasibrittle fracture, creep, and scaling through size-effect and microplane models. Innovandi coordinates collaborative research to integrate chemistry, materials science, and structural performance. Despite these advances, no single framework yet fully predicts the robustness of alternative cementitious materials across all scales and deterioration mechanisms. Current models typically address subsets of the problem, i.e., mechanics, transport, or chemistry, rather than integrating them comprehensively.

Related to hygrothermal material characterization: KU Leuven, Belgium: Research on modelling pore networks and moisture; ETH Zürich: Multiscale modelling of porous materials and moisture; Copenhagen University and Lund University: Research on moisture in wood; University of Sherbrooke, Canada: Research on modelling moisture in wood

WP3.2 Reuse of materials

Research toward low-carbon construction material through the direct reuse of structural components, across concrete, steel and timber, is concentrated in several internationally recognized groups, including the *EPFL Strucural Xploration Lab, Tempere University's Faculty of Built Environment, the Steel Construction Institute in collaboration with the University of Cambridge, the Institute of Steel Construction at RWTH Aachen University, the Fraunhofer*

Institute for Nondestructive Testing IZFP, and RISE Research Institute of Sweden. These groups collectively seek to retain structural components at their highest value after the end of service life, avoiding the carbon cost of remelting or aggregate recycling in favor of direct structural reuse. The EPFL Structural Xploration Lab develops optimization methods for reassigning reclaimed members to new structural systems. Tampere University leads the ReCreate project, focusing on structural recertification of recovered precast concrete elements across four countries. RWTH Aachen's Institute of Steel Construction derives structural design provisions for steel reuse through the PROGRESS project. The Steel Construction Institute and University of Cambridge have established testing and certification procedures for reclaimed steelwork through SCI P427. Fraunhofer IZFP provides nondestructive methods for in-situ residual mechanical property characterisation, while RISE Sweden advances structural grading and design-for-disassembly frameworks for timber. Despite these efforts, no unified structural engineering framework yet covers assessment, recertification, and redesign across all three material types.

WP3.3 Upgraded materials. Alternative materials with secondary resources

The use of supplementary cementitious materials (SCMs) to replace part of the clinker in cement is the most successful strategy to reduce CO_2 emissions in the global cement industry, but traditional SCMs are byproducts from industries that are largely phased out or changed; thus, new SCMs must be identified. The group at EPFL, led by Karen Scrivener, holds a world-leading position in calcined clay as an SCM, and new calcined-clay-based cement types are on the market. EPFL thereby holds the view that the only material available in the quantities needed to meet SCM demand is calcined clay (Scrivener et al., 2018). In this WP, we maintain that local secondary resources of various types can be turned into SCMs. In the literature, knowledge of the recycling of a specific SCM can be very extensive, and some with very good results, but the generalization of this knowledge by linking alternative SCM characteristics to material properties is lacking.

At the subsystem and structural level, relevant centres of excellence include ETH Zürich – Block Research Group for geometry-driven and compression-dominated structural systems enabling materially efficient components and the use of low-carbon, lower-strength materials; TNO for circular construction, structural reuse, digitalization, and industrial implementation of secondary-resource-based systems; The present WP specifically addresses the currently missing integration between material upgrading, heterogeneous low-carbon materials, and subsystem-level structural design by combining material characterization, geometry-driven structural strategies, multiscale modelling, and performance-based validation within a unified framework

WP3.4 Development of new materials

Research in construction materials has historically relied on trial and error, a limitation acknowledged openly by leading scientists. A true paradigm shift is now underway at a small number of elite institutions. Researchers at MIT have built a multiscale science-based design framework anchored in nanogranular mechanics, statistical nanoindentation, and in situ Raman spectroscopy, relating macroscopic concrete performance to the atomic structure of calcium silicate hydrate. At EPFL, researchers ground LC3 development in quantitative microstructural analysis, hydration-kinetics modeling, and thermodynamic phase-simulation rather than empirical mix optimization. A collaborative effort between ETH Zürich, EPFL, and Rice University produced the cemff database, an open repository of atomistic force fields enabling molecular dynamics simulation of cement minerals before any physical experiment is performed, representing an example of bottom-up materials design in the field. Nevertheless, these science-based approaches remain concentrated in a handful of leading groups; the majority of global construction materials research still relies on large-scale empirical experimentation, underscoring the potential that remains to be unlocked through systematic, structure-property-guided design.

Relevant international centres of excellence further include Bundesanstalt für Materialforschung und -prüfung (BAM) for qualification, durability, and structural assessment of heterogeneous construction materials; MIT Concrete Sustainability Hub and Admir Masic for low-carbon cementitious materials, CO_2mineralization, and multiscale characterization of sustainable construction materials; Bertoldi Group at Harvard University for architected materials and geometry-controlled mechanical behaviour across scales. The present WP contributes through the integration of these material-scale and structural-scale aspects into unified subsystem-level design strategies for materially efficient and low-carbon structural components.

WP3.5 Implementation in the building industry

Global centres of excellence relevant to implementation, reliability, standardisation, risk-informed decision-making, and digitalisation of structural engineering include the Joint Committee on Structural Safety, which represents one of the leading international reference environments for structural reliability, probabilistic methods, and code-oriented safety frameworks. Strong academic centres include Norwegian University of Science and Technology (Prof. Jochen Köhler) with internationally recognised expertise in reliability-based assessment and sustainable structural engineering; Technical University of Munich (Prof. Daniel Straub) in probabilistic engineering mechanics, Bayesian updating, and infrastructure risk management; and Ghent University (Prof. Robby Caspeele) in reliability-based design, assessment methodologies, and standardisation. Additional internationally recognised environments include Trinity College Dublin (Prof. Alan O'Connor) in structural health monitoring and infrastructure assessment; Seoul National University (Prof. Junho Song) in computational stochastic mechanics and resilience; ETH Zürich (Prof. Bruno Sudret and Prof. Eleni Chatzi) in uncertainty quantification, digital twins, and AI-supported infrastructure monitoring; and University of Technology Sydney (Prof. Mark Stewart) in life-cycle reliability, durability, and risk-informed infrastructure management. These environments collectively represent leading international expertise in translating advanced reliability, monitoring, and digital methodologies into practical implementation frameworks for the building industry.

2.2. State of the art and DK position in the research field

WP3.1 Theoretical foundation

Structure-property relations in cement-based materials are addressed through several complementary frameworks, including: i) continuum micromechanics/homogenization (Eshelby, 1957), (Mori & Tanaka, 1973), which upscale phase properties, ii) poromechanics (Biot, 1941) (Coussy, 2004) linking pore structure to mechanical response, iii) hydration models predicting microstructure evolution (Bentz, 1997), iv) quasi-brittle fracture mechanics (Bazant, & Planas, 1998), which captures size-dependent failure, v) continuum damage mechanics (Mazars, 1985), which describes progressive degradation, and vi) reactive transport models that couple chemistry to durability (Samson & Marchard, 2007). Although unified approaches remain elusive (Mehta & Monteiro, 2014), poromicromechanics (Ulm & Coussy, 2003), probabilistic quasi-brittle frameworks (Bazant & Planas, 1998), and NIST's digital cement initiative (Bullard et al., 2009) represent systematic multiscale efforts, increasingly augmented by machine-learning surrogates (Ben Chaabene et al., 2020).

Hygrothermal material characterization is based on applying standardized experimental methods to determine properties as described in standards. However, there are several challenges: existing methods and standards are largely based on the expected behavior of traditional building materials such as bricks, mortar, and concrete. In addition, many methods rely on simplifying the pore structure and leave some parts of the pore scale undescribed (Islahuddin & Janssen, 2019; Shi et al., 2024). Also, moisture storage and transport in biobased materials are further complicated by sorption kinetics in plant cell walls, which are not yet fully described (Thybring et al., 2019; Kulasinski et al., 2015). A central challenge for these materials is to separate transport properties from storage properties and to describe them as functions of moisture saturation state. For rigid materials, the distribution of water in the pore system is critical with respect to the risk of frost damage(Islahuddin & Janssen, 2019). These hygrothermal processes are also directly linked to durability concerns such as fungal growth. Predicting and preventing fungal growth requires a detailed understanding of how materials respond to moisture, and of the critical combinations of moisture content and temperature that enable microbial activity. For biobased and hybrid materials, significant knowledge gaps remain regarding the interactions among organic composition, moisture-binding capacity, and the presence of embedded fungal microbiomes. In the search to address these knowledge gaps, multiscale numerical models have been developed to describe the hygric properties of porous building materials (Isalahuddin & Janssen, 2019; Shi et al., 2024). Some recent efforts have focused on using pore networks in parametric studies (Shi et al., 2024). Other approaches can be found in other science domains, such as wood and soil science, where, for example, gas adsorption methods have been used to separate moisture transfer properties in soil (Thai et al., 2024).

Benchmark WP3.1: Establishing the framework necessary in this RF requires integrated expertise in cement chemistry and thermodynamics, microstructure characterization, multiscale mechanics, fracture and damage modelling, and reactive transport modelling. The *Section for Construction*

Materials and Durability at DTU Sustain has the (leading) expertise in corresponding modelling tools that combine hydration and thermodynamic simulations (Sharmilian et al 2022), digital microstructure reconstruction (Bin Jamal et al 2025), multiscale finite-element homogenization (Bin Jamal et al., 2026), mesoscale fracture models (Bin Jamal et al., 2026), and multiphysics reactive-transport simulations (Sharmilian et al. 2024). The principal challenge is not the absence of theory, but the integration and validation of these models into a coherent predictive platform for engineering new cement-based materials. Complementary to this, the *Section for Structures, Geotechnics and Risk at AAU BUILD* contributes expertise in digital twin frameworks (*e.g.*, Bas et. al. 2024) for integrating multiscale modelling and experimental data, enabling continuous calibration, validation, and predictive assessment of material mechanical behaviour across scales. In addition, the Building Physics Research Group and Fungi and Problematic Substances Research Group at AAU BUILD contribute expertise in hygrothermal performance, moisture-material interactions, and the mechanisms governing microbial growth and material degradation.

WP3.2 Reuse of Materials

Structural material reuse is one of the key strategies for reducing the environmental impact of the built environment by retaining embodied energy and preserving the material value. It involves the direct reuse of elements, such as concrete components, steel members, reclaimed timber, and masonry units, with minimal processing, offering significant potential to reduce greenhouse gas emissions and resource consumption. A central challenge in structural reuse is the reliable verification of material performance. Unlike new materials, reused components often lack sufficient documentation of their mechanical properties and exposure history, complicating compliance with existing standards and building regulations.

Despite its potential, the number of realized reuse cases remains limited. Küpfer et al. (2023) identified 77 cases worldwide, with most of the applications involving downcycling rather than equivalent reuse in load-bearing systems. This highlights a significant gap between the theoretical potential and practical implementation. There are recent large-scale demonstration cases, e.g., the ReCreate pilot projects that integrate material inventory, testing, and permitting processes for the reuse of structural elements such as hollow-core slabs. Among these, steel reuse is the most developed due to its predictable, homogeneous material properties. In contrast, concrete reuse remains more challenging, although advances are being made through performance-based durability approaches (*e.g.*, Dervishaj et al. 2026) and the use of NDT for reusability assessment (Ottosen et al., 2024). At the subsystem level, reused concrete floor systems have been validated at full scale, demonstrating substantial upfront emission reductions of approximately 80–94%. For timber and masonry, key challenges lie in grading and condition assessment (Bergsagel & Heisel 2023; Pasca et al. 2025; Räsänen et al. 2022), as existing standards are not adapted to reused materials. Overall, the field is transitioning from experimental research toward standardized and scalable implementation; however, the knowledge base remains fragmented and insufficiently integrated into design standards and building codes, limiting its practical application. Regarding the reuse of reinforced concrete elements in high-exposure classes, new developments are needed to predict the time to corrosion. Specifically, the initial states of the chloride and carbonation fronts in the concrete cover (the state after the previous use) need to be determined, and the penetration rate in the new placement (under new boundary conditions) needs to be modeled to predict the time to corrosion. This entails both new testing methods and extended models.

The WP3.2 under RF3 and RF7 are complementary, rather than overlapping. RF7 focuses on extending the life of existing structures through condition assessment, lifespan prediction, and renovation, whereas RF3 focuses on what happens to the components at the end of their service. Most of the work is focuses on recovering and recertifying components for reuse in new structures. The two RFs share methods, particularly around condition assessment and structural integrity verification, and together cover the full lifecycle chain from renovation to component recovery and reuse. The decision-making processes developed by both RFs can be shared as a knowledge exchange. As an example, if a structure is deemed unviable for continued use or renovation, its components may still be suitable for reuse in other contexts. Embedding component reuse as the default next step in the assessment framework would strengthen the overall circular strategy and ensure that material value is retained at the highest possible level, even when structural life extension is not feasible.

Benchmark WP3.2: The research aims to bridge the gap between experimental and data-driven advances and their practical deployment by developing decision-ready protocols for the reuse of materials and components: testing sequences, uncertainty reporting, acceptance criteria, traceability, and integration with assessment standards for existing structures. The section for *Structures, Geotechnics and Risk* at AAU BUILD has internationally recognized expertise in structural reliability, risk, and uncertainty quantification as well as in the assessment of existing structures (*e.g.*, Nielsen et. al. 2025). The section also has strong competencies in testing both conventional and hybrid testing configurations and in integrating physics-based and data-driven modeling approaches (*e.g.*, Bas et.al. 2024). This enables advanced evaluation of structural performance under realistic and complex loading scenarios. Current research at AAU BUILD (*e.g.*, Wood Vita Project) also focuses on the regrading and structural assessment of reclaimed materials, particularly timber, concrete, and FRP. Emphasis is placed on innovative AI-assisted grading and non-destructive evaluation, as well as full-scale testing, proof loading, and reliability-based assessment of existing structures, supporting capacity verification and decision-ready reuse of load-bearing components. The *Section for Construction Materials and Durability at DTU Sustain*, to the best of our knowledge, was the first to propose non-destructive testing methods for the reusability assessment of structural components (Ottosen et al. 2024) and has maintained a strong international position on this topic for both structural concrete and timber. So far, the work on concrete reuse has focused on exposure classes X0 and X01.

WP3.3. Upgraded materials. Alternative materials with secondary resources

Upgraded materials with lower CO_2 emissions than traditional materials, obtained by utilizing recycled secondary resources, often exhibit properties that are inherently less controllable than those of conventional materials, such as residual fractions from other industries (Ram et al., 2023). Other prominent research fields include concrete materials without Portland cement, *e.g.*, alkali-activated materials (Provis, 2018) and magnesia-based cement (Bernard et al., 2023). Upgraded materials can be natural, man-made (biobased or mineral, based on primary or recycled secondary raw materials), or combinations. Today's research efforts are fragmented, often focused on specific raw materials, and grounded in experience and experimentation rather than rigorous physical principles.

In the relatively short term, upgraded concrete recipes with alternative SCMs are the most realistic way to achieve significantly lower CO_2 emissions. International research efforts are massive to partially replace cement with less carbon-intensive materials (SCMs), and relatively recently, LC3 cement types have entered the market, underlining that possibility. However, LC3 cements are still produced from natural resources with significant energy use, and there is a significant underutilized option for upgrading various particulate waste materials into SCM. Many encouraging results have been reported in the literature using specific secondary resources, but generalization of the findings to broader ranges of characteristics is lacking. Today, research on the use of secondary resources as SCMs has a branch focused on improving their characteristics. For example, increasing reactivity through thermochemical treatment (Doschek-Held et al., 2024) or removing salts by washing (Sigvardsen et al., 2021). At DTU Sustain, we will build on our expertise in different methods: electrochemical upgrading for heavy-metal removal, carbonation/carbon sequestration, and phase development to optimize the chemical composition. The use of waste-derived inputs will include stringent quality control measures. We will evaluate potential hazards (e.g., leaching of harmful elements) through an in-depth understanding of binding mechanisms and ensure compliance with material safety standards.

Materials obtained from the reuse of secondary resources, including systems incorporating supplementary cementitious materials (SCMs), may exhibit complex microstructures (*e.g.*, increased porosity and heterogeneity), which directly influence mechanical performance and fracture behavior, leading to reduced and variable strength and durability compared with conventional materials. One promising strategy is to couple such materials with geometry-driven structural design (Block & Ochsendorf 2007), where structural form compensates for material limitations. In parallel, advances in architected materials demonstrate that geometry across multiple scales can control strength, stiffness, and buckling behavior (Fernandes et al. 2021). Within this WP, a multiscale design approach is coupled with digital twin frameworks integrating experimental data and models across scales to enable compliance with structural performance and safety requirements.

Within this WP, fundamental paradigms for the design of low-carbon structural components will first be developed and validated using conventional construction materials and subsequently transferred to alternative materials and systems incorporating secondary resources. Particular emphasis will be placed on geometry-resistant and force-flow-efficient structural forms, such as vaults and other compression-dominated systems, enabling reduced material consumption while maintaining structural performance. The resulting component- and subsystem-level design strategies will constitute a general framework for low-carbon structural systems and will be shared and further developed in interaction with WP3.4.

The developed paradigms will then be extended to materials characterized by lower, heterogeneous, or less predictable mechanical properties, where geometry and subsystem-level design are used to compensate for material limitations. Within this WP, a multiscale design approach is coupled with digital twin frameworks integrating experimental data and models across scales to enable compliance with structural performance and safety requirements.

Systems incorporating fiber-reinforced polymers (FRPs) from decommissioned wind turbine blades are affected by variability in original production processes and unknown service history, which can result in reduced and variable strength and durability that cannot always be fully characterized in advance (Joustra et al 2021). In response, initiatives such as the EU-funded *BLADES2BUILD* project focus on scalable solutions for the recycling and repurposing of end-of-life wind turbine blade composites into construction materials (Liu et al., 2026). Within this WP, we will develop a multiscale design approach for integrating secondary resources at the highest functional value, prioritizing minimal reprocessing and allowing progressively more intensive processing where necessary to meet performance requirements. The research will prioritize minimal reprocessing strategies, before material reprocessing, preserving as much as possible of the original material strength. This is achieved by linking material characteristics to structural performance through geometry- and subsystem-level design, supported by digital twin frameworks that integrate experimental data and models across scales for continuous calibration and validation.

Benchmark WP3.3:

The *Section for Structures, Geotechnics and Risk* at AAU BUILD contributes expertise in performance-driven design, multiscale modelling, and experimental validation. This includes computational morphologies for material-efficient structural systems and hybrid testing approaches that link material behaviour, structural form, and structural performance. The section further develops digital twin frameworks enhanced by machine learning techniques, enabling the integration of experimental data and multiscale models for continuous calibration, predictive assessment, and performance monitoring across scales. *The Section for Construction Materials and Durability at DTU Sustain* has strong expertise in upgrading (Kappel et al. 2018), testing, and modeling new types of secondary fine-particulate materials into SCMs, as well as for replacing clay in brick manufacturing (Feldthus et al., 2025), and is developing new methods for upgrading and characterization of novel low-carbon construction materials. The section coordinates the large European project Home - BLADES2BUILD and participates in the European project AshCycle project, which are both projects with a focus on alternative SCMs.

WP3.4. Development of new materials

The decarbonization of the built environment requires a fundamental transition from carbon-intensive precursors to biologically and/or chemically optimized, resource-efficient alternatives.

At present, the most mature response lies in reformulating cementitious binders, such as Limestone Calcined Clay Cement (LC3) that reduces emissions by 30-40% over ordinary Portland cement using widely available raw materials, or geopolymers and alkali-activated materials (synthesized from industrial by-products such as fly ash and slag) delivering reductions of up to 43% (Kriven et al., 2024; Ghazy et al., 2025). Building on this foundation, CO_2 mineralization has emerged as a powerful complementary strategy, sequestering carbon within the concrete matrix while simultaneously improving mechanical strength (Bernard et al., 2024). Most recently, the research has also focused on beyond mitigation toward actively carbon-negative materials. Fungal mycelium composites convert agricultural waste into thermally functional building elements, while enzymatic structural materials deploy biological enzymes to directly mineralize atmospheric CO_2 into load-bearing solids, inverting the carbon balance of construction materials entirely (Wang et al., 2026; Motamedi et al., 2025). Together, these advances outline clear advances from incremental emissions reductions toward carbon-neutral, or even carbon-negative, built environments.

At the subsystem level, we will focus on developing low-carbon structural components through reduced material use and the integration of low-carbon materials. Central to this approach is geometry-driven structural design, where structural efficiency is achieved through form rather than material intensity (Block & Ochsendorf, 2007). In parallel, advances in architected materials demonstrate that geometry across multiple scales can be used to control strength, stiffness, and buckling behaviour (Fernandes et al., 2021).

In close interaction with WP3.3, WP3.4 will contribute to the development of shared paradigms and fundamental design strategies for materially efficient structural components, combining geometry-driven design, subsystem-level optimization, and multiscale structural approaches.

Benchmark WP3.4: To further push these frontiers, a convergence of expertise and instrumentation that extends well beyond classical civil engineering is demanded. On the experimental side, researchers require proficiency in advanced microstructural characterization to quantitatively resolve phase assemblage, reaction kinetics, and nanoscale structural evolution, while, on the computational side, tools to predict structure-property relationships (as envisioned in WP3.1) before physical synthesis are required. Crucially, none of these tools operates in isolation: the most impactful contributions arise from genuinely interdisciplinary teams combining materials science (Liu et al., 2026), chemistry (Bertelsen et al., 2025), mechanics (Bin Jamal, 2025), and environmental life cycle assessment (Muhit et al., 2025), a profile that defines the Section for Construction Materials and Durability at DTU Sustain. In addition, the section has expertise in developing new materials, including microscale material design and the production of a new type of concrete with biobased binders via 3D printing (Christ et al., 2024).

The development of structurally optimized components tailored to low-carbon materials remains limited, with current practice largely relying on conventional structural typologies. The proposed work addresses this gap by advancing geometry-driven component design, enabling efficient load-bearing systems that compensate for reduced or variable material performance and providing a basis for integration into design and standardization frameworks. At AAU, the Section for Structures, Geotechnics and Risk, focuses on the optimization of structural components across macro- and mesoscales, including ongoing research on high-performance, lightweight components for the wind energy sector. This builds on prior work in computational morphogenesis for material-efficient structures and construction, positioning AAU with emerging capabilities in geometry-driven design and multiscale structural optimization, directly supporting the development of next-generation low-carbon structural components.

WP3.5. Implementation in the building industry

The Danish Building regulations (BR18) refer to the Eurocodes for design and execution of structures using traditional materials (concrete, steel, timber, masonry, aluminium). The process of making a Eurocode on glass structures, fiber-polymer composites, and tensioned membrane structures has been initiated. For other materials and structures not covered by the Eurocodes, BR18 states that the reliability level shall be verified to be sufficient. In EN 1990 Annex D, methods are given for design assisted by testing, but it was developed for traditional materials with well-established behaviour, conversion factors, and safety factors. For new materials, there may be complexities such as nonlinear behaviour, time-dependent effects, anisotropy, brittle behaviour, and moisture- and temperature-dependent variability, for which reliable models do not yet exist. The time-dependent effects are especially critical, since the need for long-term testing prevents the rapid introduction of new materials.

Despite its promising environmental and architectural potential, reusing concrete is rarely mentioned in concrete decarbonisation plans, as the knowledge about construction projects that reused concrete components has been very scattered for a long time (Küpfer et al. 2025).

Benchmark WP3.5: To ease the introduction of new construction materials, a consistent reliability framework for these materials is needed. The research group on *Risk, Resilience, Safety, and Sustainability of Systems* at AAU BUILD is an internationally recognized research group with a strong track record within standardization (Eurocodes & IEC) and pre-normative work within the *Joint Committee on Structural Safety.* In *the Section for Materials and Durability at DTU,* the cutting-edge project (Structural Reuse) on documentation of concrete and structural timber for reuse was finalized in 2005. The strong interaction with frontrunners in the Danish construction industry will be utilized in an interactive constellation, where the scientific knowledge gaps encountered when incorporating reuse in practice will be addressed to continuously remove the barriers to reuse to the highest level. Simultaneously, we will maintain a high level of dissemination to stakeholders through open events (hands-on workshops, courses, webinars, etc.). When redesigned and new materials are ready for implementation during the project, we will build on the experience of industrial collaboration and implementation from the reuse to overcome the difficult task of implementing alternative construction materials compared to those covered by Eurocodes today.

3. How will the research field address the core challenges?

The research lies at the nexus between basic research (WP3.1) and implementation (WP3.5). While all five WPs will be active for 10 years, the individual weight will change in response to short- and long-term strategies.

New theoretical framework linking key characteristics and properties (WP3.1)

We will develop a central model that links the parameters of constitutive material models to physical and chemical properties across scales, establishing correlations using statistical and AI methods. The new theoretical frame will be developed and calibrated using known materials.

Prediction of the behavior of construction materials by unraveling the microstructural origin of macroscopic behavior can lead to a paradigm shift from current practice based on experience to a science-based practice. We will support the selection of construction materials for specific cases, which is open and starts with the needed properties rather than business as usual.

The new fundamental base will be co-developed with new test methodologies. The principles and tests will support the development of robust and documented alternative materials in WPs 3.2-3.4.

Reuse of materials (WP3.2)

Non-destructive testing of materials and components for reuse for documenting properties in environmental classes beyond X0 is a novel approach. The goal is to establish reliable assessment criteria and procedures for material acceptance to maximize reuse potential, address the major question of how deterioration continues when a component is moved to another environmental class, and develop new models to evaluate this.

Redesigned materials with secondary resources (WP3.3)

The project primarily addresses the Regenerative Construction Materials and Circular Practices challenges identified in the CEBE initiative by developing materials and components with secondary resources. The research links material characterization, structural modelling, and experimental validation to establish design methods that allow alternative materials to be safely used in load-bearing applications.

Improving the environmental impact of known materials without compromising performance is of utmost importance. The use of secondary resources (biological or mineral) is one important direction of the research, and a strong focus will be on durability, structural performance, and potential toxic compounds when using alternative SCMs and FRPs. We will build a model and a test methodology that is generally applicable.

Development of new materials (WP3.4)

Develop and document new low-carbon, resource-efficient, and robust construction materials and components based on the science and framework from WP3.1. Knowledge from WP3.2 and WP3.3 will support the development of new materials for future circular use, including multiple life thinking.

The materials will be targeted towards their environmental conditions. Statistical tools, stochastic modelling, and AI will be used to extract generic knowledge, and this systematic and fundamental approach will subsequently be employed as a design basis for construction materials.

The documented material parameters relate both to the final material in the specific use case and to those important for industrializing production (to be used in WP3.5).

At the subsystem level, the work focuses on lightweight structural systems in which structural form compensates for material limitations, establishing design principles for material-efficient load-bearing solutions and optimizing performance under stability and serviceability constraints, while extending to meso-scale control of material distribution and internal structuring to enhance overall structural efficiency.

Implementation in the building industry (WP3.5)

Bridging the gaps between research and industrial adoption is in focus. Establishing a reliability framework for introducing new and alternative materials is key. Methodologies for documenting the properties of new materials are implemented through guidelines and standards as developments occur, so they enter into force as soon as possible. Industrialization is crucial for accelerating and scaling, and transition theory is used to frame the sectoral innovation and industrialization processes. A new decision-making framework will be developed to support absolute sustainable pathways for construction materials value chains. To accelerate the adoption of alternative materials in industry, methods for industrializing production are being developed. The use of monitoring for the through-life management of structures made from new materials will be included. ¨

3.1. Global Perspectives

Addressing the global dimension of low-carbon and reused construction materials and components requires explicit attention to scalability beyond European regulatory and industrial contexts. In the regions where the construction demand is highest, is where the regulatory frameworks are least developed and the pressure to build affordability at scale is most acute. A global adaptation evaluation process will be developed to assess which findings and solutions from RF3 can be directly transferred and which require contextual adaptation. This will allow solutions to be calibrated to different national contexts rather than defaulting the requirements to European standards as a global baseline. RF3 works on science-based fundamentals of material and component development strategies that are expected to be transferable across different geographical and regulatory contexts. International case studies and pilot applications will be sought in collaboration with partners outside Europe building on existing connections including Istanbul Technical University in steel and timber structures, Prof. Mohamed Moustafa at NYU Abu

Dhabi in experimental structural testing and hybrid simulation, and the National Research and Innovation Agency of Indonesia (BRIN) in structural health monitoring and AI-based condition assessment. This will generate the evidence on performance under different loading and environmental conditions, supply chain structures, and construction practices. Knowledge transfer activities will support capacity building in regions where the infrastructure needed to adopt alternative materials is still emerging, including simplified testing protocols and decision-support tools that function without the full institutional apparatus of European standardization, lowering the barrier to adoption in low- and middle-income country contexts.

4. Impact framework

4.1. Intended impact

Adaptation in the industry of reused, redesigned, and new materials with documented technical properties and much-improved sustainability indicators.

4.2. Contextual conditions

Society and industry readiness to receive and implement:

Policymakers are strongly focused on the green transition of the construction sector in Europe. In the Western world, the use of structural materials is highly regulated. On the one hand, there is demand for alternative materials with properties similar to traditional ones, but current methods cannot document their safety, and thus, they will be deselected. In low-income countries, there is a strong need to build extensively to provide good homes for all, and thus the need for technically sound, affordable alternative materials.

Key barriers and/or opportunities:

A key barrier in the EU is the experience-based sector; for example, standards and guidelines exclude other structural materials than the traditional ones. A key barrier is also the strong focus on costs. The sector today is largely optimized against price, and alternative materials are often more expensive as they have not undergone this development. The lack of a fundamental framework hinders the science-based development and testing of alternative materials, as well as their documentation, creating a global technical barrier. Competing on costs will be challenging, especially in the first implementations, but a key opportunity is to leverage society's demand for alternative materials as a push.

To address these barriers, this RF will develop a scientific foundation with the technical background needed for alternative and reused materials to enter standardization processes. In addition to developing low-carbon materials, RF3 will actively engage with national and European standardization bodies. RF3 aims to provide research-based input for revising standards and guidelines that currently exclude non-traditional structural materials. This includes developing performance-based assessment methods as alternatives to existing prescriptive, experience-based code requirements. We will establish demonstration cases that document the technical safety and cost trajectories of alternative and reused materials at a scale, building the evidence base needed to reduce perceived risk among regulators and industry. Early-stage cost barriers are best addressed not by competing on price directly on current market conditions, but by demonstrating reliability and long-term value. Low carbon materials and solutions might become competitive as resource scarcity, environmental constraints, intensify under future market conditions.

Lastly, we plan to develop decision-support tools that bridge the gap between research and practice, equipping policymakers and industry with the evidence and guidance needed to accelerate the uptake of alternative and reused materials within and beyond existing regulatory boundaries.

4.3. CEBE impact levers

The key is to convince the industry that alternative materials can be used with the same level of safety as traditional materials. The arguments must be based on scientific evidence at all levels.

RF3 will facilitate stakeholder and user engagement related to the general acceptance of alternative materials, test guidelines, and inputs to standards, evidence for informed decisions, feasible business cases, and changing legislation to support the production and adaptation of alternative materials. Rather than involving stakeholders only at the implementation stage, RF3 aims to establish co-creation processes in which industry, authorities, and end users actively contribute to shaping research directions, pilot projects, case studies, demonstration components, and future development needs.

The target groups are the construction sector at large, specifically legislators, actors in the "tekniske fælleseje", GTS institutes and consulting engineering companies, architects, construction clients, developers, and material producers. We will use the Danish stakeholders and industry as a pilot step towards international adaptation. Targeted seminars/workshops and dissemination activities will be promoted.

To foster change in the selection and use of alternative materials, we will seek strong, committed collaboration through applied projects with a theoretical foundation in CEBE developments, and we will engage in continuous outreach to the sector. Examples include co-developed demonstrators (e.g. with Acceleratorfonden, the Sustainable Building Strategy Network aiming to accelerate the testing and use of new materials (Hjem - Acceleratorfond)), dissemination through industry seminars and professional networks, contributions to technical guidelines and standardization activities, and direct involvement of stakeholders in testing and validation campaigns.

4.4. Intended outcomes and main beneficiaries

To adapt the reused, redesigned, and new materials in the industry, the most important first step is to include them in the regulations. This enables all stakeholders to select and use these materials.

The second step is to make the choice attractive, and here, all other stakeholders must be engaged to foster openness and curiosity about producing and testing them. Collaboration and common developments between the supply and demand sides for alternative materials are needed.

The intended outcomes of the RF3 are reported in the following table and grouped with respect to the stakeholder group.

Stakeholder group	Stakeholders	Primary WPs	Interaction with RF3 Outcomes
Producers	Material producer, component producer	WP1, WP3, WP4, WP5	Adopt new material formulations, secondary resource upgrades, documentation and testing methods, and industrialization methods for scaling and market entry
Designers	Strucutral engineers, Architects	WP1, WP2, WP5	Apply structure–property framework, durability prediction and service life modeling, performance-based design for reclaimed inventories, and decision-support tools for new and alternative materials
Contractors	Contractors	WP2, WP3, WP5	Assemble new and reclaimed structural elements using practical guidelines; embed design-for-disassembly in new construction; apply industrialization methods for alternative materials and components
End-of-life actors	Demolition companies, deconstruction contractors, condition assessment consultants, testing & recertification bodies, material brokers	WP2, WP5	Operate the reuse chain from assessment and dismantling through recertification and component matching
Clients	Building owners	WP2, WP5	Drive demand for circular buildings; enable design-for-disassembly through procurement decisions
Enablers	Standardisation bodies, policymakers	All WPs	Revise codes and develop harmonized standards; create regulatory conditions for RF3 outcomes to enter practice

4.5. Research outputs

RF3 will produce and deliver a (I) theoretical, multiscale framework (from nano to component level) as base for the development of alternative materials and components, (II) methods and guideline tools for testing and documentation as direct input to regulation, (III) predictive models and accelerated tests for durability assessment to support long-term safety in use, (IV) PoC to documentation of alternative materials and options for upscaling by developers and producers (V) decision-making framework to support absolute sustainable pathways for the construction material´s value chains.

Priority in the early phase of RF3 will be given to reuse-related solutions, low-carbon materials that incrementally improve existing construction material, and design strategies for materially efficient structural components. These focus areas offer both high short-term implementation potential and strong scalability across different material streams and construction contexts.

The outputs of RF3 are expected to be adopted by material producers, component manufacturers, engineering consultancies, contractors, developers, certification bodies, and regulatory authorities. The adoption will be facilitated by dissemination and co-creation activities.

RF3 output	Primary stakeholder adopters	Specific use of the output	Role of co-creation
I. Multiscale theoretical framework	Material producers, component manufacturers, engineering consultancies, research and testing organisations	Use structure–property relationships and constitutive models to formulate materials, optimise components, define performance requirements, and support numerical design models	Producers and engineers provide material systems, design requirements, manufacturing constraints, and validation cases during framework development
II. Testing and documentation methods	Condition-assessment consultants, testing and recertification bodies, demolition and deconstruction contractors, material producers, standardisation bodies	Apply sampling, NDT, grading, documentation, and recertification protocols to demonstrate whether reclaimed, secondary-resource, or novel materials are suitable for structural use	Assessment companies, certification bodies, and end-of-life actors help develop and validate specific protocols through pilot and full-scale cases
III. Durability models and accelerated tests	Material and component producers, testing laboratories, engineering consultancies, certification bodies, building owners, standardisation bodies	Predict service life, define exposure-dependent acceptance criteria, compare material alternatives, support maintenance planning, and provide evidence for	Producers, laboratories, and asset owners define relevant exposure conditions, failure mechanisms, test durations, and acceptance criteria

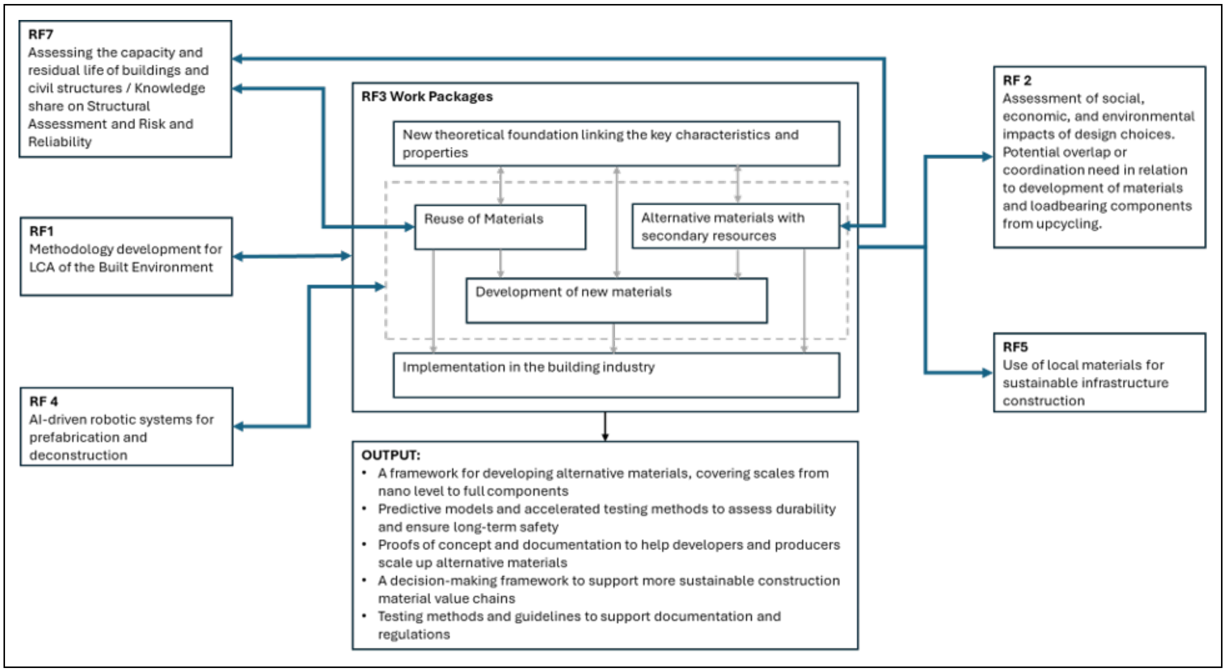
		certification and standards	
IV. Proofs of concept and upscaling documentation	Material producers, component manufacturers, contractors, developers, architects, structural engineers, certification bodies	Assess technical feasibility, manufacturability, structural performance, constructability, certification needs, and the business case for scaling specific materials and components	Co-creation is organised around individual demonstrators, with selected producers, designers, contractors, and certification bodies contributing to design, manufacture, testing, and implementation
V. xDecision-making framework for sustainable material pathways	Developers, clients, building owners, architects, structural engineers, contractors, policymakers, material platforms	Compare reuse, recycling, secondary-resource, and new-material pathways using environmental performance, technical feasibility, reliability, availability, cost, and scalability	Clients, value-chain actors, and authorities define decision criteria, constraints, weighting, and representative implementation scenarios

4.6. Research activities

The research activities in RF3 will focus on experimenting, compiling, interpreting, and integrating science, experience, and data to achieve a groundbreaking leap in fundamental knowledge by linking material characteristics (over size scales from nano to component) and the properties of construction materials. Physical experimentation and modeling are used at all stages. The research involves collaboration with other disciplines to support creativity and new thinking, as well as the building of fundamental knowledge.

RF3 has direct interfaces with four other CEBE RFs. RF3 and RF7 are complementary through their shared focus on reliability and risk assessment while maintaining distinct scientific objectives. RF7's structural condition assessment methodologies and residual capacity estimation provide an important input for the reuse-oriented frameworks in WP2 and WP3, and where lifetime extension is not possible, the structure becomes a donor for component reuse. The two fields envision coordinated activities in reliability and risk methodologies, joint contributions to standardization and Eurocode-related activities, and periodic knowledge exchange on reuse, durability, and lifetime extension. RF1 connects through a mutual exchange where LCA methodology underpins the environmental documentation across all RF3 work packages, while RF3's material characterization data and proof-of-concept outcomes enrich and refine RF1's LCA frameworks. RF4 contributes AI-driven robotic systems that enable the material and component development work across WP2, WP3, and WP4, while RF3 specifies the technical requirements that guide the development of these systems. The performance evidence, characterization frameworks, and documentation developed within RF3 serve as scientific input to RF2's evaluation of the social, economic, and environmental consequences of design choices, and to RF5's development of locally sourced materials for sustainable infrastructure.

Illustration of RF3 interactions with other RFs



4.7. Research Field specific output, outcome and impact targets

Science-based development, engineering, and implementation of durable and safe construction materials - reused, redesigned, and new types - grounded in stringent, fundamental principles while respecting planetary boundaries.

For the research field, we have defined the following targets, the realization of which will be evaluated over the course of the programme.

Targets of the research field (collaborations between AAU and DTU, with lead responsible university marked in the table)

Target name & description	Evaluation method	Impact Type	Category	Years
Position paper on low-carbon and robust construction materials with a Global perspective	Publication	Output	Other	2
Pilot and full-scale tests of reusability assessment of concrete components based on NDT	Publication	Output	New method / New concept	3

Demonstration of data-driven strength grading of timber	Demonstration	Outcome	Demonstrated in practice	4
New method for reactivation of cement from demolished concrete aiming at saving natural resources in for production of cement	Publication	Output	New method	3
Evaluation and tool for the immobilization level of inorganic hazardous compounds from secondary resources in construction materials	Publication	Output	New method	3
Database and data-driven models as a base for continuously refining non-destructive experimental protocols for reused elements	Experimental validation	Output	New method, concept/approach	5
Test methodology for durability designed by combining traditional and advanced experimental methods	Test methodology	Output	New methods	4
First validation of central, generic constitutive material model	Publication	Output	Other	6
Fundamental principles for material efficient low-carbon structural components	Modelling and experimental validation	Output	New method	3
Framework for sampling and testing of components of concrete and wood for reuse	Case study documentation	Output	New method	4
Testing protocols and physical validation for low-carbon structural components	Physical validation	Output	New method	4
Performance-based design framework combining 2-3 secondary resources into	Publication	Output	New concept	5

alternative materials and composites				
Mapping of interdisciplinary fields for inspiration to control properties through material structures at different scales	Publication	Output	New concept	2
First attempts to develop and design properties of materials based on the fundamentals and feed back to WP1	Publication	Output	New technology	6
Accelerated tests methodologies for durability in different environments – material independent	Publication	Output	New methods	6
New construction material with dual use. MOF based composite material	Publication, prototype material produced	Output	New material	8
New construction material produced based on biotechnology for aggregate production or binder	Publication	Output	New material	10
Use cases for AI of constitutive model parameters are defined for the digital twin framework	Survey	Output	New concept/approach	3
Development of a methodology to integrate composites into alternative materials and components	Stakeholder feedback	Impact	Change in perception	3
Modeling of decision scenarios based on Bayesian statistical decision theory using AI optimization approaches	Publication	Output	New method	6
Framework for the reliability of novel materials	Publication	Output	New method	4

General methodology for matching material with relevant technologies for standardization, modularization, mechanization, automation, and digitalization	Publication	Output	New method	10
Proof-of-concept structural components (beams, slabs, panels) with verified mechanical performance.	Full-scale/component testing; model validation	Outcome	Demonstrated in practice with the involvement of GTS institutes, recycling companies and consulting engineers	5

5. References

Bas, E.E., Moustafa M.A. (2020). Performance and limitations of real-time hybrid simulation with nonlinear computational substructures. Experimental Techniques, 715-734. https://doi.org/10.1007/s40799-020-00385-6

Bas, E.E., Abbiati G.A., Gomes C., Jassmann U., Larsen P.G. (2024). Digitalization of Large-Scale Testing Facilities for the Wind Industry: DIGIT-BENCH Digital Twin. J. Phys.: Conf. Ser. 2767 042033, 10.1088/1742-6596/2767/4/042033

Bazant, Z. P., & Planas, J. (1998). Fracture and size effect in concrete and other quasibrittle materials (pp. 616 s.). CRC Press,

Ben Chaabene, W., Flah, M., & Nehdi, M. L. (2020). Machine learning prediction of mechanical properties of concrete: Critical review. Construction and Building Materials, 260, 119889. https://doi.org/10.1016/j.conbuildmat.2020.119889

Bentz, D. P. (1997). Three-dimensional computer simulation of portland cement hydration and microstructure development. Journal of the American Ceramic Society, 80(1), 3–21. https://doi.org/10.1111/j.1151-2916.1997.tb02785.x

Bernard, E., Patrizio, P., Fennell, P.S., Scrivener, K. & Myers, R.J. (2024). Global decarbonization potential of CO_2 mineralization in concrete materials. Proceedings of the National Academy of Sciences, 121(29), e2313475121. https://doi.org/10.1073/pnas.2313475121

Bertelsen, I. M. G., Ottosen, L. M., Pedersen, M. T., De Weerdt, K., & Kunther, W. (2025). Relevance of the mineralogy of recycled clay brick powder as SCM for cementitious binder applications. Journal of Building Engineering, 111, Article 113580. https://doi.org/10.1016/j.jobe.2025.113580

Bin Jamal M, N., Kuang, C., & Michel, A. (2025). Microstructure-informed modelling of cement mortar using XCT imaging and phase segmentation. Construction and Building Materials, 477, Article 141342. https://doi.org/10.1016/j.conbuildmat.2025.141342

Bin Jamal, M.N. & Michel, A. (2025). A micromechanical approach to 3D damage modeling in structural steel based on unified mechanics theory. International Journal for Computational Methods in Engineering Science and Mechanics, 1–20. https://doi.org/10.1080/15502287.2025.2502939

Bin Jamal, M.N. & Michel, A. (2026), Multiscale Stochastic Modeling of Cement Materials Using UMT and Lattice Frameworks. Accepted for publication, Acta Materialia

Biot, M. A. (1941). General theory of three-dimensional consolidation. Journal of Applied Physics, 12(2), 155–164. https://doi.org/10.1063/1.1712886

Block, Philippe, and John Ochsendorf. "Thrust network analysis: a new methodology for three-dimensional equilibrium." Journal of the International Association for shell and spatial structures 48.3 (2007): 167-173.

Bullard, J. W., Stutzman, P. E., Ordoñez Belloc, L. M., Garboczi, E. J., & Bentz, D. P. (2009). Virtual cement and concrete testing laboratory for quality testing and sustainability of concrete. American Concrete Institute, Aci Special Publication, 266, 27–36.

Christ, J., Perrot, A., Ottosen, L.M., Koss, H. (2024) Rheological characterization of temperature-sensitive biopolymer-bound 3D printing concrete. Construction and Building Materials. 411, 134337.

Coussy, Olivier. (2004). Poromechanics. In Poromechanics. Wiley.

Dervishaj, Arlind, et al. "From durability to circularity: ensuring service life and enabling reuse of concrete in circular construction." Materials and Structures 59.1 (2026): 28.

Doschek-Held, K., Krammer, A.C., Steindl, F.R., Sattler, T., Juhart, J. (2024) Recycling of mineral wool waste as supplementary cementitious material through thermochemical treatment. Waste Management & Research 42, https://doi.org/10.1177/0734242X241237199

Eshelby, J. D. (1957). The determination of the elastic field of an ellipsoidal inclusion, and related problems. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 241(1226), 376–396. https://doi.org/10.1098/rspa.1957.0133

Feldthus, F. B., Ottosen, L. M., Bertelsen, I. M. G. & Kirkelund, G. M. (2025) Fluxing properties of sewage sludge ash in brick manufacturing: Effect of phosphorus extraction and brick clay composition. Case Studies in Construction Materials. 23, e05387

Fernandes, Matheus C., et al. "Mechanically robust lattices inspired by deep-sea glass sponges." Nature Materials 20.2 (2021): 237-241.

Ghazy, M. F., Maaty, E. S. A., Elaty, M. A., & Alrwashdeh, A. A. (2025). A comprehensive review of limestone calcined clay cement (LC3): Environmental and properties benefits, challenges, opportunities, and future directions. Results in Engineering, 28, 108319. https://doi.org/10.1016/j.rineng.2025.108319

Hassani, Sahar, and Ulrike Dackermann. "A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring." Sensors 23.4 (2023): 2204

Islahuddin, M., Janssen, H. (2019) Pore-structure-based determination of unsaturated hygric properties of porous materials. Transport in Porous Media 130(3), 675–698

Joustra, Jelle, Bas Flipsen, and Ruud Balkenende. "Structural reuse of wind turbine blades through segmentation." Composites Part C: Open Access 5 (2021): 100137.

Kappel, A., Viader, R.P., Kowalski, K.P., Kirkelund, G.M., Ottosen, L.M. (2018) Utilization of electrodialytically treated sewage sludge ash in mortar. Waste and Biomass Valorization, 9(12), 2503–2515

Kriven, W.M. et al. (2024). Why geopolymers and alkali-activated materials are key components of a sustainable world: A perspective contribution. Journal of the American Ceramic Society, 107(8). https://doi.org/10.1111/jace.19828

Kulasinski K., Guyer R., Derome D., Carmeliet J.(2015) Water Adsorption in Wood Microfibril-Hemicellulose System: Role of the Crystalline-Amorphous Interface. Biomacromolecules, 16 (9), pp. 2972 – 2978

Reuse of concrete components in new construction process: Critical review of 77 circular precedents. Journal of Cleaner Production, vol. 383, p. . 135235, 2023, doi: 10.1016/j.jclepro.2022.135235.

Küpfer, C., Bastien Masse, M., Guilbert, P., Weil, C., Courtin, L., Fivet, C. "Atlas of Reused Concrete" (ARC), an online platform to gather, visualise, and explore a growing international case study database. Journal of Physics: Conference Series 3140 (2025) 162010

Liu, T., Duyal, C., Paraskevoulakos, C., Enemark-Rasmussen, K., Tyurkay, A., Lushnikova, N., Gauvin, F., & Lima, A. T. (2026). Effect of wind turbine blade waste on cement hydration and gel structure: Competitive interaction of glass and polyester resin. Composites Part B: Engineering, 311, Article 113273. https://doi.org/10.1016/j.compositesb.2025.113273

Mazars, J. (1985). DESCRIPTION OF MICRO- AND MACROSCALE DAMAGE OF CONCRETE STRUCTURES. Engineering Fracture Mechanics, 25(5), 729–737.

Concrete : microstructure, properties, and materials. In Concrete: Microstructure, Properties, and Materials (pp. XXIII, 675 S. (unknown). McGraw-Hill Education.

MORI, T., & TANAKA, K. (1973). AVERAGE STRESS IN MATRIX AND AVERAGE ELASTIC ENERGY OF MATERIALS WITH MISFITTING INCLUSIONS. Acta Metallurgica, 21(5), 571–574.

Motamedi, S., Rousse, D. R., & Promis, G. (2025). A Review of Mycelium Bio-Composites as Energy-Efficient Sustainable Building Materials. Energies, 18(16), 4225. https://doi.org/10.3390/en18164225

Muhit, I. B., Al-Fakih, A., Suntharalingam, T., & Michel, A. (2025). Progress in Computational Modelling for Concrete Durability and Its Integration with Artificial Intelligence and Life-Cycle Assessment. Archives of Computational Methods in Engineering. https://doi.org/10.1007/s11831-025-10373-x

Nielsen, J. S., Clarke, R., Paquette, J., Farren, D., & Byrne, A. (2025). Risk-Based Decision Modelling for Wind Turbine Leading Edge Erosion. Energies, 18(21), 5784. https://doi.org/10.3390/en18215784

Ottosen, L.M., Kunther, W., Ingeman-Nielsen, T., Karatosun, S. (2024) Non-Destructive Testing for Documenting Properties of Structural Concrete for Reuse in New Buildings: A Review. Materials 2024, 17, 3814.

Parigi, D., Wood Vita (2024-2027) Development and Application of Advanced Constructions with Reclaimed Wood (ongoing project)

Samson, E., & Marchand, J. (2007). Modeling the transport of ions in unsaturated cement-based materials. Computers and Structures, 85(23-24), 1740–1756. https://doi.org/10.1016/j.compstruc.2007.04.008

Scrivener, K., Martirena, F., Bishnoi, S., Maity, S. (2018) Calcined clay limestone cements (LC3). Cement and Concrete Research 114, 49-56

Sharmilan, S., Stang, H., & Michel, A. (2022). A multi-species reactive transport model based on ion-solid phase interaction for saturated cement-based materials. Cement and Concrete Research, 159, Article 106861. https://doi.org/10.1016/j.cemconres.2022.106861

Sharmilan, S., Stang, H., & Michel, A. (2024). A multi-species reactive transport model based on gas-ion-solid phase interaction for the carbonation of cement-based materials. Cement and Concrete Research, 175, Article 107349. https://doi.org/10.1016/j.cemconres.2023.107349

Shi, C, Soete, J & Janssen, H. (2024) Influence of Pore Network Parameters on Hygric Property Prediction for Porous Building Materials. Transport in Porous Media 151:1333–1361,

Sigvardsen, N.M., Geiker, M.R., Ottosen, L.M. (2021) Phase development and mechanical response of low-level cement replacements with wood ash and washed wood ash. Construction and Building Materials, 121234

Thai H.N., Kawamoto K., Nguyen H.G., Komatsu T., Moldrup P. (2024) Diffusive and convective transport properties and pore-network characteristics of recycled, compacted concrete aggregates for use as road pavement materials. Construction and Building Materials, 457, art. no. 139460

Thybring E.E., Glass S.V., Zelinka S.L. (2019) Kinetics of water vapor sorption in wood cell walls: State of the art and research needs. Forests, 10 (8), art. no. 704

Ulm, F.-J., & Coussy, O. (2003). Mechanics and durability of solids. Prentice Hall.

Wang, S., Pourhaji, P., Vassallo, D., Heidarnezhad, S., Scarlata, S., & Rahbar, N. (2026). Durable, high-strength carbon-negative enzymatic structural materials via a capillary suspension technique. Matter, 9(3), 102564. https://doi.org/10.1016/j.matt.2025.102564

Research field 4 – Digitalisation and automation

1. Introduction, vision & mission

1.1. Introduction to the Research Field

RF4 addresses the transformation of construction across the entire building lifecycle, structured into four fundamental phases: (i) planning, (ii) fabrication and construction, (iii) data acquisition, and (iv) deconstruction for transformation and reuse. The field examines how robotics, computation, sensing, digital twins, and interoperable data infrastructures can support circular construction, reduce carbon emissions, improve resource efficiency, and enable lifecycle-informed decision-making.

1.2. Vision

We envision a built environment that operates within planetary boundaries, where more data leads to less waste, and material use, construction processes, and building transformation are continuously informed and controlled through reliable lifecycle data. Buildings are conceived as low-carbon, reversible and resource-aware systems, designed for material efficiency, reuse, and long-term adaptability. Construction is organised around traceable material flows, reduced carbon emissions, and automated processes supported by open and interoperable data ecosystems.

1.3. Mission

RF4 will establish the technological foundations for scalable circular construction and low-carbon building systems by integrating computational design and engineering, robotic fabrication, reality capture of the built environment, digital twins of construction operations, and interoperable data infrastructures. The research field will deliver automated prefabrication systems, including 3D concrete printing and robotic timber assembly, as well as robotic deconstruction processes for material recovery, implemented within traceable material flows and lifecycle-informed decision-making across phases.

2. State of the field

2.1. Global centres of excellence

Several international research centres are leading developments in construction automation, digital fabrication, and digital infrastructures for the built environment. In construction automation and robotic construction, *ETH Zurich*, through the *NCCR Digital Fabrication*, has established integrated design-to-production workflows and large-scale robotic construction systems. At the *University of Stuttgart*, the *ICD/ITKE and the IntCDC Cluster of Excellence* have developed computational design methods and robotic fabrication strategies for material-aware construction systems. *TU Eindhoven* has advanced large-scale additive manufacturing and 3D concrete printing, while *RWTH Aachen*, through the *Chair for Individualised Production*, focuses on robotic deconstruction and lifecycle-oriented automation.

In parallel, research on digital infrastructures and interoperability is advancing across several institutions. The *Technical University of Munich* contributes through work in *Computing in Civil and Building Engineering*, particularly on IFC-based interoperability and lifecycle assessment. *TU Eindhoven* also advances Linked Building Data and Semantic Web technologies, while the *Hong Kong University of Science and Technology* develops methods in computer vision and object recognition for the built environment. At the *Norwegian University of Science and Technology*, research addresses resource efficiency and the impact of large-scale infrastructure investments. These research environments define the current international landscape and represent strategic reference points for RF4, enabling collaboration and knowledge exchange in the development of integrated construction systems.

2.2. State of the art and DK position in the research field

Construction automation and digitalisation are increasingly interdependent and must be understood as components of integrated construction systems. Automation operates vertically on material processes such as fabrication, assembly, and deconstruction, while digitalisation enables horizontal coordination, monitoring, and control through lifecycle data. Computational design and engineering link these domains by integrating performance requirements, material behaviour, and fabrication constraints. The state of the art is therefore structured across two interrelated subdomains: construction automation and digitalisation.

State of the art in Construction Automation

Construction automation has developed from early experiments in the early 2010s with industrial robotics into an integrated field combining computational design, engineering, sensing, and fabrication. Initial work demonstrated that robotic systems could be adapted to architectural-scale processes such as bricklaying, timber assembly, and robotic welding (Bonwetsch et al. 2006; Oesterle 2009; Hack et al. 2017). Over the past decade, the field has evolved towards integrated design-to-production workflows, in which geometry, structural performance, fabrication constraints, and process control are addressed within continuous computational environments (Kohlhammer et al. 2017; Kumar et al. 2017; Gandia et al. 2019; Thoma et al. 2018; Asprone et al. 2018; Knippers et al. 2021; Menges 2015; Rogeau et al. 2022).

Current state-of-the-art systems are characterised by three areas, including material-aware computational design, where structural optimisation and fabrication logic are embedded in the design process (Bhooshan et al. 2022; Block et al. 2020; Popescu et al. 2018; Wagner et al. 2025[a]; Bechert et al. 2021; Wagner et al. 2025[b]); robotic fabrication and assembly, including additive manufacturing and automated construction systems capable of producing load-bearing elements in a controlled and automated manner (Graser et al. 2020; Burger et al. 2020; Lloret-Fritschi et al. 2020; Adel 2020; Salet et al. 2018; Ahmed et al. 2022); and sensor-driven feedback and cyber-physical integration, enabling real-time control, adaptive fabrication, and increasingly autonomous construction processes (Skoury et al. 2023; Leder and Menges 2023; Skoury et al. 2026; Opgenorth et al. 2026; Yang et al. 2025). The field is now shifting towards scaling along three directions. First, scaling in physical realisation, moving from demonstrators to complete buildings integrated with existing processes (Bhooshan et al. 2022; Graser et al. 2020; Bechert et al. 2025[a]; Bechert et al. 2025[b]; Anton et al. 2024). Second, scaling in innovation and industry transfer, with increasing involvement of start-ups and industrial actors such as MESH[1], AUAR[2], Vertico[3], etc. Third, scaling in sustainable performance, where robotic construction is evaluated in terms of material efficiency, carbon reduction, and lifecycle impact (Treml et al. 2025; Zechmeister et al. 2025; Skevaki et al. 2025; Bruun et al. 2024; Agustí-Juan et al. 2017; Vasey et al. 2024).

Denmark holds a promising but fragmented position, with emerging research in additive manufacturing, including material characterisation, process development, and structural components, at DTU Digital Building Technologies, the Danish Technological Institute, and SDU CREATE. Construction robotics research in timber has focused on material reuse, fabrication of bespoke structures, and robotic wood engineering at SDU CREATE, the Aarhus School of Architecture, and CITA at KADK (Kunic et al. 2024; Naboni et al. 2024; Yen and Svilans 2025; Galluccio et al. 2025; Kunic et al. 2025; Hudert et al. 2022). Since the 2020s, industry start-ups have begun developing robotised processes applied on construction sites, with companies such as COBOD[4], 3DCP Group[5], Gantio Robotics[6], Woodstock Robotics[7], and WOHN[8] advancing automated construction systems. However, robotic construction is primarily applied to improve productivity and precision, while its potential to systematically reduce carbon emissions, material use, and lifecycle impact remains underdeveloped

State of the art on Digitalisation

Digitalisation in the construction sector remains limited compared to other industries (Blanco JL et al. 2023), and its integration into construction processes is still uneven. While current developments build on advances in computation, including data modelling, machine learning, and distributed systems, digital systems are not yet able to consistently support lifecycle coordination or control material use and environmental performance. Current developments can be understood

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[1] https://www.mesh.ch/

[2] https://auar.io/

[3] https://www.vertico.com/

[4] https://cobod.com/

[5] https://www.3dcp.dk/

[6] https://gantiorobotics.com/

[7] https://www.woodstockrobotics.com/

[8] https://www.wohnhomes.comdemonstrates/

across three interrelated areas: interoperability, reality capture, and data-driven construction management, which together enable the linking of information, material flows, and decisions across the building lifecycle.

In the context of interoperability, research has evolved from centralised data models towards dynamic, purpose-driven data-linking strategies. Schlenger (Schlenger et al. 2025) propose a reference architecture and ontology framework for digital twin construction, representing a structured approach to data integration. In contrast, (Zhu A , 2024) demonstrates more flexible linking between BIM and robotic systems. These approaches represent complementary directions, structured integration and flexible data linking, both aiming to enable data exchange across heterogeneous systems. However, both face limitations related to long-term data persistence and reliable alignment across heterogeneous sources, which remain critical for maintaining consistent information on materials, components, and their lifecycle states. These findings indicate that dynamic data-linking approaches alone are unlikely to be sufficient for long-term information management in the built environment. There remains a need for a holistic and interoperable information structure that acts as a persistent backbone for lifecycle information. Such a structure should support the transfer of information from proprietary applications into open, vendor-independent representations, ensuring long-term accessibility and semantic consistency. Dynamic linking approaches may offer efficient short-term solutions for integrating BIM, sensors, robotics, and other digital technologies. However, maintaining reliable information about materials, components, spaces, systems, and their evolving lifecycle states over decades requires a stable semantic framework. Consequently, open information standards and interoperable data models should be regarded not as alternatives to dynamic linking, but as the long-term foundation upon which such linking strategies can operate.

Within reality capture, current research focuses on object recognition and sensor-based modelling of the built environment. Foundation models such as SAM3 (Carion N et al. 2025) enable general-purpose segmentation across heterogeneous environments, while models such as YOLO (Ultralytics, 2026) achieve higher accuracy and speed in more specialised applications. These developments enable automated detection, classification, and tracking of building elements and materials, forming the basis for linking physical construction and deconstruction processes with digital representations and enabling continuous updating of building information.

In data-driven construction management, research has shifted from isolated BIM implementations to integrated Construction 4.0 ecosystems that combine digital twins, platforms, and Industry 4.0 technologies (Li, Y et al. 2022) (Asif, M et al. 2024). These systems improve coordination, productivity, and decision-making in controlled contexts and represent an initial convergence of interoperability and sensing into integrated digital environments spanning design, construction, operation, and transformation. Recent work by (Disney O. et al., 2023) demonstrates the implementation of Total BIM concepts, where construction drawings are reduced to a minimum and replaced by digital model-based information. Combined with takt planning and system-oriented approaches, indicating a transition towards continuous, model-based coordination across project phases and improved control of construction processes.

Despite these advances, digitalisation in construction remains fragmented across the value chain, with insufficient interoperability to enable persistent, reliable data exchange. As a result, traceability of materials and components remains limited, and lifecycle-informed decision-making is not consistently achieved. Digital systems are therefore not yet operational in controlling material flows, resource use, and environmental performance across the building lifecycle, which limits their capacity to support circular construction, reduce carbon emissions, and operate in conjunction with automated construction and deconstruction processes.

Denmark has a small but dedicated research community in interoperability within the construction sector. Key contributions include the Building Topology Ontology (BOT), recognised by W3C, and involvement in the ISO 29481 Information Delivery Manual (IDM) standard, as well as contributions to buildingSMART and EU and Nordic projects. Early adoption of national openBIM requirements has positioned Denmark strongly in the digitalisation of construction, although progress over the past decade has been limited. Denmark also holds a strong international position in computer vision, particularly in object detection, tracking, and real-world perception, with potential for application in construction. The Danish construction industry has gradually adopted digitalisation over the past 30 years to optimise internal workflows. However, information exchange between organisations still largely relies on non-semantic formats such as PDF documents and Excel files shared through emails and project platforms. Some organisations have moved towards more integrated digital solutions based on proprietary platforms, whereas truly open, interoperable, and semantically structured information models with accessible long-term definitions independent of specific vendors remain largely non-existent.

3. How will the research field address the core challenges?

Building on the current state of the art and the identified limitations in the integration of automation and digitalisation, RF4 addresses key challenges of a sustainable built environment. Construction remains highly material-intensive, generating significant waste and carbon emissions, and is further compounded by limited traceability of materials and components, inefficient construction processes, insufficient digital infrastructure for reuse, and limited automation in both construction and demolition.

RF4 addresses these challenges by shifting from fragmented digitalisation and isolated automation towards coordinated lifecycle-informed construction workflows and interoperable data infrastructures. This is achieved by investigating how robotic fabrication and prefabrication processes can interact with digital twins and interoperable data infrastructures, thereby linking material processes and information flows across the building lifecycle. Within these workflows and demonstrators, automated construction and deconstruction processes are developed to enable low-carbon construction and the recirculation of high-value materials. These developments are realised through a multi-level development of technologies, methods, and experimental processes, and are tested and refined through experimental demonstrators, pilot validation activities, and collaboration with industry stakeholders to ensure applicability in real construction contexts. Sensor feedback, lifecycle data, and interoperable information models are integrated to support adaptive robotic fabrication, assembly, deconstruction, and material recovery workflows.

Through this integration, RF4 investigates how materials and components can become traceable across the lifecycle, and how construction processes can be optimised to reduce material use, waste generation, and embodied carbon. Digital twins connect material, component, and building data across scales, while interoperable data infrastructures enable coordination across stakeholders. This supports the development of construction workflows in which buildings are designed for adaptability, disassembly, and material reuse.

3.1. Global Perspectives

The research outputs of RF4 are primarily developed for implementation within European construction contexts, where regulatory frameworks, digital infrastructures, and industrial capabilities support their deployment. In other developed regions, similar approaches can be applied with adaptations to local materials, standards, and construction practices. In emerging and developing contexts, where constraints related to cost, infrastructure, and technical capacity are more pronounced, a more selective adoption is expected. In these cases, specific components, particularly those related to material-efficient design, digital modelling, and reality capture, may provide immediate value, while more advanced automation systems may require further adaptation. Overall, RF4 develops technologies and methods that are transferable in principle but require contextual adjustment to address different levels of technological maturity and the condition of local value chains.

The automation activities within RF4 investigate adaptable and scalable automation models for low-carbon and circular construction across different industrial, economic, and material contexts. Rather than relying on rigid models of vertically integrated industrial automation and repetitive mass-production logics, RF4 focuses on AI-assisted, sensor-rich, and adaptive prefabrication workflows capable of operating under varying levels of technological maturity, labour conditions, and construction capacity. Specifically, robotic timber construction and advanced prefabrication systems are particularly relevant in regions with established timber industries and industrial fabrication ecosystems, including Northern and Central Europe, North America, and parts of East Asia. RF4 will benefit from the existing collaboration with ETH Zürich and the Federal University of Rio de Janeiro (UFRJ) in this field, enabling the development and testing of methods across different timber resources, industrial ecosystems, and construction cultures. In parallel, large-scale additive manufacturing approaches such as 3D Concrete Printing provide broader applicability due to the widespread use of concrete construction across regions, including the Middle East, China, India, and Latin America. Related activities within RF4 will engage with WASP in Italy and the University of Minho in Portugal, contributing expertise in construction-scale 3D printing and facilitating validation across different material systems and regional construction practices.

RF4 further investigates adaptive fabrication cells and digitally coordinated just-in-time production workflows capable of supporting flexible construction and transformation processes without requiring fully standardised construction systems or centralised industrial production environments. Through AI-assisted robotic control, real-time sensing, and adaptive fabrication strategies, the research activities investigate how robotic systems can respond to material variability, uncertain geometries, heterogeneous building stock, and locally specific construction conditions. Particular emphasis is placed on robotic deconstruction, material recovery, and adaptive transformation processes, which are especially relevant within the European context due to the increasing importance of circular transformation and reuse of the existing building stock. RF4, therefore, investigates automation not as a fixed industrial paradigm, but as a context-responsive production ecology capable of integrating robotic systems, human-robot collaboration, and adaptive construction workflows across different construction cultures and value-chain conditions. Existing research strengths from SDU and DTU will be fused to further integrate and advance these aspects.

One of the research activities focuses on investigating how IFC can be extended to better support construction site processes and the capture of information generated during construction activities. As IFC is adopted as both an international and European standard and increasingly required in public and selected private projects worldwide, the intention is to develop the proposed extensions in collaboration with international experts and relevant buildingSMART groups, with the aim of contributing to future buildingSMART New Work Items.

The digitalisation and semantic structuring of additional sustainability-related parameters, including those addressed in RF3 and RF7, aim to support future European standardisation efforts and facilitate a higher degree of automation in sustainability assessments. The objective is to reduce time-consuming manual extraction and transfer of information from documents and thereby improve the ability to evaluate a broader range of relevant design and construction alternatives using structured and interoperable information.

The activities related to reality capture aim to investigate how relatively inexpensive devices and methods can support the generation of BIM-related objects and semantically structured information. This may reduce dependence on expensive specialised equipment and potentially make reality capture technologies more accessible, including in less economically developed regions.

By promoting standardised and semantically interoperable data structures, the research field can contribute to creating opportunities for startups and smaller software providers to develop interoperable solutions that can challenge existing proprietary ecosystems. Similar to how open internet technologies enabled the emergence of new digital actors and services, interoperable standards may support increased competition, innovation, and accessibility within the construction sector.

4. Impact framework

4.1. Intended impact

Successful implementation of RF4 will contribute to transform construction into a digitally connected and automated system, enabling significantly reduced environmental impact. Automated construction technologies will enable lower-carbon building systems and more resource-efficient use of materials, while improving accuracy, predictability, and efficiency in construction processes.

Buildings will be designed as reversible systems, enabling repeated assembly and disassembly, extending carbon storage in structural materials, and supporting component reuse. Construction and demolition processes will recover a larger share of materials, reducing waste and dependence on virgin resources.

Integrated digital construction management and reliable digital representations of the built environment will improve coordination, lifecycle transparency, and decision-making across design, construction, operation, and transformation. This will support more efficient project delivery, reduce material and process waste, and enable the identification and implementation of low-carbon solutions. Together, these developments will contribute to a more adaptive, resource-efficient, and low-carbon construction ecosystem.

The transformation of the construction industry towards greater sustainability, digitalisation, and automation is a long-term challenge that requires coordinated efforts across academia, industry, and standardisation bodies. While the CEBE project alone cannot achieve this transformation, RF4 will contribute to specific domains by advancing interoperable information structures, digital twin technologies, and automation concepts. These contributions are expected to support and enrich international standards and best practices for the construction sector.

4.2. Contextual conditions

The readiness for impact in RF4 is supported by ongoing developments in robotics, AI-assisted sensing, and interoperable digital infrastructures, together with increasing policy pressure to reduce carbon emissions, improve resource efficiency, and support circular transformation within the construction sector. These conditions are particularly relevant within European construction contexts, where regulatory frameworks, digitalisation initiatives, and industrial capabilities increasingly support experimentation with digital and automated construction workflows. At the same time, adoption remains fragmented due to varying levels of technological maturity, interoperability limitations, different regulatory constraints across countries, and heterogeneous construction practices.

Construction sector pressures - The need to decarbonise construction, together with emerging carbon quotas and regulatory constraints, is increasing demand for more resource-efficient and low-carbon building systems. In parallel, the growing need for large-scale building transformation, material reuse, and circular construction practices places additional pressure on existing construction processes and value chains, particularly within European contexts characterised by ageing building stock and ambitious climate targets. Persistent labour shortages further accelerate interest in automation within both construction and deconstruction activities.

Adaptive automation and cyber-physical workflows - Unlike manufacturing industries characterised by controlled and repetitive production environments, construction processes operate under highly variable material, geometric, and site conditions. RF4, therefore, investigates lifecycle-informed cyber-physical construction workflows integrating adaptive automation, interoperable digital infrastructures, and circular material processes. Rather than relying exclusively on rigid industrial standardisation, the research activities investigate AI-assisted robotic control, interoperable lifecycle data, and adaptive fabrication strategies supporting flexible prefabrication, robotic fabrication, deconstruction, material recovery, and transformation of the existing building stock under varying industrial and economic conditions.

Barriers and implementation conditions - Fragmented data ecosystems and limited interoperability restrict coordination and traceability across lifecycle stages, while the adoption of robotics and automation in construction continues to remain limited. Regulatory constraints, fragmented value chains, and risk-averse construction practices further slow implementation and large-scale deployment. These barriers involve both technical and non-technical aspects. RF4 primarily addresses selected technical challenges, while recognising that broader issues related to business models, incentives, project-specific collaboration, client involvement, facility management integration, and long-term access to semantically structured information remain equally important, although outside the primary scope of CEBE.

Research response and implementation pathways - RF4 addresses these barriers through demonstrator-based research, pilot validation activities, interoperability and standardisation initiatives, and collaborative development with industrial and public-sector stakeholders. The research activities aim to provide technical foundations supporting managers, clients, and policymakers in promoting more sustainable, interoperable, and transparent construction practices. Achieving meaningful interoperability and scalable implementation further requires increased transparency, shared data governance, and lifecycle-oriented collaboration across stakeholders involved in the design, construction, operation, transformation, and reuse of built assets.

4.3. CEBE impact levers

CEBE provides a framework for translating research outputs into construction practice through demonstrator activities, pilot validation, interoperability initiatives, and collaboration with industrial and public-sector stakeholders. The programme supports integration of digital and automated processes across the construction value chain and enables validation under relevant construction and building transformation conditions. Impact is realised through a dual approach combining foundational research with applied development across different TRL levels. Lower-TRL activities focus on new technologies, methods, tools, standards initiatives, and experimental workflows addressing fundamental challenges in construction automation and digitalisation. In parallel, higher-TRL activities are developed together with industrial stakeholders through testing, refinement, and pilot implementation in real construction contexts.

Demonstrators, pilot validation, and stakeholder involvement

RF4 pursues impact through iterative development, testing, and validation processes connecting experimental research with implementation. Industry stakeholders are involved from early-stage prototype development through demonstrator evaluation and pilot validation activities. Experimental demonstrators focus on robotic fabrication processes, sensing systems, semantic information structures, digital coordination methods, and building technology components. Pilot activities subsequently investigate integration within larger construction and building transformation scenarios involving contractors, engineers, architects, demolition and recycling actors, technology providers, public authorities, and facility-management stakeholders. Industrial advisory participation and collaborative supervision structures are integrated into selected PhD and postdoctoral activities to support alignment between research development and industrial requirements.

Automation and construction transformation

Within the automation domain, RF4 investigates robotic fabrication, prefabrication, deconstruction, and material recovery workflows operating under heterogeneous material and site conditions. Particular emphasis is placed on reversible construction, circular reuse, and robotic deconstruction supporting recirculation of high-value building components, especially within European building transformation contexts. Prototype testing, demonstrator activities, and industrial collaboration are expected to support transition from experimental workflows towards pilot-scale implementation and future adoption pathways.

Digital infrastructures and standardisation

Within the digitalisation domain, RF4 investigates semantic information structures supporting coordination across construction, operation, transformation, and reuse processes. buildingSMART International, including its Construction Domain, together with CEN Technical Committees 442 and 350, will be engaged to contribute to future interoperability and standardisation initiatives related to construction site digitalisation and sustainability-related information management. Research activities related to IFC extensions and machine-readable sustainability data aim to support future European standardisation efforts and improve automation and coordination of sustainability assessments. RF4 further investigates reality capture technologies and accessible sensing methods supporting scalable digital workflows across different construction contexts.

Scaling and long-term implementation

RF4 addresses implementation barriers through demonstrator-based research, collaborative innovation activities, interoperability initiatives, and pilot validation under real construction conditions. National demonstration initiatives and large-scale building transformation projects provide important environments for evaluating scalability, applicability, and operational relevance. Both established software vendors and startup companies are encouraged to participate in collaborative innovation activities supporting technological maturity and practical applicability of developed concepts and prototypes. In parallel, SDU and DTU intend to pursue additional research and innovation funding together with industry partners and public organisations to continue development and implementation of selected RF4 activities beyond the initial scope of the CEBE programme.

4.4. Intended outcomes and main beneficiaries

RF4 will lead to the adoption of integrated digital and automated construction workflows across the building lifecycle. Key beneficiaries include:

- construction companies implementing automated fabrication processes
- demolition and recycling industries adopting robotic deconstruction technologies
- architects, engineers, facility owners and facility managers using digital twins and data-driven design tools
- public authorities and policymakers implementing resource-efficient construction strategies
- technology providers, software developers, and material suppliers contributing to digital construction ecosystems

4.5. Research outputs

RF4 will generate interconnected outputs spanning adaptive automation, interoperable digital infrastructures, and digitally coordinated construction and transformation processes. The outputs range from foundational methods and experimental prototypes to demonstrators, pilot validation activities, and implementation-oriented workflows supporting contractors, prefabrication manufacturers, timber fabricators, concrete producers, demolition and recycling actors, software providers, facility managers, and public authorities.

Priority outputs in adaptive automation and robotic construction

The highest-priority automation outputs focus on autonomous and sensor-rich construction systems supporting reversible assembly, adaptive prefabrication, robotic fabrication, and circular transformation under heterogeneous material and site conditions. Early outputs expected between 2027 and 2029 include robotic fabrication demonstrators for reinforced 3D concrete printing with optimised material utilisation, sensing-integrated fabrication cells for context-aware construction processes, AI-assisted fabrication methods, and large-scale robotic systems for force- and vision-based reversible timber assembly. These outputs are intended to support prefabrication manufacturers, timber fabricators, concrete producers, robotics companies, and construction technology providers seeking low-carbon, material-efficient, and reusable construction systems.

Mid-stage outputs expected between 2028 and 2031 include autonomous robotic assembly and disassembly systems for reversible timber construction informed by material tracking data, robotic deconstruction systems for selective material recovery, AI-assisted reuse planning frameworks, and adaptive fabrication cells integrating sensing, semantic information models, and robotic control. These outputs are expected to support industrial stakeholders involved in building transformation, circular reuse, deconstruction, and material recovery processes.

Later-stage outputs expected from 2030 onwards investigate integrated cyber-physical construction frameworks combining robotic systems, sensing technologies, material tracking, and AI-assisted process optimisation within larger construction and transformation scenarios. Full-scale demonstrators and pilot validation activities are expected to support implementation pathways and future industrial adoption of selected automation workflows, prefabrication systems, and circular construction methods.

Priority outputs in interoperable digital infrastructures and lifecycle intelligence

The first major digitalisation output is expected to be an interoperable ontology and data model supporting construction site processes and cross-phase information exchange, with initial results anticipated around 2029. A key outcome is expected to be a proposed IFC extension submitted as a potential New Work Item within buildingSMART or ISO standardisation activities and evaluated through pilot cases and prototype implementations together with international experts and industry stakeholders. These outputs are intended to support software vendors, public authorities, facility managers, contractors, and other actors requiring long-term access to semantically structured building information.

Reality capture methods and algorithms for extracting geometric, semantic, and material information from the built environment are also expected around 2029 and are anticipated to support RF2, RF3, RF4, and RF7. Suggested improvements to interoperable workflows and digital construction management principles are expected to be released incrementally between 2028 and 2033. AI-assisted support systems for construction management, automation coordination, and optimisation of construction site processes are expected around 2031, while semantic integration of sustainability-related parameters and machine-interpretable EPD and LCA workflows are anticipated around 2030–2031.

Predictive and prescriptive models for construction planning, monitoring, and data-informed decision-making are expected towards 2032. Multi-scale adaptive digital twins integrating process information, sustainability data, sensor feedback, and selected automation functionalities are expected as later-stage outputs supporting coordination, transformation, and reuse processes across the built environment. These outputs are particularly relevant for software companies, startups, and emerging technology providers, as established vendors may face greater challenges in adapting proprietary ecosystems and existing business models.

4.6. Research activities

The research activities within RF4 are organised into two interconnected domains addressing material processes and information systems across the building lifecycle. The first domain focuses on robotic fabrication, reversible construction, deconstruction, and material recovery processes. The second domain focuses on semantic information systems, sensing technologies, digital twins, and data-driven coordination methods supporting construction and building transformation processes. The interaction between the two domains is enabled through shared data models, sensing systems, material tracking, and cyber-physical coordination workflows connecting physical construction processes with digital information environments.

Adaptive automation and robotic construction

These activities focus on robotic fabrication, assembly, disassembly, and deconstruction processes supporting material-efficient construction, reversible building systems, and high-value material recovery:

- (WP4.1) Robotic low-carbon reinforced 3D concrete printing of building systems
- (WP4.2) Robotic assembly and disassembly of timber structures for extended carbon capture
- (WP4.3) Automated large-scale deconstruction and material extraction

The automation-related activities are connected through shared robotic workflows, sensing methods, adaptive fabrication logics, and circular material recovery strategies supporting lifecycle-informed construction and transformation processes.

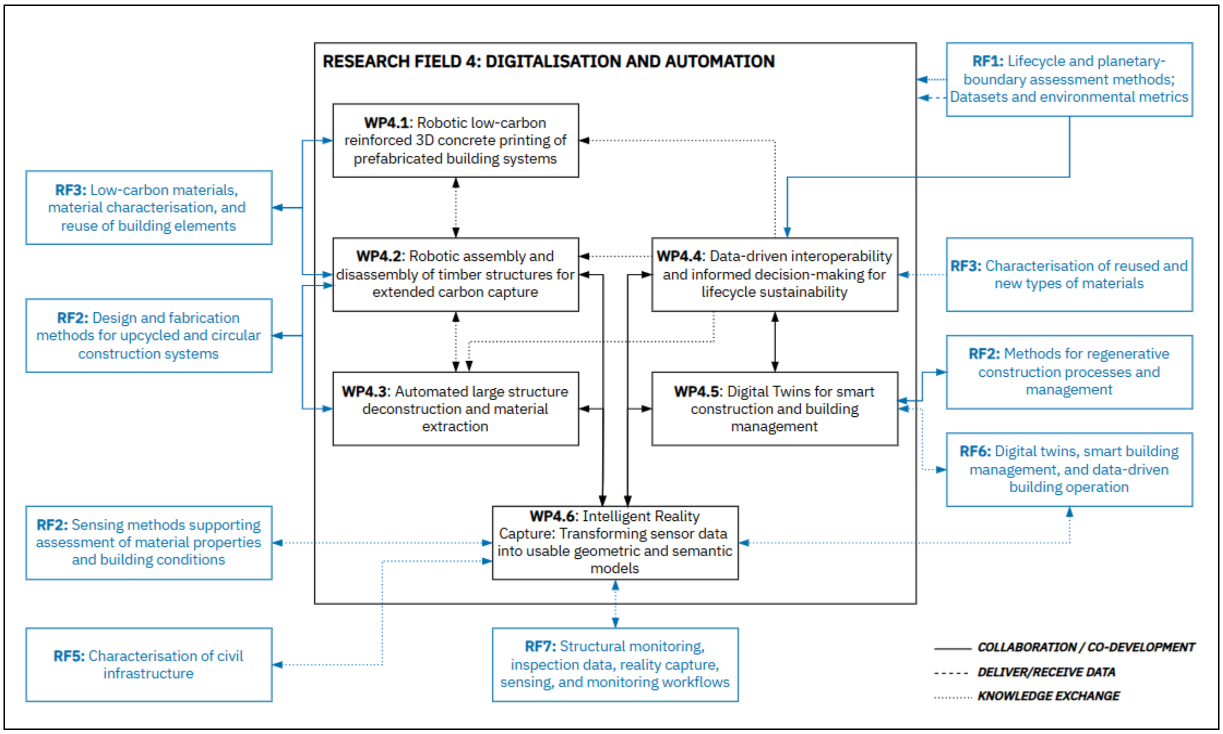
Interoperable digital infrastructures and lifecycle intelligence

These activities focus on interoperable data infrastructures, sensing systems, and digital models supporting traceability, lifecycle coordination, and data-informed decision-making across construction and building transformation processes:

- (WP4.4) Data-driven interoperability and lifecycle-informed decision-making
- (WP4.5) Digital twins for construction and building management
- (WP4.6) Intelligent reality capture technologies for digital building documentation

These activities support semantic interoperability, digital twin integration, sensing-informed workflows, and lifecycle-oriented information exchange across RF4 and the wider CEBE programme.

Illustration of RF4 interactions with other RFs



Interfaces across Work Packages within RF4

Within RF4, the interfaces between work packages are organised around three main coordination layers. First, the automation-related work packages (WP4.1-4.3) exchange knowledge and methods related to robotic workflows, sensing systems, localisation strategies, adaptive fabrication, and reversible construction principles supporting fabrication, assembly, deconstruction, and material recovery processes. Second, WP4.4 provides interoperable semantic data structures and information exchange methods supporting coordination between robotic systems, sensing technologies, construction management tools, digital twins, and material tracking workflows across WP4.1-4.6. WP4.2 and WP4.3 further collaborate with WP4.6 on robotic perception, object recognition, and sensor-based environment understanding supporting adaptive assembly, disassembly, and deconstruction processes. Third, WP4.4, WP4.5, and WP4.6 collaborate on the co-development of interoperable sensing-integrated digital twin infrastructures and semantic methods connecting machine data, sensing technologies, digital twins, and reality capture methods with robotic construction activities through cyber-physical integration and continuous data exchange between physical assets, construction processes, and interoperable digital models.

Interfaces between RF4 and other research fields

RF4 interfaces with the other research fields through reciprocal knowledge exchange, co-development activities, shared demonstrators, delivery of enabling datasets and methods, and integration of sustainability assessment workflows.

The interface with RF1 focuses on exchange of environmental metrics, planetary-boundary assessment methods, sustainability indicators, and AI-assisted optimisation workflows. RF1 provides environmental boundary conditions and assessment methodologies supporting RF4 demonstrators, while RF4 contributes sensing data, construction workflows, and digital coordination methods informing sustainability evaluation activities. This interface is active from Phase 1 and expands in Phase 2 through integrated optimisation and assessment workflows.

RF2 interfaces with RF4 through co-development of circular construction systems, regenerative construction strategies, computational design workflows, and robotic fabrication methods. RF2 contributes design methodologies, regenerative construction principles, and circular system logics, while RF4 contributes robotic workflows, sensing systems, fabrication constraints, and adaptive construction methods supporting implementation and validation of regenerative construction processes. These interfaces are active throughout both phases of the programme.

RF3 interfaces with RF4 through exchange of material characterisation data, reuse strategies, sustainability-related material information, and fabrication requirements supporting robotic construction and material recovery workflows. RF3 contributes material properties, reuse performance data, and characterisation methods informing robotic fabrication, assembly, deconstruction, and circular reuse processes. In parallel, RF4 contributes fabrication constraints, robotic machining requirements, process-specific material performance criteria, sensing-informed assembly tolerances, and construction automation workflows informing development of reusable and low-carbon material systems. This interface begins with knowledge exchange in Phase 1 and expands into integrated fabrication, reuse, and sustainability workflows during Phase 2.

RF5 interfaces with RF4 through semantic integration of EPD and LCA information, machine-readable sustainability data, and infrastructure-related lifecycle information. RF5 contributes sustainability-related data structures, assessment approaches, and lifecycle metrics, while RF4 contributes research on interoperable workflows, sensing integration, semantic information models, and digital coordination methods. The objective is to explore and demonstrate approaches for machine-readable sustainability assessment workflows rather than to establish complete sector-wide solutions. This interface becomes particularly active during Phase 2.

RF6 and RF7 interface with RF4 through collaboration on digital twins, sensing systems, monitoring workflows, inspection technologies, and operational building data. RF6 and RF7 contribute monitoring methodologies, sensing technologies, inspection workflows, and operational datasets. RF4 contributes research on semantic information structures, construction process integration, robotic sensing workflows, and cyber-physical coordination methods, with a focus on interoperability and lifecycle information management. The collaboration aims to explore and demonstrate approaches for construction management, building operation, and lifecycle data integration. These interfaces are active from Phase 1 and continue throughout the programme.

4.7. Research Field specific output, outcome and impact targets

For the research field, we have defined the following targets for which the realisation hereof will be evaluated over the course of the programme.

Targets of the research field

Target name & description	Evaluation method	Impact Type	Category	Years
Robust computer-vision and sensor-based methods for semantic recognition of built-environment objects	Publication	Output	New method	3
Adaptive robotic system for reinforced 3D concrete printing with real-time feedback and AI-assisted toolpath optimisation	Publication and Prototype Demonstration	Output	New technology	4
Large-scale robotic systems for force- and vision-based reversible timber assembly and disassembly	Publication and Prototype Demonstration	Output	New technology	4
Digital and robotic systems for mapping, localisation, material identification, and deconstruction of unknown structures	Publication and Prototype Demonstration	Output	New tool / New technology	4
Interoperable ontology and IFC-based data model for construction site processes	Submission and evaluation within buildingSMART or ISO standardisation activities	Outcome	Applied in regulation / standardisation	4
Computational workflows for stress-, carbon-, and fabrication-informed design of load-bearing concrete systems	Publication	Output	New method	5
Data-driven planning and optimisation frameworks integrating time, cost, productivity, and sustainability data	Publication and Pilot-scale Demonstration	Outcome	Applied by industry	5
Tools supporting regenerative handover and semantically structured lifecycle information exchange	Workshop-based testing and stakeholder evaluation	Output	New tool	5
AI-driven lifecycle-informed reuse and reassembly planning frameworks for reversible construction systems	Publication and Pilot-scale Demonstration	Output	New method / New tool	6

Predictive planning models, AI-driven decision-support systems, and multi-scale adaptive digital twins integrating lifecycle, sustainability, and sensing data	Pilot-scale Demonstration	Outcome	Applied by the industry	7
Integrated autonomous circular timber construction systems with lifecycle tracking and reusable building components	Publication and Pilot-scale Demonstration	Outcome	Demonstrated in practice	8
Automated deconstruction workflows with integrated material identification and lifecycle tracking	Publication and Pilot-scale Demonstration	Outcome	Demonstrated in practice	8

5. References

Adel A. Computational Design for Cooperative Robotic Assembly of Nonstandard Timber Frame Buildings. 2020. doi:10.13140/RG.2.2.34378.39360

Ahmed Z, Wolfs R, Bos F, Salet T. A Framework for Large-Scale Structural Applications of 3D Printed Concrete: the Case of a 29 m Bridge in the Netherlands. Open Conference Proceedings. 2022 Feb 15;1:5–19. doi:10.52825/ocp.v1i.74

Agustí-Juan I, Müller F, Hack N, Wangler T, Habert G. Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall. Journal of Cleaner Production. 2017 Jun 15;154:330–40. doi:10.1016/j.jclepro.2017.04.002

Anton A, Wei Lin C, Skevaki E, Wang MY, Wangler T, Flatt RJ, et al. TOR ALVA: A 3D CONCRETE PRINTED TOWER A 3D CONCRETE PRINTED TOWER. In: Fabricate 2024: Creating Resourceful Futures [Internet]. UCL Press; 2024 [cited 2026 Mar 20]. p. 252–9. Available from: https://www.jstor.org/content/oa_chapter_edited/jj.11374766.35?seq=1

Asif, M., Naeem, G., & Khalid, M. (2024). Digitalization for sustainable buildings: Technologies, applications, potential, and challenges. Journal of Cleaner Production, 450, 141814. https://doi.org/10.1016/j.jclepro.2024.141814

Asprone D, Menna C, Bos FP, Salet TAM, Mata-Falcón J, Kaufmann W. Rethinking reinforcement for digital fabrication with concrete. Cement and Concrete Research. 2018 Oct 1;SI : Digital concrete 2018112:111–21. doi:10.1016/j.cemconres.2018.05.020

Bechert S, Aicher S, Gorokhova L, Balangé L, Göbel M, Schwieger V, et al. Segmented Timber Shells for Circular Construction: Relocation, Structural Assessment, and Robotic Fabrication of a Modular, Lightweight Timber Structure. Buildings. 2025 May 28;15:1857. doi:10.3390/buildings15111857

Bechert S, Scheder-Bieschin L, Wood D, Knippers J, Menges A. Urbach Tower: Integrative structural design of a lightweight structure made of self-shaped curved cross-laminated timber. Structures. 2021 Oct 1;33:3667–81. doi:10.1016/j.istruc.2021.06.073

Bechert S, Schlopschnat C, Göbel M, Aicher S, Menges A, Knippers J. livMatS biomimetic shell: Structural advancements of segmented timber shells towards permanent building constructions. Structures. 2025 Jun 25;79. doi:10.1016/j.istruc.2025.109524

Blanco JL, Rockhill D, Sanghvi A, Torres A. From start-up to scale-up: Accelerating growth in construction technology. McKinsey and Company Report 2023.

Block P, T. V, Rippmann M, Ranaudo F, Calvo Barentin C, Paulson N. Redefining Structural Art: Strategies, necessities and opportunities. Structural Engineer. 2020 Jan 2;98:66–72. doi:10.56330/UJFI2777

Bhooshan S, Bhooshan V, Dell'Endice A, Chu J, Singer P, Megens J, et al. The Striatus bridge: Computational design and robotic fabrication of an unreinforced, 3D-concrete-printed, masonry arch bridge. Architecture, Structures and Construction. 2022 Jun 14;2. doi:10.1007/s44150-022-00051-y

Bonwetsch T, Kobel D, Gramazio F, Kohler M. The informed Wall: applying additive digital fabrication techniques on architecture. In: 25th Annual Conference of the Association for Computer-Aided Design in Architecture (ACADIA). 2006. p. 489–95.

Bruun EPG, Besler E, Adriaenssens S, Parascho S. Scaffold-free cooperative robotic disassembly and reuse of a timber structure in the ZeroWaste project. Constr Robot. 2024 Aug 18;8(2):20. doi:10.1007/s41693-024-00137-7

Burger J, Lloret E, Taha N, Scotto F, Demoulin T, Mata-Falcón J, et al. Design and Fabrication of a Non-standard, Structural Concrete Column Using Eggshell: Ultra-Thin, 3D Printed Formwork. In: RILEM Bookseries. 2020. p. 1104–15. doi:10.1007/978-3-030-49916-7_105

Carion N, Gustafson L, Hu YT, Debnath S, Hu R, Suris D, et al. SAM 3: Segment Anything with Concepts [Internet]. arXiv; 2025 [cited 2026 Mar 20]. Available from: http://arxiv.org/abs/2511.16719 doi:10.48550/arXiv.2511.16719

Disney O, Roupé M, Johansson M, Ris J, Höglin P. Total BIM on the construction site: a dynamic single source of information. Journal of Information Technology in Construction. 2023 Sep 22;28:519–38. doi:10.36680/j.itcon.2023.027

Galluccio G, Tamke M, Nicholas P, Svilans T, Gaudillière-Jami N, Thomsen MR. Material Stories: Assessing Sustainability of Digital Fabrication with Bio-Based Materials Through LCA. In: Kioumarsi M, Shafei B, editors. The 1st International Conference on Net-Zero Built Environment. Cham: Springer Nature Switzerland; 2025. p. 25–37. doi:10.1007/978-3-031-69626-8_3

Gandia A, Parascho S, Rust R, Casas G, Gramazio F, Kohler M. Towards Automatic Path Planning for Robotically Assembled Spatial Structures. In: Willmann J, Block P, Hutter M, Byrne K, Schork T, editors. Robotic Fabrication in Architecture, Art and Design 2018. Cham: Springer International Publishing; 2019. p. 59–73. doi:10.1007/978-3-319-92294-2_5

Graser K, Baur M, Apolinarska A, Dörfler K, Hack N, Jipa A, et al. DFAB HOUSE - A Comprehensive Demonstrator of Digital Fabrication in Architecture. 2020. 130 p. doi:10.2307/j.ctv13xpsvw.21

Hack N, Wangler T, Mata-Falcón J, Dörfler K, Kumar N, Walzer A, et al. Mesh Mould: An On Site, Robotically Fabricated, Functional Formwork. In. 2017 [cited 2026 Mar 20]. Available from: https://www.semanticscholar.org/paper/Mesh-Mould%3A-An-On-Site%2C-Robotically-Fabricated%2C-Hack-Wangler/e33d6ec963485e83544b50dcd56439ba32d1e6a7

Hudert M, Elvebakken MF, Meagher M, Mangliár L, Zhang X, Esterle L. Deep learning enhanced robotic fabrication of timber-to-timber connections with densified hardwood nails. Proceedings of IASS Annual Symposia. 2022 Sep 19;2022(7):1–9.

Knippers J, Kropp C, Menges A, Sawodny O, Weiskopf D. Integrative Computational Design and Construction: Rethinking Architecture Digitally. Civil Engineering Design. 2021 Jun 1;3. doi:10.1002/cend.202100027

Kohlhammer T, Apolinarska AA, Gramazio F, Kohler M. Design and structural analysis of complex timber structures with glued T-joint connections for robotic assembly. International Journal of Space Structures. 2017 Jun 1;32(3–4):199–215. doi:10.1177/0266351117746268

Kumar N, Hack N, Doerfler K, Walzer AN, Rey GJ, Gramazio F, et al. Design, development and experimental assessment of a robotic end-effector for non-standard concrete applications. In: 2017 IEEE International Conference on Robotics and Automation (ICRA) [Internet]. 2017 [cited 2026 Mar 20]. p. 1707–13. Available from: https://ieeexplore.ieee.org/document/7989201/ doi:10.1109/ICRA.2017.7989201

Kunic A, Angeletti D, Marrone G, Naboni R. Design and construction automation of reconfigurable timber slabs. Automation in Construction. 2024 Dec 15;168. doi:10.1016/j.autcon.2024.105872

Kunic A, Talaei A, Naboni R. Cyber–physical infrastructure for material and construction data tracking in reconfigurable timber light-frame structures. Construction Robotics. 2025 Apr 1;9. doi:10.1007/s41693-025-00153-1

Leder S, Menges A. Architectural design in collective robotic construction. Automation in Construction. 2023 Dec 1;156:105082. doi:10.1016/j.autcon.2023.105082

Li, Y., Sun, H., Li, D., Song, J., & Ding, R. (2022). Effects of digital technology adoption on sustainability performance in construction projects: The mediating role of stakeholder collaboration. Journal of Management in Engineering, 38(3). https://doi.org/10.1061/(ASCE)ME.1943-5479.0001040

Lloret-Fritschi E, Wangler T, Gebhard L, Mata-Falcón J, Mantellato S, Scotto F, et al. From Smart Dynamic Casting to a growing family of Digital Casting Systems. Cement and Concrete Research. 2020 Aug;134:106071. doi:10.1016/j.cemconres.2020.106071

Menges A. The New Cyber-Physical Making in Architecture: Computational Construction. Architectural Design. 2015;85(5):28–33. doi:10.1002/ad.1950

Naboni R, Kunic A, Jensen C, Sander S. Re-VoxLam Truss. Topology optimisation and reclaimed voxel lamination of horizontal wood structures. 2024. doi:10.5151/sigradi2023-510

Oesterle S. Cultural Performance in Robotic Timber Construction. In: ACADIA 09: reForm( ) - Building a Better Tomorrow [Proceedings of the 29th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 978-0-9842705-0-7] Chicago (Illinois) 22-25 October, 2009), pp. 194-200 [Internet]. CUMINCAD; 2009 [cited 2026 Mar 20]. Available from: https://papers.cumincad.org/cgi-bin/works/paper/acadia09_194

Opgenorth N, Otto JM, Menges A. Towards autonomous timber construction using a distributed robotic perception system in coordination with a tower crane [SSRN Scholarly Paper] [Internet]. Rochester, NY: Social Science Research Network; 2026 [cited 2026 Mar 20]. Available from: https://papers.ssrn.com/abstract=6192140 doi:10.2139/ssrn.6192140

Popescu M, Reiter L, Liew A, Van Mele T, Flatt RJ, Block P. Building in Concrete with an Ultra-lightweight Knitted Stay-in-place Formwork: Prototype of a Concrete Shell Bridge. Structures. 2018 Jun 1;14:322–32. doi:10.1016/j.istruc.2018.03.001

Rogeau N, Rezaei Rad A, Vestartas P, Latteur P, Weinand Y. A Collaborative Workflow to Automate the Design, Analysis, and Construction of Integrally-Attached Timber Plate Structures. In. Sydney, Australia; 2022 [cited 2026 Mar 20]. p. 151–60. Available from: http://papers.cumincad.org/cgi-bin/works/paper/caadria2022_69 doi:10.52842/conf.caadria.2022.2.151

Salet T, Ahmed Z, Bos F, Laagland H. Design of a 3D printed concrete bridge by testing. Virtual and Physical Prototyping. 2018 May 31;13:1–15. doi:10.1080/17452759.2018.1476064

Schlenger J, Pluta K, Mathew A, Yeung T, Sacks R, Borrmann A. Reference architecture and ontology framework for digital twin construction. Automation in Construction. 2025 Jun 1;174:106111. doi:10.1016/j.autcon.2025.106111

Skevaki E, Duong E, Yang HB, Parascho S. Truss from trash: a human–robot framework for adaptive timber assembly on the construction floor. Constr Robot. 2025 Dec 10;10(1):2. doi:10.1007/s41693-025-00175-9

Skoury L, Asaf O, Sprecher A, Menges A, Wortmann T. Data-informed Digital Twin for large-scale 3D printing in construction. Automation in Construction. 2026 Jan 7;182. doi:10.1016/j.autcon.2025.106706

Skoury L, Treml S, Opgenorth N, Amtsberg F, Wagner HJ, Menges A, et al. Towards data-informed co-design in digital fabrication. Automation in Construction. 2024 Feb 1;158:105229. doi:10.1016/j.autcon.2023.105229

Thoma A, Adel A, Helmreich M, Wehrle T, Gramazio F, Kohler M. Robotic Fabrication of Bespoke Timber Frame Modules. In: Willmann J, Block P, Hutter M, Byrne K, Schork T, editors. Robotic Fabrication in Architecture, Art and Design 2018. Cham: Springer International Publishing; 2019. p. 447–58. doi:10.1007/978-3-319-92294-2_34

Treml S, Riedel L, Wagner H, Tapia Camú C, Aicher S, Knippers J, et al. Concept to Construction: Co-Design and Integrative Development Processes for the IntCDC Multi-Storey Timber Building System. 2025. 90 p. doi:10.52202/080513-0012

Ultralytics. Ultralytics YOLO26 [Internet]. [cited 2026 Mar 20]. Available from: https://docs.ultralytics.com/models/yolo26/

Vasey L, Aejmelaeus-Lindström P, Jenny D, Johns RL, Hurkxkens I, Ming C, et al. Circular Robotic Construction. In: De Wolf C, Çetin S, Bocken NMP, editors. A Circular Built Environment in the Digital Age [Internet]. Cham: Springer International Publishing; 2024 [cited 2026 Mar 20]. p. 151–70. Available from: https://doi.org/10.1007/978-3-031-39675-5_9 doi:10.1007/978-3-031-39675-5_9

Wagner A, Schefer E, Reiner A, Kiesewetter L, Körner A, Menges A, et al. Computational Design Framework for Functionally Graded Self-Shaping Wood Structures. 2025.

Wagner H, Neubauer G, Alvarez M, Prandini R, Stark T, Knippers J, et al. Universal Timber Slab: Towards optimal slab segmentation and fiber arrangement strategies in compact and material efficient mass timber structures. 2025.

Yang X, Amtsberg F, Kaiser B, Skoury L, Stark T, Treml S, et al. An implementation and evaluation of large-scale multi-user human–robot collaboration with head-mounted augmented reality. Advanced Engineering Informatics. 2025 Sep 1;67:103475. doi:10.1016/j.aei.2025.103475

Yen YW, Svilans T. A DIGITAL FRAMEWORK FOR ROBOTIC PROCESSING OF RECLAIMED TIMBER. In: World Conference on Timber Engineering 2025 [Internet]. Brisbane, Australia: World Conference On Timber Engineering 2025; 2025 [cited 2025 Sep 29]. p. 3494–503. Available from: http://www.proceedings.com/080513-0428.html doi:10.52202/080513-0428

Zechmeister C, Hildebrandt H, Duque Estrada R, Chen TY, Gil Pérez M, Kannenberg F, et al. Design and development of natural fiber-timber hybrid beam elements for sustainable construction. Architectural Intelligence. 2025 Feb 27;4. doi:10.1007/s44223-025-00083-6

Zhu A, Pauwels P, Torta E, Zhang H, De Vries B. Data linking and interaction between BIM and robotic operating system (ROS) for flexible construction planning. Automation in Construction. 2024 Jul;163:105426. doi:10.1016/j.autcon.2024.105426

Research field 5 – Climate resilient and adaptive infrastructure

1. Introduction, vision & mission

1.1. Introduction to the Research field

Climate change is already here and intensifying in strength, putting urban infrastructure and coastal areas at risk. The trend will continue for decades or centuries even with a successful green transition in the coming years. Hence, we shall address climate resilient and adaptive infrastructure with focus on the boundary conditions for the build environment by combining expertise with coastal engineering, urban water, and geotechnical engineering.

1.2. Vision

Our vision is to embrace technology and innovative practices to address climate challenges within planetary boundaries and to create a meaningful impact by encouraging municipalities, agencies, and consulting engineers to adopt resilient and comprehensive solutions for urban and coastal management that prioritize biodiversity. We aim to build communities where municipalities and developers emphasize resilient buildings and infrastructure, enhancing both liveability and sustainability in a rapidly changing world.

1.3. Mission

Our mission is to promote climate resilient and adaptive infrastructure, redesigning urban infrastructure and coastal defences for resilience to climate extremes – integrating nature-based solutions, enhanced monitoring, predicted climate risks and optimised response strategies based on the concept of abandon-adapt-protect.

2. State of the field

2.1. Global centres of excellence

In this section, the state of the field is identified for each discipline involved in the research field.

Coastal: The Netherlands has a long tradition of coastal protection, with high involvement of the Technical University of Delft (TUD) and research institute DELTARES, which places particular emphasis on evaluating environmental impacts. In the United States, institutions such as Cornell University and the U.S. Army Corps of Engineers contribute significantly to the field, while the UK hosts HR Wallingford, which boasts extensive commercial capabilities in coastal engineering. Internationally, other strong research environments include Queensland University in Australia, the University of Cantabria in Spain, the University of Bologna in Italy, and the University of Braunschweig. European countries have frequently led in research initiatives, fostering substantial collaboration among the universities and three world-leading hydraulic research institutes: DHI, Deltares, and HR Wallingford. These collaborative efforts advance the state of knowledge and practice in coastal engineering globally.

Urban: Although management of sewer and rainwater infrastructure is an important field, it has struggled to attract broad scientific attention, partly because the topic lacks immediate appeal. As a result, only a few research groups worldwide have made it a central focus to understand the processes taking place in urban sewer systems and above-ground stormwater management. Substantial research expertise has been developed at ETH Zurich/EAWAG in Switzerland, Instituto Superior Técnico, University of Lisbon in Portugal, Queensland University in Australia, TU Delft in The Netherlands and several universities in China, e.g. Tsinghua University. Other research efforts have been more sporadic. In terms of engineering solutions, however, global excellence is stronger, as commercial demand is substantial. The main players are consultants based in the USA, Canada, Europe, and Australia, although major water utilities in these regions also hold a strong position.

Geotechnical: A select group of universities and research institutes globally excel in geotechnical research related to climate-resilient and adaptive infrastructure. Institutions such as UC Berkeley, the University of Texas at Austin, Imperial College London, Kyoto University, TU Delft, MIT, Stanford, and Tsinghua University continue to advance soil mechanics, advanced laboratory testing, and high-fidelity numerical modelling. Applied research organisations including NGI, Deltares, and ERDC provide essential expertise on soil–water interaction and the performance of dikes, levees, and coastal infrastructure under changing climatic conditions. Specialised centres drive progress in multimodal sensing of ground movement, notably NASA's Jet Propulsion Laboratory, GFZ Potsdam, Politecnico di Milano, the University of Salerno, and HKUST. Research on fissured and high-plasticity clays is led by the University of Cambridge, NGI, Kyoto University, UPC Barcelona, and Politecnico di Bari. Multi-physics modelling of climate-driven geohazards is advanced by TU Delft, ETH Zurich, CIMNE, and the University of Salerno.

Benefits for Danish research through collaboration with selected centers of excellence: The Danish partner universities, DTU, AAU and AU, will benefit from a collaboration with the listed global centres of excellence by leveraging on laboratory facilities not available in Denmark, starting from state-of-the-art models developed in these environments instead of building them from scratch, and by having feedback to guide the scientific direction and ensure relevance and quality of research within the field. Already, the DTU-AAU-AU team has well-established contact to several of the mentioned centres of excellence that will catalyse the early-phase collaboration.

2.2. State of the art and DK position in the research field

Like the previous section, the state of the art will be identified per discipline to provide a clear overview of what has been done and how the state is in Denmark.

Coastal: Traditional coastal protection methods, including sand nourishment and hard structures, see for instance (Brøker, 2008; Brøker et al., 2007b; Christensen et al., 2001; Drønen and Brøker, 2015; Kerper et al., 2002; Larson et al., 2005), are evolving toward a paradigm that views coastal zones as dynamic buffer areas, utilizing both soft, for instance salt marshes and mangroves, and hard measures to enhance biodiversity, in bridging gaps between engineering and environmental conservation and flexibility against climate changes. Reduction of access to materials from offshore sand mining calls for new and integrated solutions. This includes a growing focus on minimizing environmental impacts related to human interventions and climate change measures and improving biodiversity through new and stabilised habitats (Angnuureng et al., 2025; Le Xuan et al., 2022; OECD, 2018a; Richard Massenberg and Emil Panduro, 2024).

Flooding and waves in shallow water and their interaction with hard and soft coastal structures is still poorly understood and this applies also to accurate modelling of such conditions in physical and numerical models to analyse combined effects of artificial reefs seaweed, dunes and traditional methods as sand nourishment and hard emerged structures, (Burcharth et al., 2014) and (VAN DER MEER et al., 2024).

The integration of advanced techniques like Light Detection and Ranging (LiDAR) and image processing holds significant promise for mapping wave dynamics and shoreline changes, particularly in the context of coastal erosion monitoring (Collins et al., 2025). Despite their prior applications in wave measurement, the combined utilization of these technologies for the remote sensing of both dunes and wave patterns remains inadequately explored. A comprehensive understanding of the intricate interactions between flooding events, wave dynamics, and coastal infrastructure is essential for the effective implementation of innovative solutions like artificial reefs and sand dunes. Gaining a deeper understanding of the complex interactions among flooding, wave dynamics, and coastal structures is essential – particularly when implementing innovative solutions such as artificial reefs and sand dunes – where LiDAR systems can also play a key role in assessing the effectiveness of these interventions (Cesbron et al., 2021; Salameh et al., 2019).

The field of coastal engineering has notable hubs of expertise worldwide. Denmark is a prominent example, characterized by a robust collaboration among consultants such as NIRAS, COWI, SWECO, and RAMBOLL, as well as leading academic institutions including Aalborg University (AAU) and the Technical University of Denmark (DTU). Additionally, DHI stands out as a globally recognized research organization in this field.

Urban: Urban research increasingly focuses on integrating adaptive design principles to enhance infrastructure resilience against extreme weather. Yet a persistent gap exists between theoretical frameworks and their applicability to local built environments. Current mathematical frameworks predict extreme rainfall at a point location but not its spatial extent (Antoniadou et al., 2025), undermining the statistical basis for adaptation design. Compound flood hazards are largely assessed case-by-case (Green et al., 2025), leaving consistent spatial risk mapping absent. In practice, adaptation of the built environment is designed independently from day-to-day water management, as methods integrating surface and groundwater domains remain inaccurate and computationally prohibitive. Finally, the impacts of complex, overlapping regulation – economic utility regulation, water quality, flood management – and institutional arrangements are typically neglected (Haasnoot et al., 2024), creating substantial implementation risks that must be addressed through transition-based approaches.

In the technical domain, the mechanisms leading to microbially induced concrete corrosion are still quite poorly understood, especially when it comes to the interaction between the formation of corrosive sewer gases, the air of the sewers, and the biochemical process on and in the attacked concrete.

In general, the world changes much faster than the expected lifetime of infrastructure systems. This applies both to climate hazards, to the currently convoluted, entangled and fragmented regulatory system surrounding infrastructure planning, and to society's service expectations to the systems. Thus, infrastructure and facilities should be rethought to become less vulnerable and more resilient to gradually increasing and more concurrent hazards, as well as other societal drivers. Climate resilience here refers to the capacity of infrastructure systems to anticipate, prepare for, respond to, and recover from climate-related events, (OECD, 2018b), whereas adaptive refers to infrastructure that is specifically designed or modified to adjust to changing climate conditions over time, e.g. (Haasnoot et al., 2024).

The Climate change report from 2023 from IPCC presents scenarios on future climate changes and related impacts, (Calvin et al., 2023). These global impact projections need to be translated to regional and local impacts, which can serve as the backbone of future planning and design of infrastructure systems. These concepts are critical for ensuring the resilience of infrastructure in the face of evolving climatic hazards. Risk assessment and risk management are essential tools for guiding both future planning and the design of urban infrastructure.

AAU and DTU have for decades had strong research environments within urban infrastructure sewer systems, statistical methodologies for rainfall, flooding and use in management strategies. The area has many important players on municipality level, e.g. HOFOR, NOVAFOS, Aarhus Vand, but also on national level. e.g. environmental agency, GEUS, and DMI. Further, the Danish consultants, including COWI, Rambøll, NIRAS, SWECO, MOE, GEO, plays a central role in shaping practice, delivering deeply practice-driven solutions. Additionally, DHI stands out as a globally recognized research organization in this field.

Geotechnical: The international research frontier is moving toward integrated approaches that combine advanced multi-modal sensing, deeper understanding of climate-sensitive soils, and predictive modelling of ground-movement hazards. Technologies for in-situ measurement of ground movement are well-established but only allow local sensing. Interferometric synthetic-aperture radar (InSAR) has emerged as a useful technology for remote sensing of large-scale ground movement related to, e.g., landslides (Colesanti and Wasowski, 2006; Fan et al., 2026; Xu et al., 2026) as well as changing ground water levels (Amelung et al., 1999; Mondal et al., 2026), and construction activity, (Abidin et al., 2011; Hong et al., 2026; Perissin et al., 2012).

However, there is a research gap regarding the application of InSAR and distinguishing between climate-induced ground movement and movements caused by other sources in the built environment, e.g. construction activity. Hypoplastic and elastoplastic models for the constitutive behaviour of soil have existed for decades, (Alonso et al., 1990; Mašín, 2005; Niemunis and Herle, 1997; Taiebat and Dafalias, 2008) and provide useful results for soils such as sand and some types of clay, but for problematic soils such as high-plasticity, stiff and fissured clays (Sorensen et al., 2023) present in Danmark and several other countries, only few studies exist. Work has been done regarding the soil–atmosphere–vegetation interaction in slopes, (Tagarelli and Cotecchia, 2025), but generally applicable constitutive models for soil analysis in a changing climate are missing.

Advanced analysis based on finite-element and finite-difference methods has been used widely in the geotechnical community for research and design of large infrastructure and offshore projects. To tackle large deformations associated with landslides, the material point method (MPM) (Andersen and Andersen, 2010; Li et al., 2026; Su et al., 2025)and smoothed particle hydrodynamics (SPH), (Liu et al., 2026; Pastor et al., 2009; Xie et al., 2026), have been proposed. While already implemented in some commercial software and open-source frameworks, the current formulations hinder realistic and reliable analysis of multi-physics problems related to the thermo-hydro-mechanical response of soil in climate-driven wetting–drying scenarios at different time scales and with water from different sides (stormwater, waves, groundwater). The leading questions, therefore, revolve around how to fuse satellite-based and terrestrial measurements into reliable early-warning systems; how to characterise soils whose behaviour changes under extreme rainfall, drought, and long-term environmental loading; and how to build models that capture the coupled processes driving deformation in both coastal and urban settings.

Aarhus University has, in recent years, made substantial investments in geotechnical engineering and is emerging as the national research environment with the breadth and critical mass needed to address the increasingly complex challenges posed by climate change. AAU and DTU have for decades had strong geotechnical units. The Danish consulting and contractor ecosystem—including COWI, Rambøll, NIRAS, MOE, GEO, GEUS, and major infrastructure owners—plays a central role in shaping practice, delivering deeply practice-driven solutions that are often ahead of what is documented in academic literature. Altogether, this creates a strong foundation for innovation and research at the forefront of the research field, but also a need for closer collaboration between academia and industry to develop new methods, validate emerging technologies, and support a common long-term research agenda.

3. How the research field will address the core challenges

Each discipline involved in the research field will contribute to addressing the core challenges. A brief outline is given below.

Coastal: A much better link between advanced systems and analyses tools/techniques to real world data. Extensive field and lab data will support developing technologies and procedures. This will lead to a much more valuable knowledge chain along with data, analyses and design. Much data from publicly available remote sensing, i.e. Copernicus services and orthophotos, shall be explored as much as possible as it serves as an easy access to a wide range of stakeholders.

High fidelity models, as computation fluid dynamics (CFD), will be used to fundamentally study interaction between sediments, seaweed and porous structures as breakwaters and artificial reefs. This will serve as the basis for include parameterised models in regional scale models that can predict impact for future climate scenarios. The regional models shall serve as a test bench for alternative solutions where effects of climate changes and measures for enhancement of biodiversity can be tested on equal terms.

The integration of extensive field and laboratory data is essential for supporting the application of advanced models and expert systems in decision-making regarding adaptation, protection, and abandonment strategies for infrastructure. A comprehensive catalogue detailing traditional hard approaches – such as the construction of physical barriers, alongside soft approaches like sustainable land management and ecosystem restoration – will serve as a foundation for exploring innovative solutions to contemporary challenges.

To ensure the real-world applicability of these new methods, demonstration projects will be crucial in showcasing their effectiveness and encouraging broader societal adoption. Additionally, projecting climate change impact scenarios will provide a robust basis for conducting detailed risk assessments, enabling stakeholders to understand vulnerabilities and develop targeted responses. By synthesizing this data, practitioners can formulate strategic recommendations that not only defend existing systems but also promote sustainable practices that align with future environmental conditions.

Urban: The urban water infrastructure is challenged by several factors driven by climate change, a changing demography, and growing service level requirements. RF5 addresses root causes of the problem complexes, investigates key elements, and generates models, holistic solutions, and risk assessment tools.

One problem complex is related to increasing precipitation where today's extreme events will become tomorrow's norm. At the same time, urban densification and increased service level requirements mean that technical and nature-based solutions must manage a larger fraction of the precipitation to a higher quality. A major contribution to addressing this core challenge is to better understand future extreme precipitation patterns and give guidance on how to implement this knowledge for an improved design of solutions, tools, and models. Another is to increase the quality of precipitation nowcasting, i.e., to increase the accuracy of predicting the immediate future (0–6 hours) of high-intensive precipitation. This is needed for real time control in urban stormwater management, which will mitigate risk without extensive changes in the water infrastructure. A further contribution is to improve local management of stormwater by nature-based solutions that combine flood management, water quality management, and liveability in the city.

Another problem complex is related to the management of foul sewage in an aging infrastructure. Climate change cause longer droughts, higher temperatures, and lower groundwater levels, while urban densification and lower groundwater levels cause stronger wastewater. This then leads to higher biological activity in sewers and the formation of problematic gases. One is hydrogen sulphide which causes the concrete infrastructure to degrade and collapse long before the end of its planned service life. Other gases are related to odour nuisances, and some are greenhouse gases. A major contribution to addressing this core challenge is to develop sustainable technologies to counteract these gases. Another is to develop better tools and models to predict and manage sewer septicity and concrete corrosion, tools that among others allow reliable forecasting of problems and system failure.

To effectively address the challenges facing urban infrastructure, a major contribution will develop new engineering guidelines that respond to compound risks (multiple hazards including rain, river flow, groundwater and sea surge) and align with contemporary urban needs with the goal that they become implemented in the industry. These guidelines shall promote adaptive thinking within the sector, encouraging innovative solutions to the ever-evolving challenges of urban environments, notably nature-based solutions and digital solutions that enhance biodiversity and increase efficiency. Engaging stakeholders is vital for shaping and influencing future regulations that prioritize sustainable practices and will be part of this effort. Additionally, we will contribute with fostering community involvement in urban planning processes, which is essential for promoting inclusive decision-making. These efforts shall support investing in research, technology, and education that will serve as a significant vehicle for achieving these goals. This approach will facilitate interdisciplinary collaboration among urban planners, engineers, and environmental scientists, ultimately leading to more resilient and sustainable urban infrastructure.

Geotechnical: The geotechnical strand will deliver an integrated suite of activities linking multi-physics simulation, remote and terrestrial monitoring, targeted soil characterisation and modelling, and risk-mapping into operational tools for climate-resilient infrastructure.

Over the first four years, a beta computational framework will be developed to couple thermal, hydraulic and mechanical processes and to support both continuum (FEM) and particle-based (MPM/SPH) solvers; by year eight this framework will be finalised and industry-tested for analysis of settlements, landslides and coastal erosion. The aim is to produce a multi-scale and multi-fidelity hierarchical framework that allows detailed analysis of, for example, the onset of landslides as well as the ground movement over large zones.

Laboratory and field tests will quantify wetting–drying and cyclic responses of representative Danish soils, including high-plasticity and fissured clays, and form the basis for development of constitutive models, with user-material implementations for numerical solvers. Combined with the proposed numerical modelling framework, it will be investigated whether cracks formed, for example, by extreme drought should be included in the constitutive model, or if they should be modelled explicitly to analyse the effects of percolating water.

Parallel work on sensing will harmonise InSAR with terrestrial monitoring into a common data pipeline and attribution methodology, producing standardised datasets, fusion algorithms and spatially continuous deformation maps suitable for monitoring and early warning. While LiDAR processing is pursued principally within the coastal engineering research line, the geotechnical strand will focus on its integration to support nearshore geotechnical hazard mapping.

Validation follows a hierarchical pathway from element tests to instrumented plots and full-scale pilots, with midterm milestones including beta testing on 1–2 cases, code release to a public repository and co-delivery of pilot projects with industry partners. Finally, towards the end of the programme, risk-mapping activities, in collaboration with the coastal and urban strands, will translate model outputs and fused monitoring data into hazard maps and vulnerability scores for critical corridors, and will deliver an integrated dashboard that combines probabilistic forecasts with prioritisation metrics and interfaces for life-extension analyses from RF7.

3.1. Global Perspectives

The knowledge ecosystem already aligns with challenges, as Danish research institutes and consultancy companies already adopt technologies, that leads to significant knowledge exports, with over half of their revenue often generated from international projects. Research results – methodologies as well as technological solutions – can be applied worldwide with impact also in the global south. For example, coastal protection by nature-inspired solutions rather that hard protection with concrete walls is relevant for low-lying countries like Bangladesh, [43, 44], many island communities, and coastal cities in Africa. Here, an ongoing collaboration with University of Braunschweig, Germany, and National Technical University of Athens, Greece, will continue, also regarding the assessment of flooding in coastal as well as urban areas.

Communities in most developing countries are also prone to geohazards that potentially put infrastructure at risk. The work within RF5 will provide a basis for collaboration with and strengthening of research environments in these countries. For example, landslides are a major concern in the remote highlands of Ethiopia, [45, 46] and a connection has been made to researchers at Jimma University and other institutions with the aim to attract funding from Danida.

Further, researchers associated with the research field have a history of working with railways and underground infrastructure with various universities in the US and UK, including, UC Berkeley, UT Austin, University of Nottingham, University of Cambridge, and University of Southampton. In collaboration with researchers from Germany (e.g. Karlsruhe Institute of Technology, Ruhr

University Bochum) and Colombia, members of the geotechnical group from AU work have worked on advanced geotechnical modelling of soil and landslides.

The global perspectives will be pursued with three instruments: 1) Direct through research collaboration such as common EU and other international funded research and demonstration projects. 2) Indirect through global applicability of methodologies and solutions through engineering companies that introduces tailor made versions locally at global scale. Danish consultancy companies get a large part of their revenue from international projects including developing countries. 3) More traditional dissemination as academic publications, design codes and guidelines, and through open software and databases of results.

4. Impact framework

4.1. Intended impact

- Uptake of technology and methodology in industry and society enabling the actions to the green transition. (an enabler). An early-stage real impact.
- Municipalities, agencies and consulting engineers embed resilient, holistic and adaptive solutions for coasts that enhances the biodiversity in their approach to address climate changes within planetary boundaries.
- Municipalities and developers will focus on resilient buildings and infrastructure enhancing liveability and sustainability in a changing world.

4.2. Contextual conditions

The traditional practices of consulting engineers often rely on rigid business cases that may not adequately address the dynamic challenges of urban development and coastal risks. Existing legislative barriers can hinder optimal land use, limiting opportunities for innovative solutions. To promote sustainable development, legislation should be revised to incorporate flexible buffer zones and accommodate biodiversity. This will be pursued by integrating relevant public entities, Specifically, it will include the Coastal Directorate and Kommunernes Landsforening (KL) (English: Union of Municipalities). The activities will be both applied research and later demonstration projects. Today, there are opportunities to test new approaches on an experimental level under the current legislation. Eventually, the legislation can only be changed by national governments and parlements. This approach will enhance the resilience of our urban and coastal landscapes while fostering a more harmonious relationship between development and the natural environment.

4.3. CEBE impact levers

To secure the road for the intended impacts, steps to expand the funding for technological development and innovation through partnerships with industry, municipalities, and other stakeholders will be taken.

1) Very early in the project, this will include presentations at seminars and workshops with industry in the relevant national societies (e.g. Vandbygningsteknisk Selskab, Dansk Geoteknisk Forening), and by meetings with KL.

2) The outcome of the research will be disseminated through the most important channels: university degree programmes in civil engineering, and life-long education courses focused on climate-resilient and liveable solutions. This will equip professionals with essential skills for the future. The initiatives 1) and 2) have already begun and will continue throughout and after the project life.

3) An essential tool is dissemination through traditional academic channels such as peer-reviewed journal publications and conference contributions on an international level. The dissemination begins early and continue throughout the project through open access publications. National and international collaboration will aid the strengthening of academic networks and the scientific anchoring of the results.

4) The research results shall lead to the development of guidelines for implementing methods for resilience that enhance biodiversity in urban and coastal areas. This will be supported by common applications for funding aimed at innovation and demonstration projects with industry and EU partners. Seminars and workshops with industry leaders and municipal representatives will be organised to explore new technologies and methodologies.

5) To gain acceptance for solutions among a broader range of stakeholders, it is essential to launch pilot projects that challenge conventional practices. These projects should create realistic showcases of innovative approaches.

These activities are foreseen at a later stage in the CEBE programme. Items 1–3 can be carried out from the CEBE programme itself, while items 4 and 5 necessitate common research and development projects. To reach these goals, we shall reach out to national and international partners.

4.4. Intended outcomes and main beneficiaries

Workable solutions and guidelines to build future business cases to address climate changes and create liveable environments. More accurate analysis of the extent and character of settlements and landslides and the related forces on infrastructure. Better prediction of climate-driven degradation and instability in failure prone soil slopes. Better integration of solutions for land system change. Reduce use of resources based on precise and effective planning and increased accuracy in risk assessment.

The most important stakeholders are consulting engineers for the technology itself, municipalities for understanding the overall perspectives of solutions, utility companies that plan, implement and operate infrastructure investments, and governmental agencies that handles legislation. Contractors will be to less extent stakeholders as they often are supported by consulting engineers.

4.5. Research outputs

In the following, we specifically focus on the research outputs from the projects, again divided by discipline. This needs to be aligned with development and demonstration projects to achieve the full potential as outlined in Section 4.3. In the following, timing is either first (year 1–4), middle (3–7) or last (7–10). This is followed by an indication of who benefits from the activity, and finally how the adaptation is facilitated.

Coastal:

Data and methodologies:

- Remote sensing methodologies utilized to monitor shoreline movements (When: First; Who: Coastal managers; How: Dissemination of technology)
- Data-driven models provide remote wave measurements essential for understanding coastal dynamics. (When: first; Who: Scientists and engineers; How: Dissemination of technology)
- Innovations in physical model testing of coastal structures under specific wave conditions have yielded deeper insights into wave-structure interactions. (When: First; Who: Scientists and engineers; How: Dissemination in scientific publications).

Models and solutions:

- Methodologies to simulate interactions between morphology, porous reefs, and artificial protection methods. (When: First; Who: Scientists and engineers; How: Dissemination in scientific publication, and open-source software)
- Nature-inspired solutions explored for shoreline protection, integrating vegetation and marsh land as buffer zones. (When: middle; Who: scientists, engineers; How: Dissemination in scientific publication, and open-source software)
- Streamlined methods for predicting stable shoreline positions based on various protection schemes. (When: middle; Who: Scientists, engineers; How: Dissemination in scientific publication, and open-source software)
- Key advancements change best practices, emphasizing the synergy between coastal defence and biodiversity enhancement. (When: last; Who: consulting engineers and public entities; How: Dissemination in scientific publication, and at seminars and workshops)
- Downscaling of climate change scenarios to local coastal impact assessment. (When: last; Who: consulting engineers and public entities; How: Dissemination in scientific publication, and at seminars and workshops).

CEBE

Urban:

The core complex related to increasing precipitation, urban densification, and increased service level requirements will lead to several major research outputs:

- Increased knowledge of precipitation nowcasting based on weather radar data. (When: first; Who: scientists, engineers, data providers; How: Dissemination in scientific publications, conferences, meetings, and workshops)
- Deeper understanding of future extreme precipitation and how this can be applied for improved design. (When: middle; Who: scientists, engineers; How: Dissemination in scientific publications, conferences, meetings, and workshops)
- Improved data management for real time control of urban stormwater management. (When: middle; Who: scientists, engineers; How: Dissemination in scientific publications, conferences, meetings, and workshops)
- Increased knowledge on concurrency of multiple hazards that impact urban infrastructure. (When: last; Who: scientists, engineers; How: Dissemination in scientific publications, conferences, meetings, and workshops)
- Deeper insights into nature-based solutions for stormwater management. (When: first; Who: scientists, engineers, planners, vendors; How: Dissemination in scientific publications, conferences, meetings, and workshops)
- Downscaling of climate change scenarios to local urban infrastructure. (When: middle; Who: scientists, engineers; How: Dissemination in scientific publications, conferences, meetings, workshops, guidelines)
- Deeper insight into planning processes and governance mechanisms that needs aligning to support inclusive adaptive planning of resilient infrastructure. (When: last; Who: scientists, engineers, planners; How: Dissemination in scientific publications, conferences, meetings, and workshops).

The core complex related to management of foul sewage in an aging infrastructure and a changing environment will lead to several major research outputs:

- Increased knowledge on processes leading to problematic sewer gases and attack of concrete structures. (When: first; Who: scientists, engineers, model developers; How: Dissemination in scientific publications, conferences, meetings, and workshops)
- Deeper insight into processes allowing the design of sustainable technologies to counteract problematic sewer gases. (When: middle; Who: scientists, engineers, vendors; How: Dissemination in scientific publications, conferences, meetings, and workshops)
- Improved model concepts for reliable forecasting of corrosion, odour, and greenhouse gas related problems as well as system failure risk assessment. (When: first; Who: scientists, engineers, planners, model developers; How: Dissemination in scientific publications, conferences, meetings, and workshops).

Geotechnical:

In geotechnical engineering, the core challenge is to develop a framework that allows the analysis, design, and adaption of geotechnical structures (e.g. foundations, tunnels, quays, deep excavations, dikes, and embankments) to meet the future. This will be addressed via three main lines of research and their uptake by industry.

Multi-physics computational framework for climate-driven geohazards:

- A methodology and conceptual multi-physics modelling framework for the analysis of the interaction between soil, water, and structures in coastal and urban environments, and an increased understanding by the industry regarding the application of the suggested methodology (When: First; Who: Scientist, engineers; How: Dissemination in scientific publications, conferences, meetings, open-source software, public datasets)
- Improved and extended multi-physics modelling framework for the multi-scale analysis of geohazards in coastal and urban areas and testing the framework on cases selected in collaboration with industry (When: Middle; Who: Scientists, engineers, planners, developers; How: Dissemination in scientific publications, conferences, meetings, open-source software, public datasets).

Improved understanding of Danish soils under changing climatic conditions:

- Improved geotechnical understanding and baseline constitutive models of soils in a changing climate with focus on the hydro-mechanical behaviour of tertiary Danish clays, including the uptake by industry and application to selected cases (When: First; Who: Scientists, engineers; How: Dissemination in scientific publications, conferences, meetings, open-source software, public datasets)
- Further improved geotechnical understanding of Danish soils in a changing climate, with enhanced soil characterisation and advanced constitutive modelling of the thermo-hydro-mechanical soil behaviour, including the uptake by industry and application to selected cases (When: Middle; Who: Scientists, engineers; How: Dissemination in scientific publications, conferences, meetings, open-source software, public datasets).

Blending Earth observation, physics-based models, and uncertainty analysis:

- A framework for fusing satellite and terrestrial data with physics-based models for ground movement, including the uptake by industry for the assessment of geohazards with focus on quay structures in Danish ports (When: First; Who: Scientists, engineers, authorities; How: Dissemination in scientific publications, conferences, meetings, open-source software, public datasets)
- Extended framework for mapping climate-induced risks to infrastructure by blending Earth observation, physics-based modelling, and uncertainty analysis, including the uptake by industry and the application to ports in larger scale (When: First; Who: Scientists, engineers, authorities; How: Dissemination in scientific publications, conferences, meetings, open-source software, public datasets).

Risk:

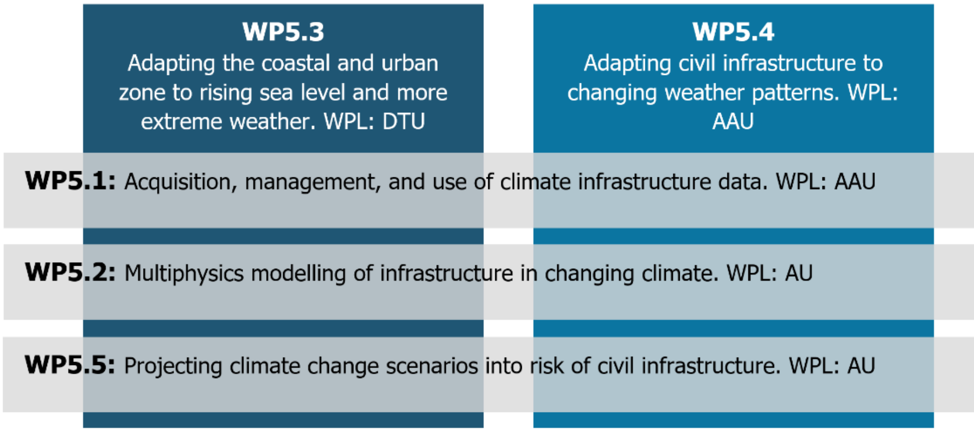
Bridging the activities related to coastal, urban, and geotechnical engineering, and merging the outcomes of the individual research lines, a framework for risk-informed decision making will be formulated with the following major outputs:

- Methodologies for prediction and mitigation of geotechnical, coastal, and urban-water hazards caused by changing climate, including monitoring and modelling, and tested and various cases selected in collaboration with industry, developers, and authorities (When: Middle; Who: Scientists, engineers, authorities; How: Dissemination in scientific publications, conferences, meetings, open-source software, public datasets)
- A framework for sufficiently accurate prediction of climate hazards and mapping their impact to risk for urban and coastal infrastructure, including uptake by industry and authorities, and tested on real cases selected in collaboration with industry, developers, and authorities (When: Last; Who: Scientists, engineers, authorities; How: Dissemination in scientific publications, conferences, meetings, open-source software, public datasets)
- A risk-informed strategy and decision framework aimed at developing strategies for protecting, adapting, or abandoning infrastructure, including uptake by industry and authorities (When: Last; Who: Scientists, engineers, authorities; How: Dissemination in scientific publications, conferences, meetings, open-source software, public datasets).

4.6. Research activities

The work package structure is illustrated below. Rather than sticking to the discipline divided identification of the state of the field, etc., the activities will be organized across the disciplines to secure integration and the common development of sensing and modelling methodologies, coastal and urban climate adaption strategies for rising sea levels and changing weather patterns, and risk assessment of civil infrastructure.

The fundamental work packages WP5.1 and WP5.2 will be the scientific fundament for developing solutions in WP5.3 and WP5.4. The climate-induced risks will be assessed in WP5.5. Each work package relies on different research disciplines that align with coastal, geotechnical, and urban engineering. In WP5.3 there will be close connection between coastal and geotechnical disciplines and in WP5.4 between geotechnical and urban disciplines. Risk analyses will draw on all three disciplines and are carried out in WP5.5.



The following gives a short description of the work packages:

WP5.1: Acquisition, management, and use of climate and infrastructure data: Multimodal sensing, data acquisition, and data-driven models can be developed for timely engineering assessment of infrastructure and risk-based decision making for infrastructural resilience in a changing climate.

WP5.2: Multiphysics modelling of infrastructure in a changing climate: Computational models based on sound physical principles and validated by rigorous experimental testing will provide increased understanding of complex processes and allow accurate forecasting of deterioration, loss of safety and collapse and guide adaptations of infrastructure related to the interactions between infrastructures and the environment.

WP5.3: Adapting the coastal and urban zone to rising sea levels and more extreme weather: Rethinking the coastal and rural areas as a buffer zone between the water and the built environment, balancing coastal protection, retention basins, and infrastructure, will reduce the negative economic and environmental consequences of climate change significantly.

WP5.4: Adapting civil infrastructure to changing weather patterns: Increasing precipitation, droughts, and temperature requires new ways to think urban infrastructure management. Cities must be adapted to meet pressures from wind, stormwater, groundwater, and temperature variations, as these affect the civil infrastructure and the subsoil. A deeper process understanding, sensing of the systems and at their boundaries, and integrated models of the infrastructure and its environment will allow the civil infrastructure to adapt to the imminent changing weather patterns including future extreme weather conditions.

WP5.5: Projecting climate change scenarios into risk of civil infrastructure: Continuously updated data-driven models combined with physics-based simulations and probabilistic methods can provide risk-based decision-making tools, accounting for hazards-vulnerability-exposure, supporting resilience of civil infrastructure beyond the capabilities of current design practices.

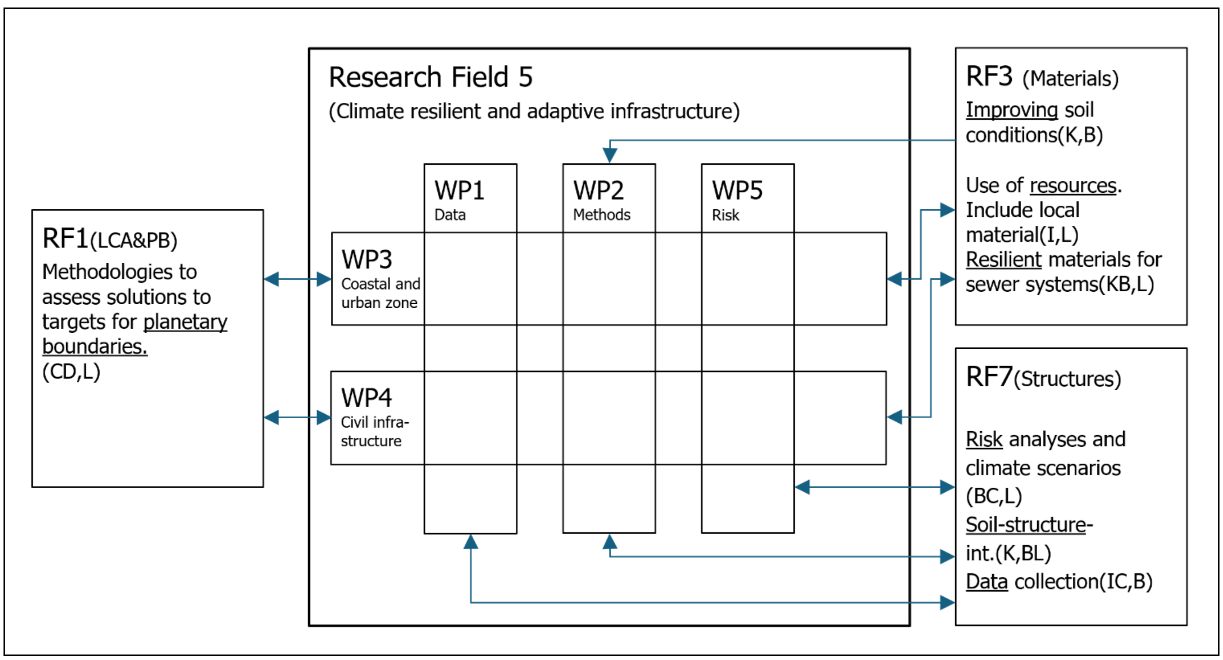
Crossfield integration

In the following an illustration of the interactions with other research fields is given. In the illustration the letters in parentheses indicate the type of interaction and the timing. For example (K, B) means (Type: Knowledge exchange for inspiration, efficiency and increased quality, Time: Beginning, year1-4.

Types of interaction:
K: Knowledge exchange for inspiration, efficiency and increased quality
B: Deliver/receive boundary conditions/context for the research activity
I: Deliver/receive necessary information on research results to enable research progress
C: Collaboration/co-development of research results.

Timing:
B: Beginning, year 1-4
L: Later, Year 5-10

Illustration of RF5 interactions with other RFs



RF5 provides crucial knowledge and technical solutions essential for the life cycle assessments and sustainability analyses outlined in RF1. The interactions between civil infrastructure and planetary boundaries – central to WP1.1 in RF1 – highlight the need for innovative approaches to climate adaption, but also a need for a new way of evaluating how well the adaption approaches tap into the green transition by offering added value and multi-faceted sustainability. RF5 proposes the development of adaptable buffer zones and green stormwater solutions that aim to mitigate the biodiversity crisis while simultaneously enhancing the resilience of infrastructure against future climate change impacts, and life-cycle assessment tools able to holistically judge the value of such approaches are yet missing.

Additionally, RF5 emphasizes the importance of utilizing local materials for infrastructure construction. The construction industry is responsible for more than half of raw material usage and landfill waste generation. In Denmark, excavated materials are seldom reused on-site; surplus soil is often disposed of as landfill or repurposed for agricultural enhancement, leading to transportation of large amounts of heavy materials over long distances. This practice not only poses environmental challenges but also exacerbates the demand for gravel and sand resources. Addressing this issue is a key focus of WP3.2 and WP3.4 in RF3, and the methodologies developed there should be integrated into geotechnical solutions explored in RF5.

Further, RF5 cross-interlinks on RF3 with respect to the use of low-carbon cement and other alternative construction materials in the aggressive environment of urban sewer infrastructure. It develops and improves methods to alleviate the conditions that cause biogenic material deterioration in drainage systems, and novel ways to select the pipe and structures material best suited for a drainage system in a changing climate.

The infrastructure and its boundaries delineate the parameters for structural analyses in RF7. There are links related to the environmental conditions and the structure-soil-interactions. While both RF5 and RF7 tackle aspects of risk management, RF5 specifically concentrates on methodologies for incorporating climate change scenarios, whereas RF7 emphasizes risk management concerning the longevity of individual buildings and civil structures such as bridges. To enhance overall effectiveness, RF7 should integrate climate change scenarios into its risk management framework for individual structures.

4.7. Research Field specific output, outcome and impact targets

For the research field we have defined the following targets for which the realization hereof will be evaluated over the course of the programme. To manage the activities throughout the project, it has been chosen to order them by discipline. The main responsible universities are indicated.

Targets of the research field

Costal: **Target name & description**	**Evaluation method**	**Impact Type**	**Category**	**Years**
Methodology to include remote sensing in shoreline movements to assess coastal morphological changes (DTU, AU)	Publication	Output	New method	4
System for remote wave measurements and a related data-driven model. (AU)	Publication	Output	New method	4

Detailed methodologies to model morphology interactions with porous reefs, stone protection, seaweed (DTU)	Publication	Output	New method	4
Overall fast methodologies to predict stable shoreline positions for varies protection schemes (DTU)	Publication	Output	New tool	5
Solutions with nature inspired protection methods acting as buffer zones with vegetation, and retention basins (DTU)	Report/publication	Output	New concept/ approach	8
New developed methods and tools for shoreline dynamics and morphological changes (DTU)	Survey	Outcome	Applied by consultancy	8
Changed view on best practices for combined coastal protection and enhancement of biodiversity. (DTU)	Survey from held seminars	Impact	Change in perception	6
Methodologies of combined coastal protection and nature-based solution (DTU)	Survey from held seminars	Impact	Change of behaviour	8
Demonstration of combined coastal protection and means to enhance biodiversity (DTU/AAU)	Report on outcome of demonstration	Outcome	Demonstrated in practice with consultants and public entities	10
Improved methodology for physical model testing of coastal structures exposed to short-crested waves in shallow water (AAU)	Scientific publication	Output	New method	4
Improved methodology for physical model testing of coastal structures exposed to short-crested waves in shallow water (AAU)	Implementation in software of experimental facilities	Outcome	Applied by the industry and research institutes	10
Deeper understanding of the wave/structure interaction processes for long- and short-crested waves (AAU)	Scientific publication	Output	New method	4
Deeper understanding of the wave/structure interaction processes for long- and short-crested waves (AAU)	Implementation in prediction tools	Outcome	Applied by industry	10

Urban: Target name & description	Evaluation method	Impact Type	Category	Years
A sustainable and green method to counteract negative impacts of sewer septicity (AAU)	Lab scale pilot	Output	New technology	4
A sustainable and green method to counteract negative impacts of sewer septicity (AAU)	Field demonstration involving wastewater utilities and material suppliers	Outcome	Applied by industry	8
A reliable numerical model to predict and manage sewer septicity impacts such as biogenic concrete corrosion (AAU)	Scientific publication	Output	New method	4
A reliable numerical model to predict and manage sewer septicity impacts such as biogenic concrete corrosion (AAU)	Field demonstration involving wastewater utilities and material suppliers	Outcome	Demonstration in practice	6
A framework for the development of real-time and near-future high-resolution rainfall data using weather radar in urban hydrological and climatological applications (AAU)	Scientific publication	Output	New approach	4
A framework for the development of real-time and near-future high-resolution rainfall data using weather radar in urban hydrological and climatological applications (AAU)	Field demonstration involving wastewater utilities and material suppliers	Outcome	Applied by the industry	10
A statistical framework understanding spatially distributed precipitation historically and in future climate scenarios, for use in urban hydrological applications (AAU, DTU)	Scientific publication	Output	New approach	4
A statistical framework understanding spatially distributed precipitation historically and in future climate scenarios, for use in urban hydrological applications (AAU, DTU)	Implementation in prediction tools by the universities	Outcome	Applied by industry	10
Statistical methods for designing water management in urban spaces that are exposed to compound water risks(rain, river flow, groundwater, sea surge): Methodologies to derive design criteria for individual infrastructure components that	Scientific publication	Output	New approach	3

down-scale and exploit data from large-scale climate projections (DTU)				
Statistical methods for designing water management in urban spaces that are exposed to compound water risks(rain, river flow, groundwater, sea surge): Methodologies to derive design criteria for individual infrastructure components that down-scale and exploit data from large-scale climate projections (DTU)	Implementation in prediction tools	Outcome	Applied in regulation/standardisation industry	4
Sustainable water management in areas exposed to compound water risks – I: Methods (quantitative screening approaches, dynamic adaptive strategies, sustainability assessments) for designing resilient water management strategies in areas that are exposed to compound water risks and where climate change impacts are uncertain. (DTU)	Scientific publication	Output	New approach	4
Sustainable water management in areas exposed to compound water risks – II: Case demonstrations in small-to-medium size Danish coastal towns that are most challenged in developing adaptive water management (DTU)	Field demonstration / pilot study involving water utilities and material suppliers	Outcome	Applied by industry	6

Geotechnical: **Target name & description**	**Evaluation method**	**Impact Type**	**Category**	**Years**
Computational framework for the simulation and prediction of climate-driven geohazards: Developing a multi-physics modelling tool for the analysis of soil-structure-water interaction in coastal and urban areas (AU)	Verification and validation	Output	New method + New Tool	4
Computational framework for the simulation and prediction of climate-driven geohazards: Developing a multi-physics and multi-scale modelling tool for the analysis of soil-structure-water interaction in coastal and urban areas (AU)	Case studies (real-event back-analysis)	Output	New method + New Tool	8
Computational framework for the simulation and prediction of climate-driven geohazards: Uptake by industry for the simulation of ground movement (AU)	Dialogue, survey, collaboration with consultants	Outcome	Applied by consultancy	4

Computational framework for the simulation and prediction of climate-driven geohazards: Uptake by industry for assessment of landslides, ground settlements, and the related forces on infrastructure (AU)	Dialogue, survey, collaboration with consultants, case studies (2-3 cases)	Outcome	Demonstrated in practice	8
Improved geotechnical understanding of Danish soils in a changing climate: Soil characterisation and simple constitutive model of the hydro-mechanical soil behaviour in a changing climate (AU)	Verification and validation, testing in an existing software environment	Output	New method + New tool	3
Improved geotechnical understanding of Danish soils in a changing climate: Enhanced soil characterisation and advanced constitutive model of the thermo-hydro-mechanical soil behaviour in a changing climate (AU)	Verification and validation, testing in different software environments	Output	New method + New tool	7
Further improved geotechnical understanding of Danish soils in a changing climate: Uptake of new knowledge by the geotechnical community (AU)	Dialogue, survey, collaboration with consultants	Outcome	Applied by consultancy	4
Further improved geotechnical understanding of Danish soils in a changing climate: Uptake of new soil models by the geotechnical community and application to real construction projects (AU)	Dialogue, survey, collaboration with consultants, case studies (1-2 cases)	Outcome	Demonstrated in practice	8
Mapping climate-induced risks to infrastructure by blending Earth observation and uncertainty analysis: Integrating satellite and terrestrial data with physics-based models for mapping climate-driven geohazards (AU)	Verification and validation + case studies (1-2 cases)	Output	New approach	4
Mapping climate-induced risks to infrastructure by blending Earth observation and uncertainty analysis: Integrating satellite and terrestrial data with physics-based models to assess geotechnical risk for civil infrastructure (AU)	Verification and validation + case studies (1-2 cases)	Output	New approach	8
Mapping climate-induced risks to infrastructure by blending Earth observation and uncertainty analysis: Uptake by industry for assessment of geohazards (AU)	Dialogue, survey, collaboration with consultants	Outcome	Applied by consultancy	4
Mapping climate-induced risks to infrastructure by blending Earth observation and uncertainty analysis: Uptake by industry	Dialogue, survey, collaboration with	Outcome	Demonstrated in practice	8

for assessing the geotechnical risk for civil infrastructure (AU)	consultants, case studies (1-2 cases)			

5. References

Abidin, H.Z., Andreas, H., Gumilar, I., Fukuda, Y., Pohan, Y.E., Deguchi, T., 2011. Land subsidence of Jakarta (Indonesia) and its relation with urban development. Natural Hazards 59, 1753–1771. https://doi.org/10.1007/s11069-011-9866-9

Ali, A., Teku, D., Sisay, T., Mihret, B., 2025. Geospatial modeling of landslide susceptibility in Debek, South Wollo, Ethiopia: comparative analysis of frequency ratio and analytical hierarchy process models for geohazards management. Front. Earth Sci. (Lausanne). 13. https://doi.org/10.3389/feart.2025.1557860

Alonso, E.E., Gens, A., Josa, A., 1990. A constitutive model for partially saturated soils.

Amelung, F., Galloway, D.L., Bell, J.W., Zebker, H.A., Laczniak, R.J., 1999. Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation. Geology 6, 483–486. https://doi.org/https://doi.org/10.1130/0091-7613(1999)027<0483:STUADO>2.3.CO;2

Andersen, S., Andersen, L., 2010. Modelling of landslides with the material-point method. Comput. Geosci. 14, 137–147. https://doi.org/10.1007/s10596-009-9137-y

Angnuureng, D.B., Charuka, B., Almar, R., Dada, O.A., Asumadu, R., Agboli, N.A., Ofosu, G.T., 2025. Challenges and lessons learned from global coastal erosion protection strategies. iScience. https://doi.org/10.1016/j.isci.2025.112055

Antoniadou, N., Stockmarr, A., Pedersen, J.W., Schmith, T., Mikkelsen, P.S., 2025. Spatiotemporal analyses of extreme rainfall frequencies in Denmark via Bayesian hierarchical modelling using SPDE with INLA. Stochastic Environmental Research and Risk Assessment 39, 4125–4143. https://doi.org/10.1007/s00477-025-03054-5

Brøker, I., 2008. The use of advanced numerical models to support the design of coastal structures. European Journal of Environmental and Civil Engineering 12, 67–86. https://doi.org/10.1080/19648189.2008.9692996

Brøker, I., Zyserman, J., Madsen, E.Ø., Mangor, K., Jensen, J., 2007a. Morphological modelling: A tool for optimisation of coastal structures. J. Coast. Res. 23, 1148–1158. https://doi.org/10.2112/04-0380.1

Brøker, I., Zyserman, J., Madsen, E.Ø., Mangor, K., Jensen, J., 2007b. Morphological modelling: A tool for optimisation of coastal structures. J. Coast. Res. 23, 1148–1158. https://doi.org/10.2112/04-0380.1

Burcharth, H.F., Lykke Andersen, T., Lara, J.L., 2014. Upgrade of coastal defence structures against increased loadings caused by climate change: A first methodological approach. Coastal Engineering 87, 112–121. https://doi.org/10.1016/j.coastaleng.2013.12.006

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P.W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W.W.L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, Y.-Y., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F.E.L., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H.-O., Revi, A., Roberts, D.C., Roy, J., Ruane, A.C., Skea, J., Shukla, P.R., Slade, R., Slangen, A., Sokona, Y., Sörensson, A.A., Tignor, M., van Vuuren, D., Wei, Y.-M., Winkler, H., Zhai, P., Zommers, Z., Hourcade, J.-C., Johnson, F.X., Pachauri, S., Simpson, N.P., Singh, C., Thomas, A., Totin, E., Alegría, A., Armour, K., Bednar-Friedl, B., Blok, K., Cissé, G., Dentener, F., Eriksen, S., Fischer, E., Garner, G., Guivarch, C., Haasnoot, M., Hansen, G., Hauser, M., Hawkins, E., Hermans, T., Kopp, R., Leprince-Ringuet, N., Lewis, J., Ley, D., Ludden, C., Niamir, L., Nicholls, Z., Some, S., Szopa, S., Trewin, B., van der Wijst, K.-I., Winter, G., Witting, M., Birt, A., Ha, M., 2023. IPCC, 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.59327/IPCC/AR6-9789291691647

Cesbron, G., Melet, A., Almar, R., Lifermann, A., Tullot, D., Crosnier, L., 2021. Pan-European Satellite-Derived Coastal Bathymetry—Review, User Needs and Future Services. Front. Mar. Sci. https://doi.org/10.3389/fmars.2021.740830

Christensen, E.D., Skou, A., Brøker, I., Rubjerg, M., Sørensen, P., 2001. Sediment transport along the west coast of Jutland, in: 12th Biennial Coastal Zone Conference. Cleveland, Ohio, USA, pp. 1–5.

Colesanti, C., Wasowski, J., 2006. Investigating landslides with space-borne Synthetic Aperture Radar (SAR) interferometry. Eng. Geol. 88, 173–199. https://doi.org/10.1016/j.enggeo.2006.09.013

Collins, C.O., Amador, A., Babanin, A., Behrens, J., Benetazzo, A., Bergamasco, F., Blenkinsopp, C., Bonneton, P., Breivik, Ø., Christensen, K.H., Colosi, L.V., Ewans, K., Gemmrich, J., Glover, H.E., Grare, L., Grigorieva, V., Gulev, S.K., Hauser, D., Hole, L.R., Hope, G., Houghton, I., Hsu, J.-Y., Laxague, N.J.M., Lenain, L., Lund, B., O'Dea, A., Pistellato, M., Magnusson, A.K., Martins, K., Matsuba, Y., McAllister, M., Müller, M., Passaro, M., Rabault, J., Roarty, H., Smit, P.B., Smith, M.M., Tamura, H., Tilinina, N., Timmermans, B., Thomson, J., Voermans, J.J., Wengrove, M.E., Wyatt, L., Yoo, J., Young, I., Zappa, C.J., Zhang, D., 2025. Measuring Ocean Surface Waves. https://doi.org/10.22541/essoar.175130482.28547248/v1

Dhillon, M.S., Sharif, M., Madsen, H., Jakobsen, F., 2023. Seasonal precipitation forecasting for water management in the Kosi Basin, India using large-scale climate predictors. Journal of Water and Climate Change 14, 1868–1880. https://doi.org/10.2166/wcc.2023.479

Drønen, N.K., Brøker, I., 2015. Kystdynamik og kystbeskyttelse Naturlige erosions-og oversvømmelsesprocesser-beskyttelsesmetoders virkning og økonomi.

Fan, Y., Zhang, H., Xu, Z., Zhang, Y., Guo, Z., Guan, S., Duan, H., Tang, Y., 2026. Reliability aware multimodal detection of active landslides via evidence theoretic fusion of InSAR, optical, and DEM data. Comput. Geosci. 211. https://doi.org/10.1016/j.cageo.2026.106139

Green, J., Haigh, I.D., Quinn, N., Neal, J., Wahl, T., Wood, M., Eilander, D., De Ruiter, M., Ward, P., Camus, P., 2025. Review article: A comprehensive review of compound flooding literature with a focus on coastal and estuarine regions. Natural Hazards and Earth System Sciences. https://doi.org/10.5194/nhess-25-747-2025

Haasnoot, M., Di Fant, V., Kwakkel, J., Lawrence, J., 2024. Lessons from a decade of adaptive pathways studies for climate adaptation. Global Environmental Change 88, 1–22. https://doi.org/10.1016/j.gloenvcha.2024.102907

Hong, M., Fu, L., Lee, J.S., Park, T., Seo, H., 2026. SBAS-InSAR analysis for ground settlement in longest railway tunnel in South Korea. Tunnelling and Underground Space Technology 170. https://doi.org/10.1016/j.tust.2025.107408

Kerper, D.R., Brøker, I., Christensen, E.D., Zyserman, J.A., 2002. Application of coastal modeling systems in support of integrated coastal zone management, in: Solutions to Coastal Disasters 2002.

Larson, M., Hanson, H., Mehta, A.J., Grella, M.J., Ganju, N.K., Paramygin, V.A., 2005. MODELING COASTAL MORPHOLOGY AND ITS EVOLUTION, Port and Coastal Engineering: Developments in Science and Technology.

Le Xuan, T., Ba, H.T., Thanh, V.Q., Wright, D.P., Hasan Tanim, A., Tran Anh, D., 2022. Evaluation of coastal protection strategies and proposing multiple lines of defense under climate change in the Mekong Delta for sustainable shoreline protection. Ocean Coast. Manag. 228. https://doi.org/10.1016/j.ocecoaman.2022.106301

Li, J.P., Jiang, S.H., Xie, J., Huang, J., 2026. Probabilistic large deformation analysis of rainfall-induced slope failures considering spatial variability of saturated hydraulic conductivity. Bulletin of Engineering Geology and the Environment 85. https://doi.org/10.1007/s10064-026-04838-x

Liu, S., Chen, J., Deng, L., Wei, H., He, L., Shao, G., 2026. A general framework for time-space adaptive smoothed particle hydrodynamics for large deformation problems in landslides. Eng. Anal. Bound. Elem. 186. https://doi.org/10.1016/j.enganabound.2026.106700

Madsen, H., Jakobsen, F., 2004. Cyclone induced storm surge and flood forecasting in the northern Bay of Bengal. Coastal Engineering 51, 277–296. https://doi.org/10.1016/j.coastaleng.2004.03.001

Mašín, D., 2005. A hypoplastic constitutive model for clays. Int. J. Numer. Anal. Methods Geomech. 29, 311–336. https://doi.org/10.1002/nag.416

Mewa, G., Mengistu, F., 2022. Assessment of Landslide Risk in Ethiopia: Distributions, Causes, and Impacts, in: Landslides. IntechOpen. https://doi.org/10.5772/intechopen.101023

Mondal, I., Ghosh, R., Bandyopadhyay, J., Alshehri, F., Jose, F., Juliev, M., 2026. Predicting coastal subsidence and sea-level scenarios in the Sundarbans Delta using InSAR and artificial intelligence for sustainable coastal management. Mar. Pollut. Bull. 226. https://doi.org/10.1016/j.marpolbul.2026.119386

Niemunis, A., Herle, I., 1997. Hypoplastic model for cohesionless soils with elastic strain range. Mechanics of Cohesive-Frictional Materials 2, 279–299. https://doi.org/10.1002/(SICI)1099-1484(199710)2:4<279::AID-CFM29>3.0.CO;2-8

OECD, 2018a. Innovative Approaches to Building Resilient Coastal Infrastructure.

OECD, 2018b. Climate-resilient Infrastructure. POLICY PERSPECTIVES.OECD ENVIRONMENT POLICY PAPER NO. 14.

Pastor, M., Haddad, B., Sorbino, G., Cuomo, S., Drempetic, V., 2009. A depth-integrated, coupled SPH model for flow-like landslides and related phenomena. Int. J. Numer. Anal. Methods Geomech. 33, 143–172. https://doi.org/10.1002/nag.705

Perissin, D., Wang, Z., Lin, H., 2012. Shanghai subway tunnels and highways monitoring through Cosmo-SkyMed Persistent Scatterers. ISPRS Journal of Photogrammetry and Remote Sensing 73, 58–67. https://doi.org/10.1016/j.isprsjprs.2012.07.002

Richard Massenberg, J., Emil Panduro, T., 2024. NATURE-BASED SOLUTIONS FOR FLOOD RISK REDUCTION A Review and Guidance for Coastal Protection.

Salameh, E., Frappart, F., Almar, R., Baptista, P., Heygster, G., Lubac, B., Raucoules, D., Almeida, L.P., Bergsma, E.W.J., Capo, S., De Michele, M.D., Idier, D., Li, Z., Marieu, V., Poupardin, A., Silva, P.A., Turki, I., Laignel, B., 2019. Monitoring Beach Topography and Nearshore Bathymetry Using Spaceborne Remote Sensing: A Review. Remote Sens. (Basel). 11. https://doi.org/10.3390/rs11192212

Sorensen, K.K., Nielsen, V.K.H., Mikkelsen, A.R., Stutz, H.H., 2023. Characterization of the rate-dependent behavior of a high-plasticity stiff sedimentary clay. Geotechnical Testing Journal 46. https://doi.org/10.1520/GTJ20230339

Su, C., Che, A., Yuan, G., Zhou, H., Li, X., 2025. Numerical prediction of progressive failure in earthquake-damaged slopes under rainfall using MPM. Landslides. https://doi.org/10.1007/s10346-025-02640-6

Tagarelli, V., Cotecchia, F., 2025. Weather-Induced Landslide Activity in Clayey Slopes: Modeling for the Design of Site-Scale Early Warning Systems. Journal of Geotechnical and Geoenvironmental Engineering 151. https://doi.org/10.1061/jggefk.gteng-13248

Taiebat, M., Dafalias, Y.F., 2008. SANISAND: Simple anisotropic sand plasticity model. Int. J. Numer. Anal. Methods Geomech. 32, 915–948. https://doi.org/10.1002/nag.651

VAN DER MEER, J., Lykke Andersen, T., Roge Eldrup, M., 2024. Rock Armour Slope Stability under Wave Attack in Shallow Water. Journal of Coastal and Hydraulic Structures 4. https://doi.org/10.59490/jchs.2024.0035

Xie, W., Han, Z., Wang, G., Chen, G., Su, B., Li, Y., Ding, H., Fu, B., Li, C., 2026. Simulation of soil-rock mixture fluidized landslide dynamics using the 3D-SPH-DEM method enhanced by reorientation and spherical cap cutting algorithms. Comput. Geotech. 193. https://doi.org/10.1016/j.compgeo.2026.107995

Xu, X., He, Y., Liu, H., Shi, Q., Yao, X., Tang, K., 2026. Landslide susceptibility assessment in a reservoir area using integrated models based on time-series InSAR. J. Appl. Geophy. 246, 106115. https://doi.org/10.1016/j.jappgeo.2026.106115

Research field 6 – Sufficiency, well-being and energy efficiency

1. Introduction, vision & mission

1.1. Introduction to the Research field

To reach sustainable and healthy buildings within planetary boundaries, research is needed that integrates the management, use and performance of buildings. Energy efficiency remains necessary, but efficiency alone cannot deliver the absolute reductions in energy demand required from the built environment because efficiency gains may be partly offset by rebound effects, increased expectations, larger floor areas, and more intensive building service provision. RF6 therefore introduces sufficiency as a complementary engineering principle that asks what level of building service is necessary, where and when it is needed, and how it can be provided with the lowest feasible demand for energy, space, materials, and operational resources while protecting occupant and user health and wellbeing.

In RF6, sufficiency does not imply reduced wellbeing or lower quality buildings. It means that design, retrofit, indoor environmental control, and smart building operation must be organised around necessary and context appropriate service levels rather than unconstrained demand. This requires new knowledge about comfort norms, human adaptation, user diversity, building performance modelling, smart control, digital twins, and interaction with energy systems. To counter rebound effects, sufficiency must be defined and integrated into building technology and smart control, including research in updated comfort norms with a strong focus on meeting sustainability goals without compromising health and wellbeing.

1.2. Vision

The vision is to bring the concept of sufficiency into the engineering disciplines of indoor environment, building design and technology as well as smart control of buildings. RF6 aims to establish sufficiency as an actionable principle for the planning, design, retrofit, operation, and management of buildings, where sufficient indoor environmental quality is achieved through adaptive comfort, personal control, intelligent building operation, and demand conscious use of building services.

In all of this it is paramount to include humans and their interaction with the buildings as well as the buildings' interaction with smart energy grids for optimised management, and utilising buildings as energy storage and for demand response capabilities. RF6 therefore positions buildings as active socio-technical assets that can support wellbeing, climate resilience, reduced energy demand, and energy system flexibility at the same time.

1.3. Mission

The mission of RF6 is to generate new interdisciplinary knowledge about sufficiency required to understand and engineer sufficiency solutions within the built environment, including developing the technological foundations of management and smart control of buildings for sufficiency. Through basic research, experimental testing, and digital design methods RF6 will accelerate the transition toward sufficiency in retrofitting and newbuild of buildings and urban environments.

The mission is pursued through five linked tasks. First, RF6 develops definitions, concepts, and indicators that make building related sufficiency meaningful for engineering research and practice. Second, RF6 translates sufficiency into updated comfort norms and human centred indoor environmental strategies that account for adaptation, health, wellbeing, vulnerability, and climate resilience. Third, RF6 makes sufficiency computable in building performance simulation, design optimisation, and retrofit decision making. Fourth, RF6 operationalises sufficiency through smart building management, digital twin-based control, and demand response, so that buildings can reduce unnecessary demand, while fifth, also contributing to flexible and resilient energy systems.

2. State of the field

2.1. Global centres of excellence

This research field brings together four different but related research fields, including 1) sufficiency in the built environment, 2) indoor environment, 3) building performance and simulation tools, and 4) smart building operation and management. The following section maps global centres of excellence within each of these four fields and clarifies how they provide foundations for the integrated RF6 agenda.

When it comes to the overall theme of sufficiency in the built environment, there are not yet any centres of excellence within this new research strand, although there are networks, journals and conferences which have been leading. A special issue of the journal Buildings and Cities came out in 2024 with the title Energy Sufficiency in Buildings and Cities. The conference series eceee, the European Council for an Energy Efficient Economy, has for some years been a hot spot for presentation of research raising the question of buildings and sufficiency, and the informal network ENOUGH, International Network for Sufficiency Research and Policy, gathers researchers and supports the exchange of publications. These environments are important because they position sufficiency as a question of absolute demand reduction, wellbeing, and social practice, but the translation into engineering methods for building design and operation remains limited.

In relation to the research question of indoor environment, centres of excellence include the EPFL Smart Living Lab HOBE in Europe, the National University of Singapore and Waseda University in Asia, The University of Sydney in Australia, and the University of California, Berkeley, in the USA. These centres are relevant because they lead ongoing research on adaptive comfort, personal comfort systems, occupant centric control, and the understanding of how indoor environmental quality can be maintained under diverse climatic, cultural, and behavioural conditions.

Within building performance and simulation tools, global centres of excellence include Lawrence Berkeley National Laboratory, the primary developer of EnergyPlus and a recognised international leader in BPS based design and co-simulation frameworks (Wetter et al. 2024). Eindhoven University of Technology has long been a leading European centre for BPS methodology and tool development, as reflected in the standard reference textbook for the field (Hensen and Lamberts 2012), with current research focusing on computational design optimisation, occupant behaviour integration, and energy flexibility (Gaetani et al. 2016). ETH Zurich is internationally leading, with extensive work on simultaneous optimisation of building envelopes and energy systems under uncertainty (Petkov et al. 2022). This work is complemented by Empa, Swiss Federal Laboratories for Material Science and Technology, through its Urban Energy Systems Laboratory and the NEST living laboratory, which further developed optimisation of buildings and multi-energy systems (Wu et al. 2017), maintains open source software repositories (313 - Urban Energy Systems), and provides a full scale experimental platform for validating advanced control and optimisation strategies in real buildings (Khosravi et al. 2024).

The most relevant international centres of excellence for smart building operation and management are environments that combine analytics, control, interoperability, and field-based validation. In the United States, Lawrence Berkeley National Laboratory and the National Renewable Energy Laboratory are strong benchmarks due to their work on demand flexibility, grid interactive efficient buildings, and campus scale intelligent energy management. In Europe, the Smart Living Lab in Fribourg and relevant Nordic research environments provide useful models for linking smart operation, user needs, and living lab experimentation. In Asia, Singapore offers strong examples of integrated research environments combining occupant centric control, tropical building operation, and full-scale testing. The most relevant active international collaboration platform is IEA EBC Annex 96 on Grid Integrated Control of Buildings. Annex 96 provides an international framework for concepts, procedures, tools, and evidence related to enabling buildings to act as flexible assets in energy systems (IEA EBC Annex 96).

Combined across the four fields

The idea of RF6 is to combine the excellence of these four research fields. There is currently limited international research that combines all four areas into one coherent research agenda. Existing international environments are strong in individual parts of the agenda, but few combine sufficiency in the built environment, updated comfort norms, building performance simulation, and smart building operation into a coherent research programme. This creates an important opportunity for RF6 to develop a distinctive international profile by translating sufficiency from a social and ethical concept into engineering indicators, simulation methods, control strategies, digital twin platforms, and demonstrations in real buildings.

Relevant international environments with competences spanning several of these fields include NTNU in Trondheim, particularly through Professor Inger Andresen at the Department of Architecture and Technology, and Carleton University in Canada, particularly through Professor Liam O'Brien at the Department of Civil and Environmental Engineering. These environments are especially relevant because they combine interests in building performance, comfort, digitalisation, and operational aspects of buildings, and because RF6 leadership already has established contact and previous collaboration with them. They therefore represent both sources of inspiration and realistic collaboration opportunities. RF6 aims to build on such international links while establishing a more integrated research pipeline from sufficiency concepts to comfort models, simulation, smart operation, demand response, and sector adoption.

2.2. State of the art and DK position in the research field

As is the case for mapping of global centres of excellence, the state of the art within RF6 can be divided into four different but related research fields, including 1) sufficiency in the built environment, 2) indoor environment, 3) building performance and simulation tools, and 4) smart building operation and management. The state-of-the-art shows that each field is progressing rapidly, but also that the integration between them remains insufficiently developed.

Sufficiency in the built environment is an emerging field dealing with questions of what is enough in terms of size of buildings and in terms of heating and cooling buildings. Especially in Europe, research has in recent years focused on underutilised space, and how sufficiency as a strategy can help to provide more, and more affordable, housing within planetary boundaries (Kromand et al. 2025; Lorek and Spangenberg 2019; Lage et al. 2024; Cohen 2021; Horn et al. 2025; Gough 2020). When it comes to sufficiency in relation to heating and cooling there is, however, less research. Notable exceptions include the study by Van Moeseke et al. (2024), who developed a field-based living lab focusing on adaptive heating practices. Here residents reduced their indoor temperature to 15°C over a longer period while using personal comfort systems, clothing and physiological adaptation. Another exception is Loche et al. (2025), who integrate residents' heating practices into energy retrofit decision making. Their argument is that in cases where residents use less than predicted energy for heating, the arguments for what is sustainable in terms of energy efficient retrofit also must change. This development is highly relevant for RF6 because it shows that sufficiency must be understood as a relation between practices, technologies, comfort expectations, and engineering decisions.

In relation to comfort norms, national, European and international standards have for many years outlined criteria for designing and operating comfortable indoor environments (DS/CEN/TR 16798-2:2019 Danish Standards; ASHRAE Standard 55). These standards include both conventional heat balance approaches and adaptive models of thermal comfort (de Dear and Schiller Brager 2001; Fanger 1970), the latter being particularly compatible with a sufficiency-oriented perspective. However, most existing knowledge is based on studies of general populations and does not consider individual characteristics such as sex, age, or neurodiversity (Rupp et al. 2023; Zaniboni and Toftum 2023). Current research therefore focuses on developing individual comfort models and understanding the resilience of diverse user groups (Hernandez-Martin et al. 2025; Kim et al. 2018). Transitioning from conventional comfort norms to sufficiency-based norms is largely unexplored. Occupant behaviour is closely linked to indoor environment control and building energy performance (Andersen et al. 2009). People with opportunities for personal control over their indoor environment have been shown to tolerate a wider range of conditions (Toftum 2010), enabling wider control bands and reduced energy use. Occupant inclusive control strategies for buildings and their technical installations are well aligned with the sufficiency concept and warrant further development and testing.

Building performance simulation is a cornerstone of evidence-based building design, with tools such as EnergyPlus, IDA ICE, and TRNSYS widely used in research and practice (Hensen and Lamberts 2012). Current state of the art BPS research is characterised by four interlinked developments: occupant centric simulation, where stochastic models of behaviour and adaptation are integrated to close the gap between predicted and actual performance (Gaetani et al. 2016); co-simulation frameworks coupling building envelope models with equation based HVAC and control representations, enabling realistic testing of advanced control strategies before field deployment (Wetter et al. 2024); multi-objective design optimisation, simultaneously balancing energy use, cost, carbon, and comfort across large design spaces (Wu et al. 2017); and energy hub optimisation, where buildings are designed as nodes in broader multi-energy systems, simultaneously sizing and integrating heat pumps, photovoltaics, and storage to minimise cost, emissions, and grid impact (Petkov et al. 2022). For RF6, BPS provides the quantitative bridge between sufficiency concepts and comfort models on one side and operational strategies on the other. The key challenge is extending existing simulation frameworks to represent sufficiency as an explicit objective, making it computable and actionable in design and retrofit practice.

Within smart building operation and management, the state of the art is increasingly characterised by the integration of advanced sensing, interoperable data infrastructures, predictive control, and AI enabled operational analytics (Taboada-Orozco et al. 2024). A parallel development is the convergence between intelligent building operation and broader building energy management approaches focused on flexibility, connectivity, and grid interaction (Bayasgalan et al. 2024). Digital twins further strengthen this transition by providing an integrative layer between sensing, simulation, operational intelligence, and lifecycle-oriented decision support (Liu et al. 2024). A further frontier area is the integration of buildings into smart grids through demand response and AI based prediction, optimisation, and decentralised coordination, considering regulatory and socio-economic barriers (Toderean et al. 2025). For RF6, the central challenge is to redirect these digital technologies from efficiency optimisation alone towards sufficiency-oriented operation, where control strategies avoid unnecessary service provision, support adaptive comfort, enable user participation, and make buildings available as flexible assets in the surrounding energy system.

Danish position in this field

In a Danish and international context, RF6 is particularly well positioned to take a leading role in developing this combined research field. The reason is not only that the participating researchers bring strong competences within each of the four constituent areas, but also that the group already has experience with interdisciplinary collaboration across engineering, social science, and building research. This is essential because the core challenge is not simply to optimise buildings within an existing efficiency paradigm, but to develop and operationalise sufficiency as a new engineering relevant paradigm for the built environment. In this regard, RF6 has a strong foundation for linking social science perspectives on sufficiency and rebound effects with technical research in comfort, simulation, and smart building management. A particular strength is the ability to connect human centred understandings of building use and energy demand with engineering methods for design, modelling, and operation. This provides a strong basis for developing new concepts, methods, and demonstration activities that are internationally distinctive and societally relevant. On this basis, RF6 has the potential not only to follow international developments, but to shape an emerging research agenda on sufficiency, wellbeing, and energy efficiency in buildings.

Notably, Professor Kirsten Gram-Hanssen and her group are among the world leading in understandings of residents in relation to buildings' energy demand, and in linking understandings of residential practices to the engineering disciplines of buildings and heating technologies. The Section for Indoor Environment at DTU Sustain has a long-standing track record within research on people and their health, well-being, comfort and performance when exposed to the indoor environment at home, during transportation, at work, or in schools. The section has a wide-reaching international network and collaborates closely with industry partners. Professor Bo Nørregaard Jørgensen and his group at SDU strengthen this position through research on smart building operation and management, digital twins, and advanced building energy management systems, with a particular focus on how buildings can interact intelligently with surrounding energy infrastructures. Finally, at Aarhus University, Associate Professor Michael Dahl Knudsen brings expertise in simulation of advanced control strategies and their experimental validation in real residential buildings, with a focus on practical deployment challenges and user acceptance, while Associate Professor Massimo Fiorentini has a strong publication record in building energy system optimisation.

The Danish position is therefore not defined by one competence alone, but by the ability to combine practice-based sufficiency research, indoor environmental quality, building performance simulation, digital twin based smart operation, and energy system flexibility. This integrated profile is well aligned with Danish strengths in energy efficiency, user centred building research, district energy systems, digitalisation, and collaborative innovation with municipalities, industry, and public institutions.

3. How the research field will address the core challenges

The core challenge for RF6 is to introduce a new paradigm in the practice of civil engineering, construction and building management. For years, the central paradigm related to sustainability has been efficiency. However, because efficiency gains may be partly offset by rebound effects, the efficiency paradigm has not delivered the required reductions in absolute energy demand from the built environment. RF6 addresses this challenge by developing sufficiency as an engineering relevant paradigm that complements efficiency. Efficiency asks how a given service can be delivered with fewer resources. Sufficiency asks which services are necessary, which levels of service are adequate for health and wellbeing, when and where services are needed. Answering these questions builds on a new paradigm of sufficiency developed from a social science and philosophy approach that are transformed into concepts aligned with and useful for engineering research approaches. Sufficiency is basically about understanding what demand is, how new demands develops in relation to the build environment, and how unnecessary existing and new demand can be avoided.

The characteristics of this paradigm can be described through five expected changes in engineering approach. *First*, comfort will increasingly be treated as adaptive, diverse and context dependent rather than as a fixed setpoint. This requires research on wider comfort bands, personal control, user diversity, vulnerable groups, and resilience under changing climate conditions. *Second*, building performance simulation will need to represent sufficiency variables such as occupancy patterns, space utilisation, adaptive comfort ranges, user practices, demand limits, and temporal flexibility. *Third*, design and retrofit decisions will need to assess not only energy efficiency, cost and carbon, but also whether proposed solutions create unnecessary new demand or enable sufficient service provision with lower absolute resource use. *Fourth*, smart building control will need to move from automatic optimisation of predefined comfort targets towards human in the loop control, where occupants, facility managers, and digital systems jointly support adequate comfort, reduced demand, and operational flexibility. This include that digital twins will be used to test sufficiency-based strategies before implementation, allowing comparison of energy demand, comfort, wellbeing, cost, resilience, and grid interaction under different scenarios. This also relate to *fifth*, that buildings will be developed as flexible assets in the energy system, where demand response and storage capability are integrated with sufficiency-based operation rather than treated only as technical optimisation problems.

Based on this, and in dialogue with the sufficiency concept development, research within the three interlinked fields of engineering research, comfort modelling, building performance and simulation, and smart building management, will be developed. Comfort modelling will translate sufficiency into updated indoor environmental criteria and investigate how adaptation, personal control, health, wellbeing, and vulnerability can be integrated into comfort norms. Building performance simulation will develop methods for embedding sufficiency indicators and adaptive comfort assumptions into simulation workflows and design optimisation. Smart building management will develop control strategies, digital twin platforms, and demand response procedures that allow sufficient comfort and operational flexibility to be tested in real and simulated buildings.

The core challenge includes the development of this engineering research as well as the adaptation of results from this research into the practice of key stakeholders within the built environment. RF6 will therefore combine conceptual development, modelling, experimental testing, pilot demonstrations, stakeholder engagement, education, and professional guidance. The research logic is sequential and iterative. Definitions and indicators of sufficiency provide the foundation. These indicators inform comfort research and simulation methods. Simulation and comfort research support design optimisation and control strategy development. Digital twins enable testing and validation before real building deployment. Demonstrations then provide evidence for sector adoption, standardisation dialogue, policy work, and education. Feedback from pilots and stakeholders will be used to refine the concepts, methods and tools throughout the programme.

3.1. Global Perspectives

The concept of sufficiency includes a global perspective. To stay within planetary boundaries and offer wellbeing for all present and future generations in relation to the built environment, energy demand in the Global North needs to be reduced to create ecological space for equitable development in the Global South. At the same time, development in the Global South should not replicate the mistakes of buildings in the Global North but should learn from the newest findings on how to build and operate buildings that are not only energy efficient, but also sufficient. This is especially important for comfort norms and models, because climate change will put high pressure on the capability of buildings to deliver wellbeing during extreme weather, including extreme outdoor temperatures.

RF6 will pursue this global perspective through comparative research across climate contexts, with particular attention to the relation between Nordic buildings and Global South building environments. RF6 is investigating optimisation strategies for achieving sufficient comfort levels in large office buildings at UNITEN Campus in Kuala Lumpur, Malaysia. This work provides a concrete Global South testbed for exploring sufficiency based smart operation in a tropical climate where cooling demand is a dominant energy challenge. The research can investigate how adaptive comfort, occupant centred control, demand limiting strategies, and digital building management can reduce unnecessary cooling demand while protecting health, productivity and wellbeing.

The UNITEN work also provides a basis for comparison with Danish and Nordic building cases. Such comparison is important because sufficiency cannot be reduced to one universal comfort temperature or one universal operational strategy. It must account for climate, culture, building type, user expectations, adaptive capacity, technology availability, and energy system conditions. Comparative work between Denmark and Malaysia can therefore contribute to three RF6 research aims: understanding comfort expectations and adaptive comfort opportunities across climates; developing smart control strategies that avoid unnecessary heating and cooling while protecting wellbeing; and translating experience from hot and humid climates into future climate resilience strategies for European buildings.

RF6 will also conduct parametric simulation studies to evaluate the performance of passive and active measures that can future-proof buildings, both in a Danish context and in other climatic regions. Practical validation of selected solutions is currently taking place in health facilities in Zimbabwe and South Africa. Pending the outcome of proposals submitted to Danida Fellowship Center and EU Horizon, additional intervention studies will be carried out in Tanzania and Greece.

The global perspective is therefore not treated as a separate add on to RF6, but as part of the core research logic. Climate change will increase overheating risks in buildings in Europe and beyond and growing cooling demand may become an increasingly important challenge even in countries where heating has traditionally dominated building energy research. Knowledge from Global South testbeds can support future proofing of the Danish and European building stock, while Danish experience with energy efficient buildings, digitalisation, and district energy systems can inform sustainable development pathways in other contexts. RF6 will use this reciprocal perspective to ensure that sufficiency is developed as a globally relevant, climate sensitive, and socially responsible engineering paradigm.

4. Impact framework

4.1. Intended impact

Intended impact is overall minimal environmental impact, including reduced demands for energy, from the building sector through sufficiency and smart operation without compromising occupant well-being. This impact will follow from adaptation of sufficiency principles in new building design, construction and smart operation of buildings, while advancing resilience of buildings and systems.

The impact is expected at several levels. At building level, RF6 will support lower energy demand, improved comfort resilience, and more appropriate service provision. At portfolio level, RF6 will support better decisions about retrofit, space use, operation, and future proofing of buildings. At energy system level, RF6 will enable buildings to contribute to flexibility, demand response, and grid interaction. At sector level, RF6 will support changes in perception, professional practice, education, policy dialogue, and possible standardisation work related to sufficiency, comfort, simulation, and smart building management.

4.2. Contextual conditions

The construction sector as well as the governmental and administrative part of society dealing with buildings and sustainability are aware of the challenges with buildings within planetary boundaries. There is an emerging understanding among key stakeholders that energy efficiency alone will not deliver the needed reductions in demand. Furthermore, there is an interest in better understanding the role of residents in relation to smart control of buildings, and there is an emerging interest in how existing buildings can be adapted to changing climate. However, there is not yet a mature understanding of how sufficiency can be part of the solution within the construction sector.

Several contextual barriers must therefore be addressed. Sufficiency is still often perceived as a social or policy concept rather than an engineering concept. Comfort expectations are frequently treated as fixed requirements rather than adaptive and context dependent conditions. Design tools and simulation workflows rarely include sufficiency as an explicit objective. Building management systems are usually configured to maintain predefined service levels, not to question whether these levels are necessary in all spaces, at all times, and for all users. Demand response is often treated as an energy system issue rather than a building operation issue that must also respect comfort, wellbeing and user competencies and interests.

RF6 will pursue impact by addressing these barriers through early and continuous stakeholder involvement. This includes dialogue with municipalities, building owners, consultants, facility managers, standardisation actors, building automation providers, energy service companies, and grid actors. The objective is to ensure that definitions, indicators, tools, control strategies, and demonstrations are developed in ways that can be understood, tested, adopted, and further developed by the sector. Contextual conditions therefore require not only research publications, but also practical guidance, pilot projects, training, workshops, decision support methods, and demonstrable examples from real buildings.

4.3. CEBE impact levers

The CEBE impact levers for RF6 are organised around the four constituent research areas. Across all four areas, the central impact principle is early involvement of relevant stakeholders, so that research outputs are shaped by practical needs and adoption barriers are addressed during the programme rather than after the research has been completed.

For sufficiency principles, the impact work is mainly communicative, educational and strategic. A major contribution is to bring knowledge and understandings to all the other RFs in CEBE, as well as to the other WPs in RF6. Bringing the concept out to the whole building and construction sector is also important and will be performed through the channels that will be established in CEBE, as well as through the network of the PI into networks of local authorities, building owners, housing organisations, building managers, public institutions, and policy actors. Activities will include CEBE internal workshops, policy briefs, seminars, teaching material, and sector-oriented guidance explaining how sufficiency can be translated into decisions about space, comfort, retrofit, design and operation.

For updated comfort models and comfort norms, impact will be pursued through research evidence, experimental testing, professional dialogue, and input to relevant guideline and standardisation communities. The work will engage indoor environment researchers, consultants, building owners, schools, workplaces, and other actors responsible for ensuring health, wellbeing and performance in buildings. Activities will include seminars with industry and academic partners, dissemination of evidence on adaptive comfort and personal control, and development of recommendations for how wider comfort bands, occupant diversity, vulnerability, and climate resilience can be considered without compromising health.

For building performance and simulation, impact levers include open publication of methods, integration of sufficiency variables into simulation workflows, pilot testing with partner consultancies, and use of methods in education, design exercises and case studies. The main collaborators will include engineering consultancies, simulation tool users, building designers, researchers, and students. Activities will focus on making sufficiency computable through indicators, input variables, modelling assumptions, optimisation objectives, and decision procedures that can be tested in refurbishment and newbuild cases.

For smart building operation and management, impact will be pursued through pilot projects with building owners, facility managers, building automation providers, energy service companies, grid operators, energy retailers, flexibility market actors, and international campus partners. The work will include the development and testing of sufficiency based control strategies, digital twin based smart building management, and demand response demonstrations. Activities will include workshops for facility managers, technical integration patterns for common building management systems, training material, operational guidelines, demonstration protocols, and evaluation reports covering platform performance, comfort, wellbeing, energy demand, and grid responsiveness. The UNITEN Campus work in Malaysia will also be used where relevant to strengthen the global perspective and provide evidence on sufficiency based operation under tropical climate conditions.

The actual impact work will therefore combine communication, stakeholder engagement, prototype testing, demonstration, training, and guidance. RF6 will use CEBE's programme approach to connect research outputs to practice through iterative interaction with stakeholders. Early activities will focus on shared definitions, conceptual understanding and stakeholder needs. Mid programme activities will focus on methods, prototypes and pilot testing. Later activities will focus on documented demonstrations, guidelines, policy briefs, professional dissemination, and contributions to standardisation or regulatory dialogue where appropriate.

4.4. Intended outcomes and main beneficiaries

The intended outcome includes uptake and integration of sufficiency principles in research and education as well as in government work, consultancy and construction practices. This will specifically include a decision making strategy for both refurbishment of existing buildings and design of new buildings. It will also include proof of concept of how occupant driven and advanced control systems may contribute to more sustainable and comfortable buildings and an integration of sufficiency based simulation components into engineering design practice, education and research. A decision making tool to optimise building design and technologies, targeting sufficiency as a quantifiable design parameter, will be developed and sufficiency guides for smart building management will be tested in pilots.

The intended outcomes can be grouped into conceptual, methodological, technological, and adoption oriented outcomes. Conceptual outcomes include a shared definition of building related sufficiency and a set of indicators that can be used across RF6 and other parts of CEBE. Methodological outcomes include updated comfort models, methods for representing sufficiency in building performance simulation, and sufficiency based decision procedures for design and retrofit. Technological outcomes include smart control strategies, digital twin based building management, and demand response procedures that can be tested in representative buildings. Adoption oriented outcomes include guidance material, training, policy briefs, professional workshops, and sector facing recommendations for consultants, building owners, facility managers, public stakeholders, and energy actors.

For smart building management, an operational digital twin based platform will be developed integrating data acquisition, state estimation, forecasting and control, validated in representative buildings, thereby enabling sufficiency principles to be tested through digital twins. Also, a field based demand response demonstration package, including experimental protocols, operational data set, and evaluation report covering platform performance, comfort and grid responsiveness, will be developed. These outcomes will support both technical validation and practical learning among building operators, facility managers, automation providers and energy system actors.

The main stakeholders and beneficiaries include governmental institutions, including municipalities, policy makers and building regulatory bodies, related specifically to principles of sufficiency. They also include engineering consultants and technology developers, such as building automation and energy service providers, specifically related to sufficiency-based design methods. They include building owners and facility managers, as well as energy retailers and flexibility market actors, in relation to smart building and grid integration based on sufficiency. Researchers and educators in CEBE and internationally are also important beneficiaries because RF6 will provide concepts, methods, datasets, cases and teaching material that can support further research and education.

RF6 will coordinate with other CEBE research fields where refurbishment, design, lifecycle decisions, building technologies and operational practices overlap. The distinct contribution of RF6 is the sufficiency, comfort, building performance simulation, smart control, digital twin, and grid interaction perspective. Coordination will ensure that sufficiency-based design and operation are connected to broader CEBE work on building transformation, materials, construction processes, circularity, and sustainability assessment without creating unnecessary overlap or duplication.

4.5. Research outputs

From this research field we will publish a policy brief on the definition of building related sufficiency to be used by the sector and in the project, and we will contribute our knowledge to other CEBE researchers through CEBE internal workshops. Output will also include a roadmap to future proof the building stock for future weather, including a decision making strategy for refurbishment and newbuild. It will include a proof of concept for occupant driven control systems, including evaluation of potential energy savings.

The outputs are interrelated and will be delivered in a sequence that reflects the internal logic of the research field. The first group of outputs is foundational and will be developed mainly in years 1 to 2. These outputs include a definition of building related sufficiency, a conceptual framework for sufficiency in engineering, initial indicators, and internal CEBE guidance. These outputs are necessary because the following work on comfort, simulation, control and impact requires a shared understanding of what sufficiency means in building research and practice.

The second group of outputs translates sufficiency into engineering methods and will be developed mainly in years 2 to 4. These outputs include updated comfort models, resilience criteria, sufficiency variables for building performance simulation, and methods for representing adaptive comfort, occupancy, space use, demand limits and user practices. These outputs will be used by researchers, students, consultants and simulation tool users to move sufficiency from conceptual discussion to analysis and decision support.

The third group of outputs consists of prototype and tool oriented outputs, developed mainly in years 3 to 5. Sufficiency variables will be implemented in state of the art building performance simulation tools such as EnergyPlus, alongside the development of an initial methodology for optimising building designs and technologies using sufficiency criteria and data driven approaches. In parallel, sufficiency based control strategies will be developed and validated to balance energy performance, comfort, cost, wellbeing and environmental impact. This work also includes the creation and validation of a digital twin platform capable of integrating sufficiency measures, optimising building performance, and enabling real time demand response through sufficiency based control algorithms.

The fourth group of outputs consists of demonstration outputs, developed mainly in years 4 to 6. The solutions will be demonstrated in selected buildings, where the platform’s performance, occupant comfort, wellbeing, energy demand and grid responsiveness will be evaluated. Demonstration outputs will include pilot protocols, operational datasets, case evaluation reports, and documentation of smart building operation under sufficiency based control. Where relevant, Danish cases will be compared with Global South testbeds such as UNITEN Campus to support the global and climate resilience perspective.

The fifth group of outputs consists of adoption oriented outputs, mainly developed in years 5 to 7, with longer term impact possibly extending beyond year 7 where standardisation, regulation or broad sector practice change is involved. These outputs include guidelines, training material, policy briefs, professional workshops, standardisation input where relevant, and sector facing recommendations. Adoption will be facilitated through CEBE networks, industry and public sector collaboration, pilot partners, educational activities, and professional dissemination.

The distinctive ambition of RF6 is not only to advance research within four individual fields, but to combine them into a new interdisciplinary research direction that integrates sufficiency in the built environment, indoor comfort models, building performance and simulation tools, and smart building operation and management. While strong international research environments can be identified within each of these areas, there are currently very few centres internationally that combine all four in a coherent research agenda. This creates an important opportunity for RF6 to establish a unique and internationally visible position with its own research field established by the end of the CEBE initiative.

4.6. Research activities

The research activities in this research field are interlinked in the way that definition of building related sufficiency and operationalisation of sufficiency to be used in construction engineering is a foundational work that is supposed to feed into other parts of the research. First, it will feed into the research on updated comfort norms, including resilience of buildings, systems and people, and to the work with high performance buildings with humans in the control loop. The combined efforts of research on sufficiency and comfort norms then feed into the more technology-oriented types of research in this research field. This includes mapping sufficiency principles and updated comfort models to building performance simulation tools and developing and piloting a sufficiency-based optimisation method.

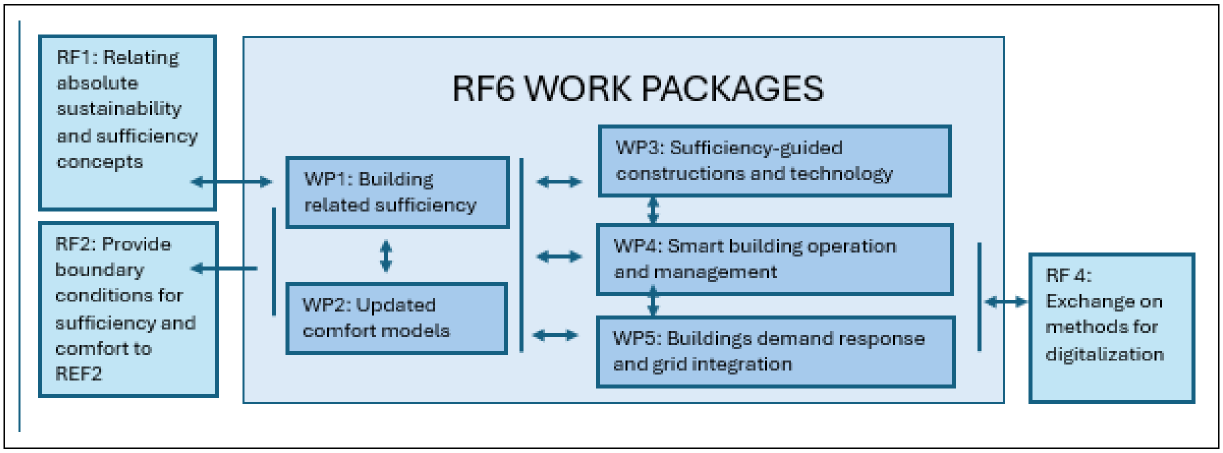
In relation to smart building operation and management, activities will include developing sufficiency-based control strategies, and a digital twin based smart building management platform. In relation to buildings' demand response and grid integration, the activities will also include a digital twin-based platform for demand response management and demand response demonstration in selected buildings. These activities will be developed iteratively, so that simulation, digital twin testing, real building pilots, and stakeholder feedback inform each other.

The activity chain can be described as follows. First, RF6 defines building related sufficiency and develops indicators that can be used in engineering contexts. Second, RF6 translates sufficiency into comfort norms, resilience criteria and human centred indoor environment research. Third, RF6 maps sufficiency and comfort models into building performance simulation and design optimisation. Fourth, RF6 develops smart control strategies and digital twin-based management platforms that operationalise sufficiency in real and simulated buildings. Fifth, RF6 tests demand response and grid interaction in selected buildings. Sixth, RF6 evaluates the results and translates them into guidance, policy briefs, training, professional recommendations, and possible standardisation input. Alongside this activity chain, feedback loops at all relations exist, thus research on digitalization, building performance and comfort models also provide knowledge backwards to each other and to the development of the sufficiency concept.

The interfaces between RF6 activities and other CEBE research fields can be represented through a layered logic in which sufficiency concepts form the foundation, comfort models and resilience criteria provide the human centred translation layer, building performance simulation and design optimisation form the analytical layer, smart building operation and digital twins form the operational layer, and demand response provides the energy system interaction layer. Feedback loops from pilots and demonstrations connect operational evidence back to concept development, comfort modelling, simulation and control. Interfaces to other RFs occur where sufficiency informs refurbishment, design, material strategies, sustainability assessment, circularity, construction processes and lifecycle decision making.

Specific relations to other RF and CEBE in general are shown in the figure below. Specifically, there will be collaboration to develop the sufficiency concept from WP6.1 and absolute sustainability from RF1 to each other. Furthermore, work from RF6 on sufficiency and comfort, WP6.1 and 6.2, will serve as input, and background context for work in RF2. In WP6.4 and WP6.5 there will be extensive work with digitalization, which will be integrated and aligned with work from RF4. Finally, the overall work from RF6 will be communicated to all CEBE RFs to be included in their work as background knowledge.

Illustration of RF6 interactions with other RFs



4.7. Research Field specific output, outcome and impact targets

For RF6, the following targets define how progress will be evaluated over the course of the programme. The targets use a seven-year implementation horizon as the main planning logic. Years 8 to 10 are reserved only for longer term impact processes, such as influence on standards, regulation, sector practice, or international replication, where such change cannot realistically be completed within the first seven years. Finally, the full integration of the research fields included in RF6 is expected to be fully implemented as a new internationally known research field.

Target name & description	Evaluation method	Impact Type	Category	Years
Definition of building related sufficiency	Publication, policy brief and internal CEBE guidance	Output	New concept / approach	2
Operationalisation of sufficiency in construction engineering	Guidelines and indicator framework for CEBE and stakeholders	Output	New concept / approach	4
Updated comfort norms, resilience and Global North / Global South comparison	Recommendation and dialogue with guideline or standardisation actors	Outcome	Applied in regulation / standardisation	4
Updated comfort models with humans in the control loop under changed global climate	Simulated and real case validation in Danish cases and relevant global South testbeds	Output	New concept / approach	6
Mapping sufficiency principles and comfort models to building performance simulation	Publication, simulation workflow and case demonstration	Output	New tool	4
Sufficiency based design optimisation method	Documented use in one to two design, construction or refurbishment cases	Outcome	Applied in construction	6

Sufficiency based smart building control strategies	Validation through simulation, digital twin testing and selected real building cases	Output	New concept / approach	3
Digital twin based smart building management	Prototype integrating data acquisition, state estimation, forecasting and control	Output	New tool	5
Digital twin based platform for demand response	Prototype and pilot dataset demonstrating demand response potential	Output	New tool	4
Demand response demonstration in selected buildings	Experimental protocol, operational dataset and evaluation report	Outcome	Demonstrated in practice	7
Input to standards, guidelines, policy and professional practice	Documented contribution to guidelines, policy briefs or sector training	Impact	Change of practice / change in perception	8
Establishing of a new combined engineering research field of sufficiency and wellbeing	Establishing international research community activities such as journals and conference series for a new research field	Outcome	Change of research practice	10

5. References

313 - Urban Energy Systems. n.d. 'Software - 313 - Urban Energy Systems - Empa'. Accessed 20 March 2026. https://www.empa.ch/web/s313/software-tools.

IEA EBC Annex 96. n.d. 'About IEA EBC Annex 96: Grid Integrated Control of Buildings'. Accessed 20 March 2026. https://annex96.iea-ebc.org/about.

Andersen, Rune Vinther, Jørn Toftum, Klaus Kaae Andersen, and Bjarne W. Olesen. 2009. 'Survey of Occupant Behaviour and Control of Indoor Environment in Danish Dwellings'. Energy and Buildings 41 (1): 11–16. https://doi.org/10.1016/j.enbuild.2008.07.004.

ASHRAE Standard 55. n.d. 'ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy'. Accessed 20 March 2026. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy.

Bayasgalan, Anujin, Yoo Shin Park, Seak Bai Koh, and Sung-Yong Son. 2024. 'Comprehensive Review of Building Energy Management Models: Grid-Interactive Efficient Building Perspective'. Energies 17 (19): 4794. https://doi.org/10.3390/en17194794.

Cohen, Maurie J. 2021. 'New Conceptions of Sufficient Home Size in High-Income Countries: Are We Approaching a Sustainable Consumption Transition?' Housing, Theory and Society 38 (2): 173–203. https://doi.org/10.1080/14036096.2020.1722218.

Dear, R. de, and Gail Schiller Brager. 2001. 'The Adaptive Model of Thermal Comfort and Energy Conservation in the Built Environment'. International Journal of Biometeorology 45 (2): 100–108. https://doi.org/10.1007/s004840100093.

Danish Standards. n.d. 'DS/CEN/TR 16798-2:2019: Energy Performance of Buildings. Ventilation for Buildings. Interpretation of the Requirements in EN 16798-1'. Accessed 20 March 2026. https://webshop.ds.dk/en/standard/M313129/ds-cen-tr-16798-2-2019.

Fanger, P. O. 1970. 'Thermal Comfort: Analysis and Applications in Environmental Engineering'. Danish Technical Press.

Gaetani, Isabella, Pieter-Jan Hoes, and Jan L. M. Hensen. 2016. 'Occupant Behavior in Building Energy Simulation: Towards a Fit-for-Purpose Modeling Strategy'. Energy and Buildings 121 (June): 188–204. https://doi.org/10.1016/j.enbuild.2016.03.038.

Gough, Ian. 2020. 'Defining Floors and Ceilings: The Contribution of Human Needs Theory'. Sustainability: Science, Practice and Policy 16 (1): 208–19. https://doi.org/10.1080/15487733.2020.1814033.

Hensen, Jan L. M., and Roberto Lamberts. 2012. Building Performance Simulation for Design and Operation. Routledge.

Hernandez-Martin, Mar, Fernando Del Ama Gonzalo, and Roberto Alonso González-Lezcano. 2025. 'Indoor Environmental Quality to Ensure the Health and Wellbeing of Vulnerable People in Residential Buildings: A Systematic Review'. Frontiers in Built Environment 11 (November). https://doi.org/10.3389/fbuil.2025.1652527.

Horn, Stefan, Ian Gough, Charlotte Rogers, and Rebecca Tunstall. 2025. 'Meeting Housing Needs within Planetary Boundaries: A UK Case Study'. Ecological Economics 230 (April): 108510. https://doi.org/10.1016/j.ecolecon.2024.108510.

Khosravi, Mohammad, Benjamin Huber, Antoon Decoussemaeker, Philipp Heer, and Roy S. Smith. 2024. 'Model Predictive Control in Buildings with Thermal and Visual Comfort Constraints'. Energy and Buildings 306 (March): 113831. https://doi.org/10.1016/j.enbuild.2023.113831.

Kim, Joyce, Yuxun Zhou, Stefano Schiavon, Paul Raftery, and Gail Brager. 2018. 'Personal Comfort Models: Predicting Individuals' Thermal Preference Using Occupant Heating and Cooling Behavior and Machine Learning'. Building and Environment 129 (February): 96–106. https://doi.org/10.1016/j.buildenv.2017.12.011.

Kromand, J. B., J. P. Tilsted, and A. Bjørn. 2025. 'Developing Sufficiency-Based Sharing Principles for Absolute Environmental Sustainability Assessment Using Decent Living Standards and Planetary Boundaries'. Sustainable Production and Consumption 54: 516–29. Scopus. https://doi.org/10.1016/j.spc.2025.01.008.

Lage, Jonas, Luisa Cordroch, Johannes Thema, Florin Vondung, and David Schöpf. 2024. 'Housing for Millions without New Buildings? An Analysis of the Theoretical Housing Potential of under-Occupied Dwellings in the European Building Stock'. Environmental Research Letters 20 (1): 014045. https://doi.org/10.1088/1748-9326/ad9c97.

Liu, Wenhui, Yihan Lv, Qian Wang, Bo Sun, and Dongchen Han. 2024. 'A Systematic Review of the Digital Twin Technology in Buildings, Landscape and Urban Environment from 2018 to 2024'. Buildings 14 (11): 3475. https://doi.org/10.3390/buildings14113475.

Loche, Iris, Carolina Recart, Lenneke Kuijer, and Roel Loonen. 2025. 'Integrating Residents' Heating Practices into Energy Retrofit Decision-Making: A Sufficiency-Oriented Approach'. Journal of Building Engineering 112 (October): 113781. https://doi.org/10.1016/j.jobe.2025.113781.

Lorek, Sylvia, and Joachim H. Spangenberg. 2019. 'Energy Sufficiency through Social Innovation in Housing'. Energy Policy 126 (March): 287–94. https://doi.org/10.1016/j.enpol.2018.11.026.

Petkov, Ivalin, Georgios Mavromatidis, Christof Knoeri, James Allan, and Volker H. Hoffmann. 2022. 'MANGOret: An Optimization Framework for the Long-Term Investment Planning of Building Multi-Energy System and Envelope Retrofits'. Applied Energy 314 (May): 118901. https://doi.org/10.1016/j.apenergy.2022.118901.

Rupp, Ricardo Forgiarini, Jacob Feder Piil, Claes Cubel, Lars Nybo, and Jørn Toftum. 2023. 'Implications of Lower Indoor Temperatures – Not Cool for Cold Susceptible Individuals across Both Sexes'. Energy and Buildings 284 (April): 112829. https://doi.org/10.1016/j.enbuild.2023.112829.

Taboada-Orozco, Adrian, Kokou Yetongnon, and Christophe Nicolle. 2024. 'Smart Buildings: A Comprehensive Systematic Literature Review on Data-Driven Building Management Systems'. Sensors 24 (13): 4405. https://doi.org/10.3390/s24134405.

Toderean, Liana, Tudor Cioara, Ionut Anghel, Elissaios Sarmas, Vasilis Michalakopoulos, and Vangelis Marinakis. 2025. 'Demand Response Optimization for Smart Grid Integrated Buildings: Review of Technology Enablers Landscape and Innovation Challenges'. Energy and Buildings 326 (January): 115067. https://doi.org/10.1016/j.enbuild.2024.115067.

Toftum, Jørn. 2010. 'Central Automatic Control or Distributed Occupant Control for Better Indoor Environment Quality in the Future'. Building and Environment, International Symposium on the Interaction between Human and Building Environment Special Issue Section, vol. 45 (1): 23–28. https://doi.org/10.1016/j.buildenv.2009.03.011.

Van Moeseke, Geoffrey, Denis De Grave, Amélie Anciaux, Jean Sobczak, and Grégoire Wallenborn. 2024. 'New Insights into Thermal Comfort Sufficiency in Dwellings'. Buildings & Cities 5 (1). https://doi.org/10.5334/bc.444.

Wetter, Michael, Kyle Benne, Hubertus Tummescheit, and Christian Winther. 2024. 'Spawn: Coupling Modelica Buildings Library and EnergyPlus to Enable New Energy System and Control

Applications’. Journal of Building Performance Simulation 17 (2): 274–92. https://doi.org/10.1080/19401493.2023.2266414.

Wu, Raphael, Georgios Mavromatidis, Kristina Orehounig, and Jan Carmeliet. 2017. ‘Multiobjective Optimisation of Energy Systems and Building Envelope Retrofit in a Residential Community’. Applied Energy 190 (March): 634–49. https://doi.org/10.1016/j.apenergy.2016.12.161.

Zaniboni, Luca, and Jørn Toftum. 2023. ‘Indoor Environment Perception of People with Autism Spectrum Condition: A Scoping Review’. Building and Environment 243 (September): 110545. https://doi.org/10.1016/j.buildenv.2023.110545.

Research field 7 – Extending the life of the built environment

1. Introduction, vision & mission

1.1. Introduction to the Research field

A substantial portion of the built environment has reached, or is approaching, the end of its original service life, with many structures no longer compliant with current design codes. In addition, evolving and unforeseen loading scenarios often lead to demands that exceed those assumed in design. Despite this, there is broad consensus that, in many cases, service life can be safely and cost-effectively extended through targeted, proactive interventions - provided that more advanced assessment tools and technologies are available. This research field addresses this need through coordinated efforts that integrate structural engineering, monitoring technologies, data science and AI, and reliability-based methods to understand, predict, and extend the service life of existing buildings and civil infrastructure.

1.2. Vision

RF7 envisions a built environment in which extending the service life of existing buildings and infrastructure becomes the preferred pathway. Through science-based, risk-informed, and sustainability-driven approaches, we enable safe, reliable, and resource-conscious performance, well beyond original design expectations.

1.3. Mission

RF7 develops an interdisciplinary framework for lifetime extension by quantifying deterioration and capacity, forecasting climate-driven demands, creating adaptive retrofit solutions, and delivering transparent risk-and-reliability-based sustainability-informed decision support that integrates structural health monitoring information.

2. State of the field

2.1. Global centres of excellence

Structural Reliability & Risk: RSUQ group, ETH Zurich, (https://sudret.ibk.ethz.ch/); ERA Group, TU Munich (https://www.cee.ed.tum.de/era/era-group/); SURI group, Stanford University (https://urbanresilience.stanford.edu/); Reliable Structures Department, Mobility & Built Environment Unit, TNO (https://www.tno.nl/en/about-tno/organisation/units/mobility-built-environment/reliable-structures/); TU Delft (https://www.tudelft.nl/en/ceg/about-faculty/departments/hydraulic-engineering/sections/hydraulic-structures-and-flood-risk/)

The Risk, Safety & Uncertainty Quantification (RSUQ) Group at ETH Zurich, led by Prof. Bruno Sudret, is internationally recognised for advancing probabilistic methods in structural engineering. At Technical University of Munich (TUM), the Engineering Risk Analysis Group, founded by Prof. Daniel Straub, is widely known for its contributions to probabilistic modelling of infrastructure and natural hazards. The group develops Bayesian networks, system reliability methods, and risk-based decision frameworks. The Stanford Urban Resilience Initiative (SURI) at Stanford University brings a multi-disciplinary perspective to structural reliability, focusing on urban systems subjected to natural hazards such as earthquakes, floods, and wildfires. Their research integrates structural reliability modelling with socio-technical systems analysis, emphasising performance-based design, community-level risk assessment, and resilience optimisation. The Reliable Structures Department at TNO (Mobility & Built Environment Unit) is a leading applied research centre in Europe for performance- and reliability-based assessment of civil and offshore structures. TNO specialises in integrating structural reliability theory with full-scale testing, monitoring data, and industry-driven applications. At TU Delft, research within the Hydraulic Structures and Flood Risk section addresses reliability and risk in the context of hydraulic infrastructure, flood defences, and coastal systems. Their work strongly influences Dutch and international practice in flood-risk management, integrating structural reliability with climate adaptation strategies.

Wind Engineering & Climate-Loading: BLWT laboratory, Western University Canada (https://www.uwo.ca/projects/heritage/heritage4/); WERC, Tokyo Polytechnic University (https://www.collaborate.wind.t-kougei.ac.jp/en/); CWE, RWTH Aachen University (https://www.cwe.rwth-aachen.de/home-2/).

Leading centres such as the Boundary Layer Wind Tunnel Laboratory (BLWTL) at Western University, the Wind Engineering Research Center (WERC) at Tokyo Polytechnic University, and the Institute for Structural Mechanics and Wind Engineering (CWE) at RWTH Aachen University represent the forefront of wind engineering and climate loading research. At Western University, Professor Greg Kopp has been a leading figure in advancing boundary layer wind tunnel testing, full-scale measurements, and wind load modelling on buildings and bridges, contributing to improved design standards and resilience against extreme wind events. At Tokyo Polytechnic University, Professor Yukio Tamura has made seminal contributions to wind-resistant design, aerodynamic stability, and wind-induced vibration of structures, shaping international standards and advancing understanding of typhoon and strong wind effects on the built environment. At RWTH Aachen University, Professor Christian Bucher and Professor Christoph Geißler have contributed to probabilistic modelling, stochastic dynamics, and experimental wind engineering, focusing on the interaction between wind loads and structural response under uncertainty. Collectively, these centres integrate experimental, numerical, and probabilistic approaches to quantify wind and climate-induced loads, supporting the design and assessment of resilient infrastructure under changing environmental conditions.

Structural Health Monitoring & Digital Twins: V4RL/IRIS labs, ETH Zurich (https://v4rl.com/); SMM group, ETH Zurich (https://chatzi.ibk.ethz.ch/); Dynamics Research Group, University of Sheffield (https://drg.ac.uk/); STAIRlab, UC Berkeley (https://stairlab.berkeley.edu/) Civil Engineering Safety and Durability, Tsinghua University. (https://www.civil.tsinghua.edu.cn/ceen/info/1052/1341.htm); Smart Structures Technology Laboratory (SSTL), University of Illinois Urbana (https://sstl.cee.illinois.edu/); Illinois Structural Health Monitoring Project (ISHMP) (http://shm.cs.illinois.edu/).

Leading international centres such as ETH Zurich, the University of Sheffield, UC Berkeley, Tsinghua University, and the University of Illinois Urbana-Champaign are driven by key researchers who have shaped the modern field of structural health monitoring and digital twins. At ETH Zurich, Professor Eleni Chatzi has made seminal contributions to physics-informed machine learning, system identification, and digital twinning, developing hybrid modelling frameworks that fuse real-time data with reduced-order physics-based models for infrastructure monitoring and decision support. At the University of Illinois, Professor Bill Spencer has been instrumental in advancing wireless smart sensor networks and decentralized monitoring systems, enabling scalable, real-time SHM deployments on full-scale infrastructure and establishing new paradigms for autonomous monitoring. At the University of Sheffield, researchers such as Professor Keith Worden and Professor Elizabeth Cross have pioneered data-centric and machine learning approaches to SHM, including novelty detection, population-based SHM, and uncertainty quantification, which are central to modern digital twin concepts. At UC Berkeley, Professor Kenichi Soga and colleagues at STAIRlab have driven innovations in distributed sensing, cyber-physical systems, and data integration for infrastructure monitoring, with strong emphasis on field deployment and infrastructure resilience. At Tsinghua University, leading researchers in civil engineering safety and durability have advanced large-scale monitoring systems and durability assessment methods for bridges and major infrastructure, combining sensing technologies with long-term performance evaluation under environmental and operational loading.
https://www.ucl.ac.uk/infrastructure-systems/https://www.tudelft.nl/citg/over-faculteit/afdelingen/materials-mechanics-management-design-3md/integral-design-management/groups/engineering-systems/researchhttps://www.ntnu.edu/ivb/civil-engineering-and-geomatics

Adaptive Systems & Retrofitting: SSTL, University of Illinois (https://sstl.cee.illinois.edu/); SMARTI Lab, University of Illinois (https://sychterz.cee.illinois.edu/); University of Stuttgart (https://www.sfb1244.uni-stuttgart.de/en/); Space Structures Laboratory, Caltech (https://www.pellegrino.caltech.edu/); Compliant Mechanisms, TU Chemnitz (https://www.tu-chemnitz.de/mb/mp/forschung/nachgiebige_systeme/index.html.en)

Leading centres such as the Smart Structures Technology Laboratory (SSTL) and SMARTI Lab at the University of Illinois Urbana-Champaign, the Collaborative Research Centre SFB 1244 at the University of Stuttgart, the Space Structures Laboratory at Caltech, and the Compliant Mechanisms group at TU Chemnitz represent the forefront of adaptive systems and structural retrofitting. At the University of Illinois, Professor Bill Spencer has been a central figure in the development of smart damping and semi-active control systems, including magnetorheological devices, enabling real-time structural adaptation and advanced retrofit solutions for civil infrastructure. At the University of Stuttgart, Professor Werner Sobek has led pioneering work on adaptive and lightweight structures, developing systems that actively respond to changing loads and environmental conditions to improve resource efficiency and extend structural lifespan. At Caltech, Professor Sergio Pellegrino has advanced deployable and transformable structures, including origami-inspired systems and lightweight adaptive mechanisms, with strong relevance for reconfigurable and retrofittable structural concepts. At TU Chemnitz, Professor Lutz G. Friebe and colleagues have contributed significantly to the development of compliant mechanisms, enabling flexible, jointless systems that allow controlled motion and adaptability, with potential applications in structural components and retrofit technologies. Together, these centers integrate control systems, material innovation, and structural mechanics to enable adaptive, resilient, and resource-efficient solutions for both new and existing infrastructure.

Structural Engineering and Modelling: ETH Zurich, Concrete Structures and Bridge Design (https://kaufmann.ibk.ethz.ch/); ETH Zurich, Steel and Composite Structures (https://taras.ibk.ethz.ch/); Structural Engineering Research Group, Universidad Politécnica de Madrid (https://www1.caminos.upm.es/estructural/language/en/).

ETH Zurich holds a leading international position in structural engineering, particularly in the fields of concrete structures and steel structures. The Chair of Concrete Structures and Bridge Design, led by Prof. Walter Kaufmann, is widely recognised for its rigorous development of mechanically consistent models for the design of new and assessment of existing concrete structures. The Chair of Steel and Composite Structures, headed by Prof. Andreas Taras, is well-known for innovative, industry-oriented research, including models for fatigue capacity of steel structures and performance-based fire design. Both chairs have world-class experimental facilities, enabling validation through large-scale testing. At Universidad Politécnica de Madrid (the Structural Engineering Research Group) Prof. Miguel Fernández Ruiz (formerly at *EPFL*) continues his internationally recognised work on capacity models for reinforced concrete. He has contributed to research that forms the basis of the shear and punching shear provisions in the next generation of Eurocode 2.

Deterioration modelling: International Center for Numerical Methods in Engineering (CIMNE), Structural Mechanics (https://cimne.com/research/research-clusters/structural-and-particle-mechanics/); University of Texas at Austin (UTA) https://sites.utexas.edu/ferche/ and The Laboratory of Materials and Durability of Constructions (LMDC), Toulouse https://www.lab-lmdc.fr/en/le-laboratoire-english/#, University of Ottawa https://www.uottawa.ca/faculty-engineering/department-civil-engineering

CIMNE holds a leading international position in the modelling of corrosion-induced deterioration of reinforced concrete. The group's work is strongly influenced by Prof Carmen Andrade, one of the leading experts on reinforcement corrosion mechanisms, monitoring and predictive modelling. University of Texas at Austin is together with University of Ottawa, some of the leading institutions on structural capacity of ASR deteriorated concrete structures. Their contributions help quantify the long-term structural implications of ASR damage and support the development of assessment and mitigation strategies for affected infrastructure. Many other research groups have focused on the material and chemical understanding of ASR deterioration mechanism. Among those, the Laboratory of Materials and Durability of Constructions (LMDC) in Toulouse is widely recognized for its mechanistic studies and predictive models related to ASR expansive chemical reactions. LMDC integrates microstructural analysis, chemo-mechanical modelling, and long-term exposure studies to characterize ASR-induced cracking.

Benefits for Danish Research through Collaboration

Collaboration with these leading international centres would directly support the objectives of the CEBE programme, in particular within the research fields related to lifetime extension of structures, climate resilience, and sustainable building and infrastructure systems. Access to state-of-the-art methodologies in structural reliability, capacity modelling, steel fatigue, wind and climate loading, structural health monitoring, digital twins, and adaptive systems would strengthen the scientific foundation of Danish research and enhance the ability to address complex, multi scale challenges across the built environment.

Such partnerships would enable integration of advanced sensing, physics informed modelling, and probabilistic risk frameworks into Danish research on both buildings and infrastructure, supporting more accurate condition assessment, predictive maintenance, and decision making under uncertainty. Access to large scale experimental facilities, long term monitoring datasets, and validated digital twin platforms would accelerate the transition from research to implementation, which is central to the CEBE ambition of bridging fundamental research and real-world application.

Furthermore, collaboration would enhance the development of resource efficient and adaptive design strategies for both buildings and infrastructure, contributing to reduced material use, extended service life, and improved resilience of the built environment within planetary boundaries. It would also strengthen Denmark's international research positioning, support joint funding initiatives, and foster the training of early career researchers within a globally connected research ecosystem.

2.2. State of the art and DK position in the research field

RF7.1 Assessing the capacity and residual life of buildings and civil structures

Assessment of load-carrying capacity of aging structures is still largely governed by deterministic code-based checks originally developed for new design. This is suboptimal for non-code compliant and deteriorated structures, where material degradation and evolving loading conditions play a significant role. While key components for advanced assessment exist - such as monitoring techniques (e.g. ETH Zürich, TUM, TU Delft), load-capacity models (EPFL, UPM, ETH Zürich, DTU, SDU), deterioration modelling including corrosion and ASR (CIMNE, UPM, DTU, Chalmers, UTA), and probabilistic decision frameworks (Stanford, University of Colorado, Trinity College Dublin) - these elements remain fragmented and lack a unified, validated framework with consistent interaction between them.

Structural health monitoring (SHM) has matured significantly, encompassing sensor fusion, operational modal analysis, vision-based systems, UAV and robotic inspections, and virtual sensing approaches. However, in current practice, monitoring data is rarely translated into quantitative updates of structural capacity or reliability. The integration of SHM with physics-based models through Bayesian updating, Kalman filtering, and inverse methods remains limited, and end-to-end frameworks linking measurement, model updating, and decision-making are still lacking.

In Denmark, a strong combination of modelling expertise, monitoring capabilities, and experimental infrastructure provides a unique foundation for addressing this gap. Research spans transport mechanisms (Sharmilan et al., 2024), corrosion propagation modelling (Michel et al., 2016), ASR-induced degradation (Hansen, 2019; Barbosa et al., 2018), and mechanical shear-transfer models for non-code compliant structures (Autrup et al., 2023; Sørensen et al., 2025), supported by efficient numerical tools (Vestergaard et al., 2021).

At the same time, Denmark has a strong tradition in vibration-based SHM and operational modal analysis, with increasing focus on data assimilation techniques such as Kalman filtering for system identification, load estimation, and damage detection. Recent developments include applications in weigh-in-motion and model updating (Lai et al., 2022), physics-informed latent force models for complex loading (Caglio et al., 2025), and machine-learning-assisted fatigue prognosis using multi-fidelity modelling (Al-Hagri et al., 2026). Emerging technologies such as UAV- and robotics-based inspections (Kapoor et al., 2021) further expand the data acquisition capabilities, although their integration into assessment frameworks remains limited.

RF7.1 will bridge these gaps by developing a coherent, data-informed assessment framework, where monitoring data, deterioration models, and structural analysis are consistently integrated through probabilistic updating. This will enable condition-dependent evaluation of residual capacity and remaining service life, moving beyond deterministic checks toward continuously updated, reliability-based assessment of existing structures.

CEBE

RF7.2 Predicting future use and load scenarios of buildings and civil structures

State-of-the-art load scenario prediction increasingly combines wind engineering, climate projections, and machine learning, including inverse methods for inferring loads from structural response (Zhi et al., 2017). However, engineering practice still relies largely on stationary load assumptions, and current codes do not adequately account for evolving climate-driven phenomena such as non-synoptic storms.

Micro- and mesoscale forecasting capabilities are rarely integrated into reliability assessments or consequence-based decision models, leading to fragmented lifetime extension strategies. While climate storyline approaches have begun to quantify intensification of extreme events (Øelund et al., 2026), these are not yet systematically incorporated into structural workflows.

In Denmark, research is advancing toward data-driven predictive frameworks, including LSTM-based short-term extreme wind forecasting (Mode et al., 2025) and exploration of directionality–predictability relationships (Modé et al., 2024).

RF7.3 Engineering solutions for life extension of buildings and civil structures

Engineering solutions for life extension increasingly draw on advances in structural aerodynamics and control. Concepts such as flexible retrofit configurations, aerodynamic modifications, and vortex-induced vibration mitigation build on established flow–structure interaction principles (Andersen & Brandt, 2018; Gao et al., 2021).

However, current approaches face limitations in scalability, applicability across structural typologies, and practical constraints related to retrofit implementation. Most solutions remain based on deterministic loading and classical control strategies, with limited incorporation of data-driven and probabilistic adaptation, and scarce full-scale validation.

Recent developments in Denmark include adaptive aerodynamic control strategies, spanning compliant mechanism synthesis, selective compliance, shape morphing, and model predictive vibration control (Seltmann & Hasse, 2025; Reksowardojo et al., 2022; Dakova et al., 2025).

RF7.4 Risk-based decision support systems for extending the life of the built environment

Risk- and reliability-based approaches are increasingly recognised as valuable tools for decision making under uncertainty; particularly in light of existing structures and the green transition (Köhler and Baravalle, 2019; Diamantidis et al., 2025; Melhem et al., 2020; Hingorani and Köhler, 2023). As a result, the shift towards these methods is also increasingly reflected in standards and guidance documents, see e.g. EN 1990:2023 or DS 11990:2024. Nevertheless, their routine application in engineering practice remains limited. A key reason is the lack of concrete and consistent guidance for the many (probabilistic) modelling choices required in such assessments. Consequently, there is an increasing call for clearer and more transparent practical guidance on probabilistic modelling choices (Hingorani and Köhler, 2023; Diamantidis et al., 2025; Steenbergen and Vrouwenvelder, 2025).

Denmark has a long-standing tradition of risk- and reliability-based methods. Reliability-based code calibration has been part of Danish practice for decades (Sørensen, 2001). This is also reflected in national guidance for reliability-based assessment of existing bridges issued by the Danish Road Directorate (Vejdirektoratet, 2024). In addition, risk-based decision making has been widely explored in areas such as wind turbines (Nielsen and Sørensen, 2011). Ongoing work also addresses challenges related to probabilistic modelling, including system reliability modelling (Meinen and Steenbergen, 2025) and model uncertainties in wave load models (Meinen et al., 2020).

3. How will the research field address the core challenges?

RF7 addresses one of the core challenges of CEBE by shifting engineering practice from replacement toward active, risk-informed lifetime extension of existing infrastructure.

The fundamental challenge is not the absence of knowledge, but the fragmentation between structural assessment, monitoring, environmental loading, and decision-making. RF7 resolves this by developing a coherent, interdisciplinary framework that integrates structural engineering, data science, and reliability-based methods into a unified workflow.

First, RF7 establishes quantitative models for deterioration and residual capacity, capturing time-dependent mechanisms such as corrosion propagation, fatigue crack growth, and material degradation within probabilistic frameworks. These models will be integrated with advanced numerical methods and experimental validation to enable condition-dependent capacity assessment of non-code-compliant structures, reducing epistemic uncertainty and avoiding overly conservative deterministic checks.

Second, RF7 advances data-driven structural assessment by transforming monitoring data into actionable information. Through structural health monitoring, UAV- and robotic-based inspections, and virtual sensing, combined with physics-informed machine learning and Bayesian data assimilation, structural states, loads, and model parameters will be continuously updated. This enables near real-time system identification, eventual damage detection, and probabilistic model updating, leveraging CEBE's cross-cutting enablers in digitalization and automation.

Third, RF7 develops and evaluates adaptive and retrofit solutions that enhance structural performance and extend service life. This includes both conventional strengthening approaches and advanced concepts such as aerodynamic load mitigation, morphing structural components, and adaptive or performance-enhancing intervention strategies. These interventions are formulated within reliability-based design and assessment frameworks to ensure safety while minimizing material use and intervention, supporting circularity and design for regeneration principles.

Fourth, the research establishes probabilistic frameworks for future loading and climate effects, linking large-scale climate projections with local structural demand through multi-scale modelling and machine learning. Inverse methods and system identification techniques will enable estimation of environmental loads from measured structural response, while accounting for non-stationary processes and extreme events. This directly supports the CEBE objective of climate-resilient infrastructure, ensuring that lifetime extension strategies remain robust under evolving environmental conditions.

Finally, RF7 will strive to develop AI-supported, risk-informed decision-support tools that integrate monitoring data, deterioration modelling, load prediction, and reliability analysis into transparent engineering workflows. These tools will enable quantitative evaluation of intervention strategies (repair, retrofit, or replacement) under uncertainty, supporting lifecycle optimization and sustainability assessment while reducing CO_2 emissions associated with reconstruction.

By integrating these components, RF7 acts as a system-level enabler across CEBE, linking digitalization, sustainability, and climate adaptation into implementable engineering solutions. The outcome is a transition from conservative, fragmented assessment practices toward data-driven, reliability-based, and resource-efficient lifetime extension of the built environment.

3.1. Global Perspectives

The research within this field is primarily focused on challenges relevant to lifetime extension of ageing building and infrastructure systems, subjected to changing climate and increasing loading. These challenges are particularly pronounced in developed economies, where the built environment is older and subject to stringent performance, safety, and durability requirements. In this highly industrialized context, the methodologies being developed, including structural health monitoring, digital twins, probabilistic risk assessment, and adaptive systems, are very likely to be quickly adopted by both asset managers and the industry.

As building stocks and infrastructure systems in the Global South continue to expand and mature, they will increasingly face similar challenges related to durability, maintenance, and climate resilience in the future. Moreover, due to underfunded maintenance, such scenarios will be likely to occur earlier than in developed economies. Therefore, the research conducted in this research field is very relevant and timely world-wide.

However, a major obstacle to infrastructure lifetime extension in the Global South is the limited availability of engineering data. Many regions lack complete infrastructure inventories, systematic inspection records, maintenance histories, and reliable traffic or environmental monitoring data. As a result, sophisticated AI-based methods, which require extensive digitalization and large amounts of data might not be applicable soon. Instead, it is envisioned that low-data tools such as the risk-based decision framework developed in RF7.4 will play a central role in projecting CEBE's impact there. By enabling risk-based decision-making, decisions can be based on whatever data is available, making the approach robust even in data-scarce contexts. In regions with limited data availability, the resulting higher uncertainties are explicitly incorporated into the risk analysis, ensuring that decisions remain transparent and systematically informed despite data constraints.

A key pathway for global impact is through contributions to international codes of practice and standardisation bodies, including fib, PTI, IABSE, and JCSS. Through active engagement in these organisations, the research is expected to influence future design guidelines, reliability frameworks, and lifecycle management practices for both buildings and infrastructure. This approach ensures immediate relevance within advanced economies while enabling long term international impact through the gradual diffusion of knowledge into global engineering practice, without diluting the scientific and technical focus of the research field.

4. Impact framework

4.1. Intended impact

Once the research outcomes are implemented, society will increasingly maintain, adapt, and extend the service life of existing buildings, bridges, and other civil infrastructures rather than replacing them. A larger share of the built environment will undergo transformation and structural adaptation that safely prolongs its use, resulting in fewer demolitions and fewer new constructions. Better knowledge of deterioration processes and more reliable assessment of the actual structural capacity of infrastructures, including their performance in fire, will reduce uncertainty about the current and future condition. This will allow authorities and owners to plan retrofitting, repair, or delayed replacement in a more informed and strategic manner. Therefore, maintenance actions that require large amounts of raw materials and energy will be avoided more often, leading to a substantial reduction in CO_2 emissions. Communities will also benefit from safer infrastructures, reduced costs related to repair, or reconstruction, and improved decision making regarding structural adaptation. Over time, this will lead to broader adoption of adaptive engineering solutions that enable safe lifetime extension of infrastructures while supporting sustainability and long-term resilience of the built environment.

4.2. Contextual conditions

Barriers

- Engineering practice relies on established codes and conservative design traditions, which can slow acceptance of new assessment approaches for existing structures.
- Limited long term monitoring data and uncertainty about deterioration processes may reduce confidence in decisions to extend service life.
- Implementation requires new analytical competencies and digital tools, which may initially challenge consulting firms and infrastructure owners.

- Regulatory approval procedures and liability concerns can discourage stakeholders from applying innovative structural assessment and retrofit strategies.
- Fragmented ownership and management of infrastructure assets may complicate coordinated adoption of new maintenance and assessment frameworks.

Facilitation is intended to happen through university/industry courses, code-committee activity, and industrial pilot projects.

Opportunities

- Aging infrastructure networks create strong demand for reliable methods that safely extend structural service life.
- Climate targets and resource efficiency policies encourage solutions that reduce demolition, reconstruction, and associated material and energy consumption.
- Advances in sensing technologies, data analysis, and modelling enable improved monitoring, reliable diagnosis and prognosis of infrastructure performance and health.
- Collaboration between universities, consulting firms, and public authorities supports rapid transfer of validated research results into engineering practice.
- Greater awareness of lifecycle sustainability encourages decision making that prioritizes adaptation and transformation of existing buildings and infrastructures.

4.3. CEBE impact levers

- Develop practical guidelines, demonstration projects, and open datasets to translate validated models and monitoring methods into engineering workflows used by consultants, infrastructure owners, and public authorities.
- Establish an RF7 Industry Advisory Board comprising representatives from infrastructure owners, consulting engineering firms, contractors, technology providers, and public authorities. The board will provide strategic feedback on research priorities, identify barriers to implementation, and help ensure that research outputs address real industry needs and opportunities.
- Collaborate with consulting firms, infrastructure owners, and public authorities to co-develop and validate methods through pilot projects and demonstration cases. Industry experts will be involved where appropriate in project steering groups, co-supervision of MSc, PhD and postdoctoral researchers, guest lectures, workshops, and examination activities. Examples may include collaboration with the Danish Road Directorate, which manages critical bridge assets within the national transport network, while facilities scheduled for transformation or decommissioning, such as parts of the existing Odense University Hospital campus, may provide unique testbeds for validating new monitoring technologies, assessment methods, and decision-support frameworks. The strong industrial networks of SDU, AU, and DTU, including collaboration with engineering consultancies such as COWI, Ramboll, and NIRAS, will help ensure continuous alignment between academic developments and engineering practice.

- Establish pilot monitoring platforms and data-sharing partnerships among universities, industry, and public authorities to address data gaps, accelerate technology validation, and support coordinated infrastructure management.
- Utilise the strong position of CEBE to secure external funding for follow-up research, innovation, and demonstration activities, including industrial PhDs, industrial postdoctoral projects, collaborative research initiatives, and implementation-oriented projects with industry partners.
- Support innovation and knowledge transfer through dedicated innovation management resources and close engagement with industry. Where appropriate, research outcomes may provide the foundation for new startups, spin-outs, software tools, digital services, and monitoring technologies that can accelerate adoption and societal impact.
- Engage regulators, standardisation bodies, and professional organisations through established links to organisations such as CEN, IABSE, fib, and JCSS to facilitate the integration of new reliability frameworks, assessment methodologies, and lifetime-extension approaches into engineering standards, guidelines, and approval procedures.
- Provide training programmes, workshops, continuing education activities, and digital tools to support the adoption of advanced modelling, monitoring, AI-enabled inspection, and data-driven decision-support methods by practicing engineers and infrastructure managers.
- Update MSc programmes and educational activities to equip future engineers with the competencies required to assess, maintain, retrofit, and extend the life of the built environment using the methods and technologies developed within RF7.

4.4. Intended outcomes and main beneficiaries

To achieve the desired impact, the methods and frameworks developed in the research field must be widely adopted by professional engineers, infrastructure owners, and public authorities responsible for managing the built environment. Engineering consulting firms play a central role since they will apply the new scientific knowledge and analytical tools in practical assessments, monitoring activities, and maintenance planning for bridges, buildings, and other civil infrastructures. By adopting these approaches, consultants will be able to evaluate structural performance more reliably, monitor larger portfolios of infrastructure assets, and support safer and longer service lives through informed maintenance and retrofit strategies. Infrastructure owners and operators, including public agencies, municipalities and private foundations, will benefit from improved decision support for planning repairs, retrofitting, or delayed replacement. The research will also strengthen the capacity of consulting firms to quantify environmental actions such as wind loading through virtual sensing and predictive environmental modelling. These advances will increase awareness and acceptance of adaptive structural systems as viable solutions for extending service life. At the same time, the generated knowledge will inform future discussions on reliability targets in structural design and assessment standards. The main beneficiaries will therefore include infrastructure owners, engineering consulting firms, public authorities, and the wider community that depends on safe, reliable, and sustainable infrastructure.

4.5. Research outputs

The research field will deliver a set of validated scientific methods, digital tools, experimental datasets, and practical frameworks that enable reliable assessment and lifetime extension of the existing built environment.

To support lifetime extension of the existing build environment in general, RF7 will develop sensing and monitoring technologies that support data driven assessment and adaptive operation of infrastructure. The work will deliver systems for automated inspections using unmanned aerial vehicles, algorithms for virtual sensing of wind loading from structural response measurements collected through multi modal sensor networks, and artificial intelligence methods that support the assisted operation of structural health monitoring systems. The research will also produce synthesis and control approaches for adaptive structural systems based on formal optimization and data driven modelling, enabling infrastructures to respond to changing environmental and operational conditions while extending their service life. Together, these outputs will form a comprehensive scientific and technological foundation for assessing, monitoring, and extending the lifetime of the built environment.

For assessment and lifetime extension of existing concrete structures, RF7 will produce more accurate and computationally efficient methods for assessing the load bearing capacity of reinforced concrete bridges and buildings that do not comply with current design standards (e.g. lack of minimum reinforcement and/or use of outdated reinforcement type and layout), supported by experimental data for validation. This work will also provide improved modelling tools and experimental techniques for characterizing rebar corrosion and alkali silica reaction and for understanding how these deterioration mechanisms influence structural behaviour.

For assessment and lifetime extension of existing steel structures, RF7 will deliver a framework for diagnosing fatigue induced cracking and estimating the remaining fatigue life of steel structures, supported by multi fidelity structural models, virtual sensing tools based on Kalman filtering for estimating loads and stresses, and advanced fracture mechanics-based fatigue models for simulating crack initiation and growth.

For more accurate assessments of load- and environmental impact, RF7 will develop machine learning models for probabilistic prediction of wind conditions affecting structural performance, and a multi physics modelling framework that links large scale climate developments with the local environmental conditions acting on structures.

To ensure optimized and safe lifetime extension of buildings and bridges, RF7 provides practical improvements to current risk- and reliability-based assessment frameworks, which can incorporate the models and experimental knowledge established in RF7. Where useful, improved guidance on target reliabilities for existing structures is established.

In addition to above specific output, RF7 has the ambition to acquire additional funding for research that will focus on:

- Evaluation procedures and numerical methods for assessing and extending infrastructure resilience to modern (and future) fire loads.
- Finite Element Limit Analysis of existing masonry structures
- Extended pilot studies for advanced structural health monitoring systems, with a focus on damage detection.
- Extension of extreme event analysis using combined physical modelling and data-driven techniques.
- Use of aerodynamic control as a means of active excitation for condition assessment.
- A digital engineering tool for risk- and reliability-based decision making that is applicable for practicing engineers without specialised probabilistic expertise. The tool should embed the relevant probabilistic modelling choices and methods, be able to incorporate in-situ data, and be based on both newly developed and existing probabilistic modelling guidance.

4.6. Research activities

The first group of activities focuses on assessing the capacity and residual life of structures. This includes the development of advanced analytical and numerical approaches for evaluating the load bearing capacity of reinforced concrete bridges and buildings that do not comply with current design provisions. The research will also include modelling and laboratory investigations of deterioration mechanisms such as rebar corrosion and alkali silica reaction and their influence on structural behaviour and safety. In parallel, methods will be developed for diagnosing and predicting fatigue damage in steel structures through multi-fidelity fracture mechanics models supported by ML algorithms as well as virtual sensing of loads and stresses. Field based inspection and monitoring technologies will also be investigated, including automated structural inspections using unmanned aerial vehicles combined with computer vision and artificial intelligence supported structural health monitoring systems.

A second group of activities addresses the prediction of future loading and use scenarios for buildings and infrastructures. Research will develop software sensing approaches that infer wind loading from structural response data and machine learning models that support probabilistic prediction of wind conditions affecting structural performance. These developments will be combined with analyses of how climate change may influence environmental loading processes and how these changes affect structural safety and long-term durability.

A third group of activities focuses on engineering solutions that enable safe lifetime extension. Research will investigate strengthening and repair strategies that increase the capacity and remaining service life of buildings and civil infrastructures. The work will also explore adaptive solutions such as active aerodynamic control of slender or line-like structures to reduce loading effects and improve structural resilience.

A final group of activities will develop decision support frameworks for risk-informed lifetime extension of the built environment. This includes determining suitable reliability levels for existing structures, establishing improved probabilistic assessment frameworks for standardized evaluations, and developing practical guidance for risk informed decisions on repair, retrofitting, and transformation. Data driven modelling approaches will also be investigated to support the planning and design of retrofitting and structural transformation processes. Together, these activities will provide the scientific and technological basis needed to assess, monitor, and extend the lifetime of existing infrastructure.

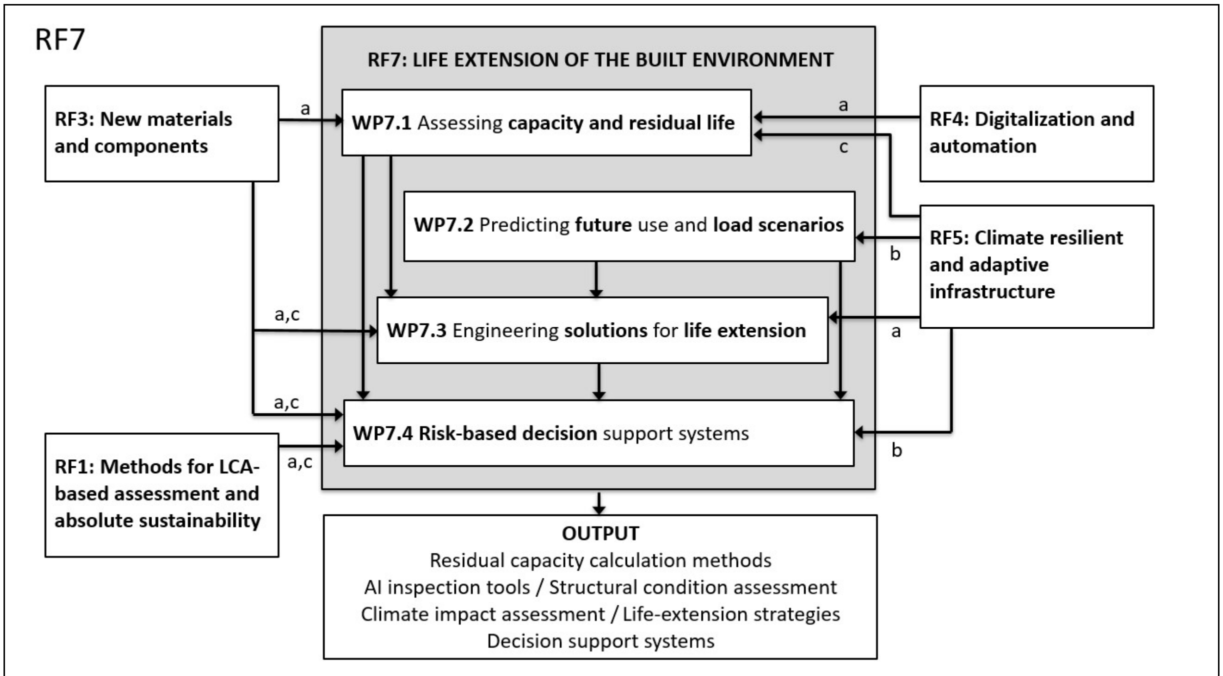
RF7 Interfaces and interactions

RF3 and RF7 are complementary through their shared focus on reliability and risk assessment, while maintaining distinct scientific objectives. RF3 focuses on component reuse, material robustness, and sustainable construction materials, whereas RF7 focuses on structural lifetime extension, deterioration assessment, residual capacity estimation, and intervention planning for existing buildings and infrastructure. In this context, the structural condition assessment methodologies developed within RF7 provide an important basis for the reuse-oriented frameworks developed within RF3. The two fields therefore envision coordinated activities in reliability and risk methodologies, joint contributions to standardization and EC-related activities, and periodic knowledge-exchange meetings related to reuse, durability, deterioration, and lifetime extension strategies.

RF4 and RF7 share several enabling technologies, including AI, robotics, sensing systems, and digital twins, but apply them to distinct and complementary phases of the built environment lifecycle. RF4 focuses on digital fabrication, automated construction and deconstruction, interoperability, semantic modelling, and BIM-driven digital workflows, while RF7 focuses on structural health monitoring, condition assessment, deterioration quantification, residual capacity estimation, and risk-informed decision support for existing structures and infrastructure. The two fields therefore converge through clearly defined technical interfaces while maintaining distinct scientific ownership. In particular, RF4 develops enabling digital and automation ecosystems for the construction lifecycle, whereas RF7 develops engineering methodologies for interpreting structural condition, predicting deterioration, assessing reliability, and supporting lifetime extension decisions. To strengthen these interfaces, RF4 and RF7 envision co-hosted training and knowledge-exchange activities on topics such as agentic AI deployment, robotics platforms, digital twin engineering, physics-informed machine learning, and advanced sensing technologies.

RF5 and RF7 also interact through complementary scientific scopes. RF5 focuses on geotechnical systems, coastal systems, climate hazards, and environmental boundary conditions, whereas RF7 focuses on exposed structural systems of buildings and infrastructure. In many respects, the two research fields act as each other’s boundary conditions, particularly in relation to soil-structure interaction, environmental loading, resilience, and climate adaptation. The two fields also share interfaces related to environmental and infrastructure monitoring, particularly in areas such as remote sensing, satellite imaging, and soil-structure interaction assessment. Consequently, RF5 and RF7 envision joint activities related to interface problems and environmental boundary-condition assessment for resilient infrastructure systems.

Illustration of RF7 interactions with other RFs



Definitions
a. Knowledge exchange for inspiration, efficiency and increased quality
b. Deliver/receive boundary conditions/context for the research activity
c. Deliver/receive necessary information on research results to enable research

4.7. Research field specific output, outcome and impact targets

For the research field we have defined the following targets for which the realization hereof will be evaluated over the course of the programme.

Targets of the research field

Target name & description	Evaluation method	Impact Type	Category	Years
Validated analytical and computational methods for capacity assessment of non-code-compliant RC structures	Publications	Output	New methods: Experimentally validated limit analysis and numerical (FELA and/or FESA) methods for calculating the capacity of non-code-compliant RC buildings and bridge structures	4
Experimental validated model linking corrosion to structural capacity	Publications	Output	New method: Experimentally validated corrosion models suitable for integration into limit	4

			analysis for the capacity assessment of corroded RC structures	
Model predicting ASR effects on structural performance	Publications	Output	New method: Experimentally validated limit analysis approaches for evaluating the structural performance of RC structures affected by alkali–silica reaction (ASR).	4
Framework for capacity assessment and strengthening of RC buildings and bridges that are non-code-complaint and deteriorated by corrosion and/or ASR.	Publications	Output	New method: Experimentally validated framework that integrates in-situ testing with limit and/or numerical analysis to assess the structural performance of non-code-compliant structures affected by one or more deterioration mechanisms, including ASR and corrosion	8
Framework predicting fatigue crack growth in steel structures	Publications	Output	New concept/approach	4
Virtual sensing load estimation tool	Publications	Output	New tool: mathematical framework for evaluating applied loads based on measure structural response	4
Structural models integrating sensing and fracture mechanics	Publications	Output	New concept/approach	4
UAV based inspection system using computer vision	Publications	Output	New technology: description of cyber-physical system composed of UAVs, multi-modal sensors and computer vision to automate inspections on buildings and infrastructures.	4
UAV based inspection system using computer vision	Prototype	Output	New technology: proof-of-concept prototype of a cyber-physical system composed of UAVs, multi-modal sensors and computer vision to automate inspections on buildings and infrastructures.	10
AI/Robot assisted operation of structural health monitoring systems	Publications	Output	New technology: description of cyber-physical system composed of terrestrial robots, multi-modal sensors and orchestrated by AU to automate inspections on buildings and infrastructures.	4

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AI/Robot assisted operation of structural health monitoring systems	Prototype	Output	New technology: proof-of-concept prototype of cyber-physical system composed of terrestrial robots, multi-modal sensors and orchestrated by AU to automate inspections on buildings and infrastructures.	8
Algorithm estimating wind loads from structural response data	Publications	Output	New tool: mathematical framework for estimation on wind-structure interaction models based on structural response data	4
Machine learning model predicting wind conditions for structures, with a focus on extremes	Publications	Output	New method: published SotA on evaluation methods for extreme wind and other environmental condition assessment	4
Enhanced machine learning model predicting wind conditions for structures, with a focus on extremes	Publications	Output	Advanced method: published enhanced methodology for extreme wind and other environmental condition assessment	10
Case studies defining reliability targets for existing structures	Publications	Output	New concept/approach: published risk-based assessment framework demonstrating reliability targets for multiple existing structures	4
Multi-physical model for wind action in the built environment	Publications	Output	New concept/approach	4
Consulting engineers apply new capacity assessment frameworks from initial projects	Survey and *fib*, IABSE, JCSS Bulletins	Outcome	Applied by consultancy: developed outputs are disseminated through fib, IABSE, and JCSS, enabling initial uptake and application by consulting engineers	4
Consulting engineers apply new capacity assessment frameworks from further developed output	Survey and *fib*, IABSE, JCSS Bulletins	Outcome	Applied by consultancy: following further development and dissemination, broader adoption of the methods by consulting engineers is expected and will be monitored through surveys	7
Consulting engineers apply new capacity assessment and strengthening frameworks that involve multiple of the outcomes developed	Survey and *fib*, IABSE, JCSS Bulletins	Outcome	Applied by consultancy: integrated frameworks combining monitoring, in-situ testing, and analytical and numerical models within a risk-based approach are disseminated through professional organizations and	10

			adopted by consulting engineers	
Monitoring systems implemented for infrastructure asset portfolios	Published methodology	Outcome	Trialled by industry: engineering consultants test automated inspection systems based on robotics, AI and computer vision.	5
Enhanced monitoring systems implemented for infrastructure asset portfolios	Published enhanced methodology	Outcome	Applied by industry: infrastructure and building owners via engineering consultants adopts automated inspection systems based on robotics, AI and computer vision.	10
Wind loading estimation tool applied for retrofitting and lifetime extension	Published methodology	Outcome	Trialled by industry: engineering consultants test the wind loading estimation tool in the context of aerodynamic retrofitting and lifetime extension.	10
Enhanced wind loading estimation tool applied for retrofitting and lifetime extension	Published enhanced methodology	Outcome	Applied by industry: infrastructure and building owners via engineering consultants adopts the wind loading estimation tool in the context of aerodynamic retrofitting and lifetime extension.	10
Public agencies apply probabilistic assessment in maintenance planning	Survey	Outcome	Applied by industry: Public agencies (e.g., Danish Road Directorate and Railway Denmark) apply risk-based assessment methods for maintenance planning of infrastructure assets	10
Reliability concepts included in future design and assessment codes and recommendations	JCSS, fib, IABSE	Outcome	Applied in regulation/standardization: reliability indices derived from case studies are incorporated into bulletins and recommendations for the assessment of existing structures	6
Reliability concepts included in future design and assessment standards	CEN, Danish Standards or Danish road directorate bulletin and similar international docs	Outcome	Applied in regulation/standardization: reliability indices and risk-based assessment approaches are incorporated into standards, bulletins, and recommendations for assessing existing structures	10

Full-scale micro-pilot study applying developed monitoring and assessment tools	Practical case studies (requires additional funding)	Outcome	Demonstrated in practice: Micro pilot in full-scale conditions to assess new monitoring tools	4
Full-scale macro-pilot study applying developed monitoring and assessment tools	Practical case studies (requires additional funding)	Outcome	Demonstrated in practice: Micro pilot in full-scale conditions to assess enhanced monitoring tools	10
Impact assessment of climate change on wind load, structural response and durability	Publications	Outcome	Application in regulation/standardization	10
The service life of buildings and bridges are extended with least possible intervention	Survey and case studies	Impact	Change of practice: The developed assessment frameworks enable industry to extend the service life of existing buildings and bridges with least possible intervention.	10
Lower CO_2 emissions from avoided reconstruction activities	Survey and case studies	Impact	Change of practice: the frameworks support improved decision-making that reduces CO_2 emissions by enabling service life extension and avoiding unnecessary reconstruction.	10
Decision makers favour adaptation over demolition	Survey	Impact	Change in perception: reliable assessment methods enable decision-makers to prioritize adaptation and extended service life over demolition of existing structures	10

5. References

Akbar, M. A., Qidwai, U., & Jahanshahi, M. R. (2019). An evaluation of image-based structural health monitoring using integrated unmanned aerial vehicle platform. Structural Control and Health Monitoring, 26(1), e2276.

Al-Hagri, A., Stang, H., Paamand, J., Kolios, A., & Katsanos, E. (2026). Fatigue crack propagation and life prediction in offshore steel jackets using multi-fidelity modeling and machine learning. *Engineering Fracture Mechanics, 332*, 111800.

Andersen, M. S., & Brandt, A. (2018). Aerodynamic instability investigations of a novel, flexible and lightweight triple-box girder design for long-span bridges. *Journal of Bridge Engineering, 23*(12), 04018095.

Autrup, F., Jørgensen, H. B., Fernández Ruiz, M., & Hoang, L. C. (2023). Mechanical modelling of dowel action and the influence of small amounts of shear reinforcement on the shear-transfer actions in RC beams. *Structural Concrete, 24*, 5928–5946.

Barbosa, A. R., Hansen, S. G., Hoang, L. C., & Hansen, K. K. (2018). Residual shear strength of a severely ASR-damaged flat slab bridge. *Engineering Structures, 161*.

Caglio, L., Sadeqi, A., Stang, H., & Katsanos, E. (2025). Joint input-state estimation of structures subjected to complex loads via augmented Kalman filter with physics informed latent force models. *Mechanical Systems and Signal Processing, 223*, 111852.

Dansk Standard. (2024). *DS 11990:2024 Bæreevnevurdering af eksisterende konstruktioner* [Structural appraisal of existing constructions]. Dansk Standard.

Dakova, S., Zeller, A., Riese, J., Briem, D., Stiefelmaier, J., Böhm, M., & Sawodny, O. (2025). Active vibration control in adaptive high-rise structures using model predictive control. *Engineering Structures, 344*, 121317.

Diamantidis, D., Tanner, P., Holicky, M., Madsen, H. O., & Sykora, M. (2025). On reliability assessment of existing structures. *Structural Safety, 113*, 102452.

European Committee for Standardization. (2023). *EN 1990: Eurocode—Basis of structural and geotechnical design*. CEN.

Gao, D., Deng, Z., Yang, W., & Chen, W. (2021). Review of the excitation mechanism and aerodynamic flow control of vortex-induced vibration of the main girder for long-span bridges: A vortex-dynamics approach. *Journal of Fluids and Structures, 105*, 103348.

Hansen, S. G. (2019). *Influence of Alkali-Silica Reaction on the Shear Capacity of Reinforced Concrete Slabs without Shear Reinforcement* (PhD thesis). SDU.

Hansen, S.G., Abildgaard N.E., Jørgensen H.B. (2018). Strengthening Strategy for the Shear Capacity in Existing Concrete Structures. Structural Engineering International, 28(4): 489–497.

Hingorani, R., & Köhler, J. (2023). Towards optimised decisions for resource and carbon-efficient structural design. *Civil Engineering and Environmental Systems, 40*(1–2), 1–31.

Kapoor, M., Katsanos, E., Nalpantidis, L., & Thöns, S. (2021). Structural health monitoring and management with unmanned aerial vehicles: Review and potentials (BYG No. R-454). Technical University of Denmark (DTU).

Köhler, J., & Baravalle, M. (2019). Risk-based decision making and the calibration of structural design codes – Prospects and challenges. *Civil Engineering and Environmental Systems, 36*(1), 55–72.

Lai, X., Furkan, M., Bartoli, I., Aktan, A. E., & Grimmelsman, K. (2022). Bridge weigh-in-motion using augmented Kalman filter and model updating. *Journal of Civil Structural Health Monitoring, 12*(3), 593–610.

Meinen, N. E., & Steenbergen, R. (2025). Application of the Rosenblatt transformation in first-order system reliability approximations. *Structural Safety*, 112, 102521.

Meinen, N. E., Steenbergen, R. D. J. M., Hofland, B., & Jonkman, S. N. (2020). Applicability of the Goda–Takahashi wave load formula for vertical slender hydraulic structures. *Journal of Marine Science and Engineering*, 8(11).

Melhem, R. M., Caprani, C. C., Stewart, M. G., & Zhang, S. (2020). Bridge assessment beyond the AS 5100 deterministic methodology. Technical Report AP-R617-20. Austroads Ltd., Sydney, Australia (Austroads Project No. ABT 6111).

Michel, A., Otieno, M., Stang, H., & Geiker, M. R. (2016). Propagation of steel corrosion in concrete: Experimental and numerical investigations. *Cement and Concrete Composites, 70*.

Mode, P., Demartino, C., Georgakis, C. T., & Lagaros, N. D. (2025). Short-term extreme wind speed forecasting using dual-output LSTM-based regression and classification model. *Journal of Wind Engineering and Industrial Aerodynamics, 259*, 106035.

Modé, P. D., Demartino, C., Lagaros, N. D., & Georgakis, C. T. (2024). Correlation between predictability of extreme wind speeds and wind directionality: A preliminary analysis. In *International Conference on Optimization Driven Architectural Design* (pp. 284–294). Springer Nature Switzerland.

Nielsen, J. J., & Sørensen, J. D. (2011). On risk-based operation and maintenance of offshore wind turbine components. *Reliability Engineering & System Safety*, 96(1), 218–229.

Øelund, J. K. H., Christensen, J. H., Zeitzen, R. M. K., Vedel, H., & Feddersen, H. (2026). Assessing the intensification and impact of a historical storm in a warmer climate. *Natural Hazards and Earth System Sciences, 26*. https://doi.org/10.5194/nhess-26-1039-2026

Reksowardojo, A. P., Senatore, G., Srivastava, A., Carroll, C., & Smith, I. F. (2022). Design and testing of a low-energy and-carbon prototype structure that adapts to loading through shape morphing. *International Journal of Solids and Structures, 252*, 111629.

Seltmann, S., & Hasse, A. (2025). Nonlinear synthesis of compliant mechanisms with selective compliance. *International Journal for Numerical Methods in Engineering, 126*(14), e70084.

Sharmilan, S., Stang, H., & Michel, A. (2024). A multi-species reactive transport model based on gas-ion-solid phase interaction for the carbonation of cement-based materials. *Cement and Concrete Research, 175*, 107349.

Sørensen, J. D. (2001). Calibration of partial safety factors in Danish structural codes. JCSS Workshop on Reliability-Based Code Calibration.

Sørensen, J. H., Hoang, L. C., & Ruiz, M. F. (2025). Shear failures in pile caps: Governing mechanisms and influence of size on the resistance. *Structural Concrete*.

Steenbergen, R. D. J. M., & Vrouwenvelder, A. C. W. M. (2025). The JCSS probabilistic model code, future developments. *Structural Safety, 113*, 102540.

Vejdirektoratet. (2024). Reliability-based classification of existing bridges.

Vestergaard, D., Larsen, K. P., Hoang, L. C., Poulsen, P. N., & Feddersen, B. (2021). Design-oriented elasto-plastic analysis of reinforced concrete structures with in-plane forces applying convex optimization. *Structural Concrete, 22*(6), 3272–3287.

Zhi, L.-H., Fang, M.-X., & Li, Q. S. (2017). Estimation of wind loads on a tall building by an inverse method. *Structural Control and Health Monitoring, 24*(4), e1908. https://doi.org/10.1002/stc.1908

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