White Paper

Task Force 2: Efficient Building Operation

Topic B:

Optimised building costs

Revision: V3

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Executive summary

The SmartBuilt4EU project has set up four task forces investigating issues related to smart buildings. Their objective is to identify the remaining challenges and barriers to smart building deployment, and the associated research and innovation gaps that should be addressed in the near future.

Task force 2 focuses on the optimal integration and use of smart solutions to allow an efficient building operation. A first white paper discussed the interoperability requirements to ensure a seamless operation, as well as the optimisation in terms of building costs and reduction of environmental impacts, over the full life cycle and is available via https://smartbuilt4eu.eu/publications/.The topic currently addressed by this task force and presented in this paper is ***the optimisation of building costs.***

The way we live in the built environment needs to become more sustainable. Going from the current renovation rate below 1% to an average 3% is a major challenge that will require technology cost drops, flexible and performance-based products and services, as well as new financing schemes. Digitalisation is a steppingstone to achieve the required industrialisation of the sector. For instance, it is estimated that full-scale digitalisation in non-residential construction would lead to annual global cost savings of 13% to 21% in the engineering and construction phases and 10% to 17% in the operations phase[1]. These gains will be enabled by the full deployment of Building Information Management (BIM) and, in the longer term, (dynamic) Digital Twins, by automation and robotics; and more generally by data-based tools and services which make use of the latest advances in IoT and embedded sensors, cloud computing, massive processing of Big Data, and Artificial Intelligence. However, these smart solutions bring additional capital and operating costs: building costs must therefore be optimised with a life cycle approach, i.e. from planning to end-of-life.

This white paper therefore aims to provide an overview on what is known and what should be further investigated to answer the following questions:

- How do we define optimisation and from which perspective? (i.e. building user, building operator, 'society' as a whole?)
- What are the digital tools and solutions available today to lower the overall building costs and what are their respective impacts?
- How can Energy Performance Certificates, Digital Building Logbooks, Building Renovation Passports and certifications contribute to the optimisation of life cycle costs?
- How should this knowledge be transferred to the many actors of the value chain, to make sure that there is a paradigm shift from targeting the lowest CAPEX to optimising the life cycle costs?

In its first part, this paper provides a state of the art regarding the following issues, specific attention being paid to EC-funded projects:

- Life cycle approach to optimise costs (scope and scale of the assessment, optimisation approach)
- Digital tools and solutions (including digital twins, BIM, IoT, 3D scanning, BEMS, BACS, integration of machine learning and AI)
- Certificates and tools pushed by regulation such as Energy Performance Certificates, digital building logbooks, building renovation passports

A brainstorming process then enabled to identify some key barriers and drivers regarding the optimisation of building costs. The next diagrams provide an overview of the main barriers and drivers discussed.

[1] BCG (2016). Digital in Engineering and Construction https://www.bcg.com/industries/engineered-products-infrastructure/digital-engineering-construction.aspx

VALUE CHAIN	Decision-makers giving the preference to construction costs in the planning stage, i.e. targeting the lowest CAPEX instead of optimising the life cycle costs
	Construction companies working in silo with no overall guarantee of performance
	Mismatch between lowest bid costing and actual delivered cost (changes in cost from project approval to project delivery)
REGULATION	Regulatory framework for optimisation not simple enough for non-specialist end-users
SOCIAL	Lack of trust in digital solutions and security concerns from users, fear of loosing privacy
	Lack of user involvement limiting the optimisation potential and hindering the decision to invest
	Lack of knowledge on savings opportunities to guide decision-making and then the operation
ECONOMIC	Long payback period, as externalities such as CO2 and co-benefits are not considered
	Lack of clear and easy-to-understand data-driven business models (e.g. Energy Performance Contracts and other ESCO-based business models)
	Lack of tools to assess/ optimise investments and address uncertainty, especially in future energy prices
	Split incentives (owner/tenant or builder/owner)
TECHNICAL	Low smart readiness of the building stock and lack of interoperability between active systems and software
	Complex costs, rapidly changing (depending on location and time), without any common up-to-date database providing realistic costs for materials/ equipment over the whole life-cycle

Top barriers according to the Task Force

Figure 1: Overview of main barriers

VALUE CHAIN	New tools to support decision-making (new technologies for the construction sector + co-design methodologies)
	Evidence of reduction of O&M costs through Energy Performance Contracts and ESCOs
REGULATION & STANDARDS	Push from EU Regulation: EPBD, SRI, Digital Logbook, Fit for 55 package, etc.
SOCIAL	Increased awareness and transparency thanks to open comparison with peers or supported by manufacturers and trade associations
	Opportunity to go beyond the building scale by mobilising (energy) communities
	Digital natives more open to digital concepts
ECONOMIC	New business opportunities arise with new technologies and services
	Evidence of increase in property value thanks to increased energy efficiency & smartness
	Incentives and new financing opportunities thanks to the Recovery Plan
TECHNICAL	Reduced cost of digital tools: digitalisation becoming ubiquitous and more affordable
	Standard data models and semantics for data interoperability

Top drivers according to the Task Force

Figure 2: Overview of main drivers

Based on the State of the Art and the barriers and drivers, a number of research and innovation gaps were identified. They are synthetised in the next diagrams.

These ‘gaps’ will feed the elaboration of the Strategic Research and Innovation Agenda on smart buildings that will be produced by the SmartBuilt4EU consortium by mid-2023, together with some recommendations targeting policy makers.

R&D	**Develop affordable and intuitive digital platforms, covering all stages of a building life,** for co-construction with all stakeholders, collaboration and communication, user involvement and decision-making (inc. simulation functionalities, gamification)	*Top priorities according to the Task Force*
	Develop methods to better link relevant (open) standards in the data sharing workflow to support the optimisation of costs	*Top priorities according to the Task Force*
	Develop harmonised tools and approaches for life cycle costing to enable a paradigm shift from targeting lowest CAPEX to optimising life cycle costs • Including co-benefits and externalities in the optimisation equation as well as validated models of occupant behaviour • Supported by an uncertainty analysis to assess the influence of various parameters	*Top priorities according to the Task Force*
	Develop **low-cost and plug&play sensors** for energy and comfort monitoring as well as innovative solutions to interface with legacy equipment and upgrade smartness /optimise the operation and maintenance of buildings	
	Develop and maintain **common, up-to-date and reliable databases providing costs for materials and equipment over the whole life cycle** (similar to LCA databases)	
DEMO	**Create a programme (“demo spaces”) that support the trials and demonstration of technical/social R&D actions in privileged conditions** (early access, reduce licencing costs etc) for SMEs and other construction actors: • with experimental facilities and test beds as well as real buildings involving all stakeholders of the built environment • promoting the involvement of potential early-adopters • with key metrics to quantify user involvement • with a strong focus on data sharing to enable the optimisation of costs	
	Implement a SRI pilot project in every Member State at least in one public building with calculation of costs and (wider) benefits	

Figure 3: R&I gaps

SCALING UP & INDUSTRLIALISATION	Implement specific programmes to attract investors so as to finance innovation and technology transfer for new solutions enabling the optimisation of building costs	
	Set up smart modular platform strategies to address the complexity of innovation in buildings, reduce direct costs and shorten project lead times	
REGULATION & LEGAL FRAMEWORK	**Update buildings regulations** to make them easier to understand and comply with, **imposing a minimum level of smartness for new and renovated buildings** (as well as rented dwellings), with a minimum set of parameters to be measured to monitor building performance (e.g. energy efficiency, IEQ)	*Top priorities according to the Task Force*
	Encourage **Member States to set clear long-term objectives and corresponding requirements for buildings** (including for building codes) and invest in their implementation	*Top priorities according to the Task Force*
CERTIFICATION & STANDARDISATION	Make sure the **digital platforms** developed to enable the optimisation of building costs over the different life stages are **GDPR compliant and give control and security to the data owners, and use harmonised data exchange standards**	*Top priorities according to the Task Force*
	Include the **SRI rating in all building digital certificates**, e.g. EPC, Digital Building Logbook, Building Renovation passport	
	Encourage the use of **standardised methodologies for building lifecycle management**	

Figure 4: “Go-to-market’ gaps

Table of content

List of abbreviations

AECOO	Architecture, Engineering, Construction, Ownership AND Operation
AI	Artificial Intelligence
BACS	Building Automation and Control System
BCT	Blockchain Technologies
BDA	Big Data Analytics
BDT	Building Digital Twins
BE	Built Environment
BEMS	Building Energy Management Systems
BIM	Building Information Modelling
BMS	Building Management Systems
BREEAM	Building Research Establishment Environmental Assessment Method
BRP	Building Renovation Passport
CDB	Circular Digital Built environment
CE	Circular Economy
DBL	Digital Building Logbook
DR	Demand Response
DT/DTwins	Digital Twins
EC	European Commission
EEB	Energy Efficient Building
EMS	Energy Management Systems
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificates
EOL	End of life
GDPR	General Data Protection Regulation
GIS	Geographic Information Systems
HVAC	Heating Ventilation and Air Conditioning
ICT	Information and Communication Technologies
IEQ	Indoor Environmental Quality
IFC	Industry Foundation Classes
IoT	Internet of Things
LCA	Life cycle Analysis
LCC	Life cycle Cost
LCSA	Life cycle Sustainability Assessment
LEED	Leadership in Energy and Environmental Design
KPI	Key Performance Indicator
ML	Machine Learning
nZEBs	Nearly Zero Energy Buildings
PEBs	Plus Energy Buildings
RFID	Radio Frequency Identification
R&I	Research and Innovation
SCAS	Smart, Connected Asset Systems
SEOL	Sustainable end-of-Life
SRI	Smart Readiness Indicator
TF	Task Force

1. Introduction

This white paper is produced in the context of the SmartBuilt4EU project, a coordination and support action funded by the European Commission to bring together the research and innovation community on smart buildings.

The SmartBuilt4EU project has set up four task forces with volunteers all across Europe, investigating topics related to smart buildings. They respectively address the interaction between building and end-user, efficient building operation, interactions between the building and the external environment, and cross cutting issues.

Figure 5: The four task forces set up by the SmartBuilt4EU project

SmartBuilt4EU task force 2 focuses on the optimal integration and use of smart solutions to allow an efficient building operation. The task force investigates what are the interoperability requirements to ensure a seamless operation, as well as the optimisation in terms of building costs and reduction of environmental impacts, over the full life cycle.

The task force will focus on 3 topics (one per semester):

1. **Interoperability:** Interoperability among building components & systems
2. **Optimised building costs:** Integrating tools for optimised costs over the full life cycle (incl. BIM, digital twin, predictive maintenance, Artificial Intelligence, weather forecast, predictive control)
3. **Smartness to reduce building's environmental impacts:** Integrating tools to reduce the environmental impact over the full life cycle, paying attention to the carbon footprint of smart solutions (incl. Resource efficiency, Environmental impact management, Integration of renewable energies)

The present White Paper focusses on the second topic, i.e. 'Optimised building costs', and presents the outcomes of a collective work, carried out with the members of the Task Forces, in several steps:

- Agreement on the scope
- Review of the State of the Art and identification of the points to be investigated in particular
- Analysis of barriers and drivers
- Identification of R&I gaps
- Key conclusions on the topics and recommendations

2. Topic under investigation by the Task Force

2.1. Rationale

The way we live in the built environment needs to become more sustainable. Going from the current renovation rate below 1% to an average 3% is a major challenge that will require technology cost drops, flexible and performance-based products and services, as well as new financing schemes. Digitalisation is a steppingstone to achieve the required industrialisation of the sector. For instance, it is estimated that full-scale digitalisation in non-residential construction would lead to annual global cost savings of 13% to 21% in the engineering and construction phases and 10% to 17% in the operations phase[2]. These gains will be enabled by the full deployment of Building Information Management (BIM) and, in the longer term, (dynamic) Digital Twins; by automation and robotics; and more generally by data-based tools and services which make use of the latest advances in IoT and embedded sensors, cloud computing, massive processing of Big Data, and Artificial Intelligence. However, these smart solutions bring additional capital and operating costs: building costs must therefore be optimised with a life cycle approach, i.e. from planning to end-of-life.

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2.2. Scope

The purpose of this section is to define the scope of the topic being investigated. Potential interactions with other topics addressed by the different SmartBuilt4EU Task Forces are also clarified.

The following 'blocks of knowledge' were identified during the 1st meeting of the task force:

- **Life cycle approach to optimise costs** (scope and scale of the assessment, costs to be included, optimisation approach)
- **Digital tools and solutions** (including digital twins, BIM, IoT, 3D scanning, BEMS, BACS, integration of machine learning and AI)
- **Certificates and tools pushed by regulation** such as Energy Performance Certificates, digital building logbooks, building renovation passport

Interoperability and data exchange protocols are not addressed in this White Paper, as they were already covered by the Topic A of task force 2. Environmental impacts and Life Cycle Assessments will be covered in the 3rd Topic addressed by task force 2.

[2] BCG (2016). Digital in Engineering and Construction https://www.bcg.com/industries/engineered-products-infrastructure/digital-engineering-construction.aspx

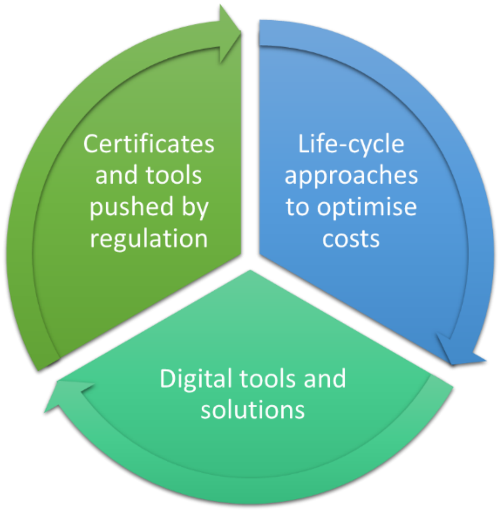

Figure 6: Identified blocks of knowledge

3. State of the Art

3.1. Literature review

3.1.1. Life cycle approaches to optimise costs

Life cycle approaches allow to identify improvement possibilities and as such enable better and more-informed decision-making. It implies that everyone in the whole chain of the construction/building's life cycle has a responsibility and role to play, taking into account all the impacts on the economy, the environment and the society. It goes beyond the traditional silos and considers builders and manufacturers, tenants, building owners, occupants, building managers, energy utilities and system operators.

Life cycle costs

ISO 15686-5:2017 provides requirements and guidelines for performing **life cycle cost (LCC)** analyses of buildings and constructed assets and their parts, whether new or existing. This method takes into account costs and cash flows, i.e. relevant costs (and income and externalities if included in the agreed scope) arising from acquisition through operation to disposal. The building life cycle phases generally included in the assessment are the cost for the initial investment (design and construction), the cost for operation and maintenance and the end-of-life (EOL) costs. LCC calculations can include a comparison between alternatives or an estimate of future costs at portfolio, project or component level. This approach allows selecting the most cost-effective solution, undertaking financial options evaluation and constitutes, in this way, a tool that supports the decision-making process. LCC assessment allows to:

- Balance the cost of ownership and occupation, analysing initial investment and running costs;
- Assess risks and costs connected to maintenance and replacement due to failure;
- Give awareness of total costs and the possibility to adjust these total costs at the design stage.

Relying on this standard, the **CRAVEzero** project proposed a structured methodology for assessing buildings' LCC. In the methodology proposed, costs are grouped according to the phases of the life cycle (design, construction, building site management, operation and maintenance and EOL), including the determination of the energy costs, cost of land and the non-construction costs (fees and enabling costs, planning fees, user support costs and other externalities).

To optimise the building cost, a **total cost approach** considering benefits should be envisaged. CRAVEZero's calculation proposes a uniform approach in quantifying non-monetary benefits, including:

- **uncertainty analysis**, related to the predicted energy performance of the building and components during lifetime and to future trends of economic boundaries (interest rate, energy costs and inflation)
- **co-benefits** such as increased productivity, improved health, publicity value, higher renting opportunities, reduced employee turnover and reduced absenteeism.

The objective is to present new business advantages and opportunities to potential investors, going beyond technical performance analysis.

The AZEB project focuses on the life cycle cost reductions of new nZEB´s (Nearly Zero Energy Buildings) through integral process optimisation in all construction phases. According to the project, the following solutions for cost reduction should be considered:

- **Involving all stakeholders from the start**, creating explicit functional requirements as a starting document and applying continuous validation in all project phases: **define clear performance indicators on cost, energy, environment and social sustainability**.
- **Implementing contracting practices** that stimulate integrated working methods from the start of a project, allow for a guaranteed performance and stimulate transparent cost optimization throughout the value chain
- **Applying costing methods to projects from a value stream perspective,** i.e. considering the set of actions that take place to add value to a customer from the initial request through realization of value by the customer, in all project phases

The project proposes a **common methodology for cost reduction of nZEBs**, based on existing identified solutions in a range of disciplines associated with building project, technical as well as non-technical. Among the methods, AZEB provides a **tool facilitating life cycle cost and environmental analysis**, which are often limited in application to research projects or policy evaluation. The 17-step AZEB methodology is a roadmap which shows all steps to be taken in an nZEB project to **increase its cost-effectiveness.** Note that AZEB proposes a free online training to help stakeholders to customize the 17 steps for their own project. By actively using the roadmap, project owners become skilled in the application and discover their personal best route towards an affordable nZEB.

Use of Life Cycle Assessment to optimise design (and overall costs)

Performing a Life Cycle Assessment (LCA) is today required by some government and integrated in building standards. In practice, it is commonly employed to study the primary energy uses and associated environmental impacts of the different phases of a building's life cycle. This tool is multi-disciplinary in the sense that impact on the natural environment and even peoples' relations to such impacts can be modelled[3]. **Life cycle Sustainability Assessment (LCSA)** is a framework integrating different models concerning all the three bottom lines of sustainability (environmental, economic and social). Performing LCA is still a challenging and complex process, mixed with the possibility of significant errors—namely due to unreliable input data derived from unrepresentative sampling (Shahabian et al., 2020). However, using Artificial Intelligence (AI) and the Internet of Things (IoT), collecting real-time data (e.g., energy and carbon input/outputs) via sensors, can make LCAs much more precise and automated compared with conventional methods. Thus, LCA can better serve the procedures of optimal design and informed decision making.

[3] LCA will be investigated in more details in the Topic C of Task Force 2.

Cultural-E H2020 project provides guidelines and specifications for LCA of Plus Energy Buildings (PEBs). The overall framework envisages three levels for the assessment, which are represented by products (single units), solutions sets (consists of different components and products) and buildings (gathering information on building constructions and systems and on building operation). For buildings three further analyses modes (compliance, operation and sustainability) are distinguished. The guidelines present core rules for the lifecycle modelling and impact calculation methods, based on standards ISO 14040 and ISO 14044. Furthermore, specifications for buildings and building products provided by EN 15804, EN 15643 and EN 15978 are considered. LCAs in PEBs of CULTURAL-E consider the whole lifecycle of products solution sets and buildings in order to evaluate a 'payback period'. The assessments performed analyse and define social co-benefits/impacts in the context of a community system. Analysis have been performed based on the technical and functional factors for IEQ (Indoor Environmental Quality) for each geo-cluster. This, together with cost analyses, contributes to evaluate the whole work and activities in a holistic way, by considering the 3 dimensions of sustainability and by not disregarding the technical quality of the developed technologies, solution sets and PEBs.

Circular strategies

Another approach to consider is the **circular economy**. According to Arup and the Ellen MacArthur Foundation, "adopting circular economy principles offers businesses profitable service offerings, developers more adaptable assets, cities reduced waste management costs and citizens improved services with lower economic and environmental costs". The ReSOLVE framework proposed by the MacArthur Foundation, outlines 6 actions to guide the transition towards a Circular Economy (CE): (1) Regenerate, (2) Share, (3) Optimise, (4) Loop, (5) Virtualise, (6) Exchange. Applied to the built environment, the circular economy approach could help the sector to reduce its environmental footprint and to avoid rising costs and delays, among other things.

The Buildings as Material Bank (BAMB) project has been one of the pioneers in developing and testing circular strategies and tools to recover value from buildings. To support resource effective decision making in the building process, BAMB intends to develop a decision-making model (the Building Level Integrated Decision Making Model). The model is a methodology whereby new buildings and existing buildings can be assessed for resource productivity, based upon material selection and design decisions. The ambition of the project is then to develop a BIM compliant Circular Building Assessment Prototype as a proof of concept of how the assessment and decision-making model could aid real world BIM users in making better choices and designs to enhance reuse potential and transformation capacity through the different phases of the life cycle of the building. This prototype can be used to assess reuse potential and resource productivity alongside more traditional performance parameters such as work scheduling, project cost, energy performance etc.

However, the lack of cross-sector communication and coordination tools remains a challenge to be addressed in order to enable the broad implementation of a feasible circular design strategy in current construction practice. Digitalisation could offer some of the tools needed (Iyer-Raniga, 2019).

3.1.2. Digital tools and solutions available today

The last decade has seen the advent of a large panel of digital tools and solutions for the construction sector and the built environment. They provide a unique opportunity to enable the optimisation of building costs across all stages of a building life cycle.

An overview of the use of the Digital Technologies across the life cycle stages of buildings is provided below and focusses on **BIM, Digital Twins (DTwin), IoT, Artificial Intelligence (AI), Building Automation Control**

Systems (BACS) and Big Data Analysis (BDA). This overview is adapted from the Circular Digital Built environment framework (CDB framework) proposed by Cetin et al (2021), which mapped 10 enabling Digital Technologies. Using the CDB framework, practitioners may create roadmaps for circular economy (CE) implementation by choosing their circular building strategies and identifying the set of technologies that best support the selected strategies. The CDB framework integrates four core CE principles of regenerating, narrowing, slowing and closing (circular economy).

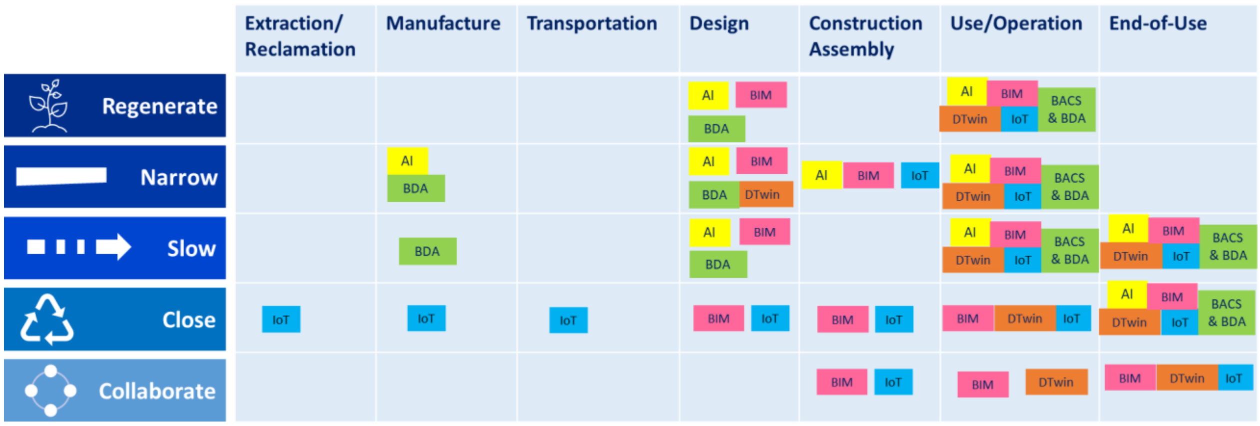

Figure 7 Mapping of enabling digital technologies for a circular built environment (adapted from Cetin et al., 2021)

An overview of these technologies, their maturity, how it can support the optimisation of building costs and the remaining challenges is presented below.

Building Information Modelling (BIM): BIM is the digital representation of a built asset to be projected, constructed or operated (Poljansek et al., 2017). It contains relevant information such as the building's geometry, material properties, and quantities of elements and form a reliable basis for decisions (from strategic planification to end of use) (ISO 19650).
Building life stage: from manufacturing to end of use
Maturity: widely accepted in industry
Contribution to the cost optimisation:

- Reduce inefficiencies in traditional construction processes and help optimise building design to reduce natural resource used and waste creation (Won and Fan, 2013)
- ISO 19650 aims to further extend the collaborative exchange of information among the AECOO stakeholders (Architecture, Engineering, Construction, Ownership AND Operation). BIM models facilitate collaborative construction delivery methods such as integrated project delivery, construction project management, and integrated design and delivery system.
- Structural design directly impacting the disassembly potential of a building. It supports pre-demolition activities and overall traceability of building materials. The Iceberg project has developed a new BIM-aided-Smart Pre-Demolition tool to enable a higher accuracy estimate (>80%) of end-of-life building material in pre-demolition waste audits keeping their cost down significantly (<2 €/m² of built surface).
- Integration of life cycle analysis (LCA) into the building design process (Xue et al., 2021)
- Emerging sensing technologies integrated into the BIM models provide new capabilities to minimise construction project time and cost overruns. In its digital construction toolbox, the COGITO project integrates 'Reality capture technology' (satellite images, 3D scanning, aerial vehicles, weather predictions, sensing technology) to collect data about the actual state of operations from constructions sites. These 'as-built-data' feed the BIM that is continuously updated in the COGITO

Digital Twin platform. Innovative integrated data management and software solutions allow then to optimise site operations (Health & safety, Quality control adaptative workflow management, GUI & support apps) and costs.

- BIM supports material passports and databanks and is used either as a source of material data or as a platform to operate on.

Remaining challenges:

- Current BIM models have their limitations since they do not reproduce near real-time behaviour of the asset once in-service or in-use (Matarneh et al., 2019). The main challenge is then to reach a proper combination of BIM datasets, procedures, and professionals, with other systems of information.
- Technological innovation on BIM tools needs to be supported by a major awareness of the actors involved, improved skills and competences by focused BIM trainings and educational programmes (Alhamami et al., 2020), as well as an important change of approach in the current construction/renovation practice. (Elagiry et al., 2019 – BIM4Ren project)
- For renovation projects, there is a lack of BIM tools application. Specific challenges of existing buildings need to be carefully analysed.
- Further research could be undertaken for the development of the existing BIM uses that have been modified by the integration of the SEOL phase into the building life cycle (Charef and Emmitt, 2020)
- Explore the potential of automation for checking the huge amount of data generated throughout the asset and material life cycles. The use of Artificial Intelligence (AI), particularly machine learning (ML), as a facilitator, seems to be a promising technology. (Charef and Emmitt, 2020)
- The use of radio frequency identification (RFID) and blockchain technologies (BCT) have potential to secure the access and quality of the data throughout the asset and materials life cycles.

Building Digital Twins (BDT): Digital twins is a realistic representation of the physical counterpart that links the physical to the digital in various ways for desired intents and purposes, where physical aspects of an object or infrastructure system are 'twinned' to a digital representation (Alonso et al. 2019). A Building Digital Twin (BDT) can be considered as an extended BIM model integrating real time data.

Under the SPHERE project, a set of definitions have been developed by the consortium to help drive the technical Digital Twin development for the Architecture, Engineering, Construction, Ownership AND Operation (AECOO) sector. For new buildings, a Building Digital Twin describes the AECOO assets during its design and construction but also during operation and maintenance phases. It contains the informational sets necessary to describe and produce a physical version that duplicates or twins the virtual version. For existing buildings, an open opportunity for implementing Building Digital Twins arises during any major retrofitting, bringing the entrance of new methods and technologies to allow their progressive Digitalisation.

By creating a Digital Twin Environment, two main purposes are sought: Predictive – the BDT would be used for predicting future behaviour and performance of the physical product – and Interrogative – the BDT could be interrogated for the current and past histories. These two basic drivers may include completely different requests depending on which is the role of the stakeholder interacting and the typology of the Digital Twin.

Building life stage: from manufacturing to end of use

Maturity*:* early research and development stage in both industry and academia

Contribution to the cost optimisation (SPHERE White paper, 2021)

- BDT supports easier and more reliable renovation implementation with a continuous monitoring to decide future change, reduced construction time and costs. It allows scheduling the next renovation, easier commissioning, and less ad hoc repairs (proactive). Moreover, it helps to reduce project completion time and to reduce costs due to the efficient use of labour and resources.

  BDT supports an easy and transparent cost assessment and establishing a mutual trust between subcontractors for renovation works and their clients.

- For public/government owners, BDT provides a central database with regard to materials, enables easier sharing with different stakeholders, saves time and costs and enables better control of quality.
- For tenants, BDT facilitates the reduction of energy consumption by custom optimisation of explicit demand response, based on historical time series of the tenant energy demand, allowing better contracts with the ESCO.
- Updated energy data and simulations for energy certificates in new/retrofitted buildings.
- BDT supports operational energy control, and feedbacks from operations to design. Digital twins allow to simulate best operation and maintenance parameters. It provides an overall knowledge of the state of the building for daily management tasks and for the implementation of routine maintenance tasks.

Remaining challenges:

- New roles (Digital Twin Manager) are needed for the implementation of Digital Twins in the AECOO sector.
- Most homes are not yet smart, and the capabilities of so-called smart homes should also be examined in more detail, as for example the lack of communication capability could hinder the twinning capabilities of any asset.
- A standard framework for future development of Building Digital Twins, providing an environment for Smart, Connected Asset Systems (SCAS) throughout their entire life cycle needs to be developed. The SPHERE project will provide an on-field testing of how the proposed BDT definitions and BDT profiles will not only withstand the complex reality of AECOO sector, but enable value enough to support the extra cost associated due new IT tools and personnel involved.
- New data-driven paradigms shall be developed to unlock the deployment of digital building twins. Four pillars need to be addressed: (1) modelling and integration of information; (2) data enrichment; (3) assuring their interoperability with different data hubs; and (4) linking them with real business cases. (Hernández-Moral et al., 2021)

Artificial Intelligence (AI) and Machine Learning (ML): Artificial intelligence is a field, which combines computer science and robust datasets, to enable problem-solving and decision-making. AI includes sub-fields of machine learning (ML) and deep learning. These disciplines are comprised of AI algorithms which seek to create expert systems that make predictions or classifications based on input data (quoting IBM).

Building life stages: from design to operation and maintenance phase, considering the living environment (may also become useful for end of use)

Maturity: rapid technological advances made, but limited acceptance/usage in industry (depending on the phase of the building life cycle)

Contribution to the cost optimisation:

- ML/AI and data-driven approaches can support actual operational costs definition and characterisation of the building performance.
- ML/AI and real time location tracking, combined with 4D BIM models, reduce costs in the construction phase through optimal health & safety and workflow management.
- AI can help reducing operating costs by optimising user interaction with building technologies through alerts and suggestions.
- It allows the automated assessment of individual versus collective solutions.
- Combined with big data and IoT, AI techniques and algorithms provide capabilities to predict defects in systems and determine resource and maintenance requirements in buildings.
- ML/AI techniques are also useful for end-use phase activities. Rakhshan et al. proposed a predictive model to estimate and evaluate the economic reusability of structural elements.

Remaining challenges:

- Overcome the lack of high-trained IT experts in the construction sector to develop sector specific applications.
- The high fragmentation of the value chain and the changes from project to project make the development of a long-term learning strategy very difficult. Changes in regulation and short-term learning strategy need to be developed to tackle the gap on skills and considering the complexity of projects and of the value chain.
- Standardized methodologies for data management, and processes, and consolidation of proprietary data formats and languages are needed for implementing AI.
- Social perception of AI as a threat is another challenge to overcome. The promotion of pilot cases and dissemination of success stories will facilitate the adoption of AI technologies and will help to extend the market for innovative solutions.

Building automation control systems supported by Internet-of-Things and Big Data Analytics

Building automation control systems (BACS) ensure the operational performance of a building (energy efficient, economical and safe operation) and aim to **achieve high comfort levels and well-being** for building occupants as well as integration of the building comfort conditions with **energy and cost-saving strategies**. Through automatic control it facilitates the manual management of technical building systems.

BACS are now supported by Internet-of-Things (IoT) for the built environment, i.e. digital and connected technologies able to sense the indoor and outdoor environment and allowing the real-time monitoring of a building. Overall, deploying IoT technology in the built environment enables the performance optimisation in various application areas such as: (i) tracking building material properties for reuse (ii) preserving resources (energy, water etc), (iii) offering a healthier and comfortable indoor environment by controlling heating, ventilation, and space conditioning systems etc.

Building life stage: from manufacturing to operation & maintenance phase, considering the living environment
Maturity level*:* early stage of acceptance/usage in industry for the IoT part
Contribution to the cost optimisation:

- **IoT and BIM**-coupled platforms can provide various decision support tools and services for improving the efficiency and effectiveness of daily operations, decision making, collaboration, and supervision throughout on-site assembly processes of prefabricated construction.
- Together with **Big Data Analytics (BDA)**, sensor systems help to track, monitor, and control failures (Bressanelli et al., 2018), predict the maintenance needs of installations (Panfilov et al., 2018); and enable remote maintenance, repair and upgrades (Ingemarsdotter et al., 2019). BDA might play a key role to prolong the lifespan of building assets (e.g. HVAC units) by providing insights into sustainability-oriented decision making during the operational phase (e.g. detecting and preventing failure).
- **IoT together with Artificial Intelligence** can deliver more efficient management of the infrastructure and its maintenance and so reduce the related costs.
- **IoT** can enable interaction with the energy grid, allowing cost savings thanks to demand response and setup of energy communities. To illustrate this aspect, we can cite the SIM4BLOCKS project focused on the development of innovative demand response services for residential and commercial applications. It combined decentralised energy management technology at the blocks-of-buildings-scale to enable demand response. The DRIMPAC project is instead focusing on a unified demand response interoperability framework, enabling market participation of active energy consumers.
- **IoT** could contribute to the transition to a circular economy (CE), through supporting circular business model and design strategies (Ingemarsdotter et al., 219).

- With the help of **sensing technologies, BDA** offers for the construction sector several opportunities including the improvement of building's energy performance during the operational phase of a building, **leading to a lower use of resources, and so lower operating costs.**

Remaining challenges:

- Building a control algorithm that explicitly takes weather effects into account remains difficult. Among promising methods, the model-based predictive control method takes into account disturbance predictions such as the weather in regulating the control activities along with the chosen optimization strategy and energy price variations. However, for medium-sized buildings this method it is not valid since it involves significant costs of modelling, data collection, and monitoring (Shaik et al., 2014)
- Develop hybrid and innovative IoT solutions and communication technology to reach effective real time communication between IoT and BIM
- Slow communication between IoT and Digital Twin platform, low accuracy and frequency data from affordable IoT, or high-performance data with expensive IoT are major challenges to be tackled

Digital technologies and advancements in big data analytics bring promising opportunities for smart monitoring and **predictive maintenance analysis**. Katona and Panfilov (2018) proposed a distributed data-driven architecture of predictive maintenance framework based on the principles of Industry 4.0 and recent developments in distributed computing, Big Data and Machine Learning. Predictive maintenance is emerging as a powerful maintenance strategy that can significantly **reduce operation and maintenance costs** of public, commercial and industrial environment. By reducing human effort and sending early alerts to the building managers' dashboard, it reduces maintenance costs while enhancing its performance. In addition, technologies such as virtual reality and augmented reality can improve decision-making processes and the daily work of maintenance personnel by providing innovative reports and a holistic view of the smart environment.

Finally, while digitalisation and advanced control strategies show promise to optimise building performance, standard comparison frameworks and benchmarks are needed to help practitioners choose the most promising approaches to implement. Indeed, while smart solutions can have a huge impact on reducing operating costs, smart solutions can have a high cost themselves and can represent a barrier to the overall cost optimisation. **To avoid over or underinvesting, understanding which level of technology should be implemented to achieve a required result is key**. Building simulation can be used to create standard comparison and **benchmarking frameworks** through standardized building models, boundary conditions, solvers, and performance metrics (BOPTEST Framework).

3.1.3. Tools pushed by the EU regulatory framework

Successive EU regulations have introduced tools and frameworks to better assess the level of performance of buildings (e.g. their energy efficiency, smartness), make it more transparent to users and occupants, and easier to track. This information enables buildings owners or managers to make informed decisions to improve building performance and reduce operational costs.

Energy Performance Certificates (EPCs) have existed since the implementation of the Energy Performance of Buildings Directive (EPBD) in 2002 (2002/91/EC). In 2020, the recast of the EPBD (2010/21/EU) strengthened the legislation to make the energy performance of individual buildings more transparent. Among the problems that EPCs face, there is still a lack of interoperability between data sources, and the complexity of this management means that its reliability is limited. EU member states have implemented national EPC regimes, following different approaches, with different scope and acceptance. However, EPCs can be a relevant instrument to empower different types of stakeholders: from end users to policy makers, supporting decision-makers to evaluate policies and financial schemes.

EPC data can be useful for several purposes: firstly, it allows for analysis and prediction of energy use, for better resource planning or to examine the energy baseline of the building. This can also be used as a basis for designing new building solutions and better estimating the energy saving potential of refurbishment actions, in order to propose energy and cost-effective options. This information, in combination with heterogeneous data and machine learning techniques, allows proposing cost-effective solutions with limited computational effort. Different procedures can be considered to support different types of stakeholders: the integration of cost-optimal methodology analysis into certification schemes, roadmaps to achieve energy efficiency targets, the inclusion of specific cost-optimal targets based on combination of measures or practices, etc.

Several EU projects and initiatives focus on improving the capabilities and potential of EPCs. Overall, these projects aim to **create dynamic EPCs by capturing real-time date on performance and operational costs using digital tools** (smart sensors, Building Digital Twins, BIM etc).

Project	Main aim
EPCrecast	EPC recast provides a toolbox for assessing building energy performance and retrofit needs, with a deliberate focus on existing residential buildings, for which retrofit is one of the most challenging and pressing issues.
E-DYCE	E-DYCE (Energy flexible DYnamic building CErtification) is the natural evolution of the conventional EPC towards real time optimization of building performance and comfort. One of the main aims is to assist the owner in the selection of an appropriate monitoring plan through extensive simulation and optimization techniques.
D^2EPC	D^2EPC aspires to deliver the next generation of dynamic EPCs for the operational and regular assessment of buildings' energy performance through a set of cutting-edge digital design and monitoring tools and services. D^2EPC relies upon and adjusts accordingly to the smart readiness level of the buildings and builds upon actual data and the 'digital twin' concept to calculate energy, environmental, financial, and human comfort indicators.
ePANACEA	ePANACEA comprises the creation of a prototype using the most advanced techniques in dynamic and automated simulation modelling, big data analysis and machine learning techniques, to estimate potential energy savings and check economic viability.
X-tendo	The X-tendo project proposes a new methodology for the inclusion of next-generation EPC features, aiming to improve compliance, usability and reliability. The main goal is to handle EPC data and maximise its value to building owners and other end-users.
BEYOND	The BEYOND project is a reference big data platform implementation and AI analytics toolkit toward innovative energy service ecosystems for the building sector and beyond, driven by data sharing. BEYOND solutions enable the analysis of buildings' performance in real-time and at different spatial granularity, towards delivering dynamic EPCs (accompanied by relevant insights) in the form of enhanced Display Energy Certificates.

The ePANACEA project has investigated how the current EPC schemes best make the link towards the Building Renovation Passport (BRP) and the Digital Building Logbook (DBL) to further incentivise and stimulate cost-effective deep energy renovations of buildings across Europe (Androutsopoulos et al., 2021)

According to the surveys performed, EPC data records are used by national or regional energy agencies for statistical reasons and their access is publicly available in half of the responding countries. Many common data is stored in the EPC database, half of them being already linked with other tools.

Building Renovation Passport (BRP) has been conceived as a tool that can **stimulate cost-effective renovation,** thereby complementing EPCs, in the form of a step-by-step deep renovation roadmap following defined quality criteria, and outline energy renovation measures that will improve the energy performance of the building. Using BRPs, retrofitting activities are tracked and properly planned in advance, **finding the optimum between cost and performances**, avoiding last minute investments to replace defaulting system. A review of existing European schemes by ePANACEA project showed that **successful BRPs have combined the renovation advice with financial support, legal requirements and/or communication campaigns**. An important factor of the BRP is that it should be issued by a qualified expert and should provide customised measures for the specific building together with the investment costs per renovation measure(s).

The ePANACEA project intends to integrate a **cost-optimal methodology into EPC schemes as a tool to evaluate the economic feasibility of integrated packages** of business-as-usual technologies and smart novel technical solutions (Boneta and Regoton, 2021). Investments and operational costs associated with energy efficiency measures are considered in the method proposed. The project explores the integration of the economic assessment into staged deep renovation roadmaps and BRP.

Other EU funded projects, such as BIM4Ren and BIMSpeed, focus on BIM-based solutions and the integration of IFC and linked data in a single environment to facilitate data collection and management, and design of renovation scenarios and BRPs to catalyse the deep renovation of the existing building stock. The ALDREN project proposed a **common EU wide assessment framework to trigger more ambitious renovation projects through the inclusion of holistic sustainability metrics** as eligibility criteria for investments. ALDREN proposed a protocol to evaluate impacts of energy and non-energy benefits associated with deep renovation on the financial value and risks of office and hotel buildings. The information and sustainability metrics provided by ALDREN modules and the Renovation Roadmap of the ALDREN BRP is shared with financial valuation experts who compare the financial impacts – costs, risks, and value – associated with different renovation scenarios.

Digital Building Logbook (DBL) can serve as an archive where all building information can be stored and continuously updated. In this way a full record of the building history will be electronically available with data regarding construction plans and permits, maintenance and system replacement activities, energy and heat consumption and production, etc. The DBL analysis performed by the ePANACEA project showed that it should provide access to building information and contribute to better decision-making for future interventions as well as operation, use and maintenance records. The building owner/user is proposed to have full access to the logbook and provide input about energy bills and building plans/construction materials info. An important aspect is that every time the building undergoes intervention works the DBL should be updated accordingly. The most important barrier is the lack of motivation to update the DBL contents followed by the absence of synergies and consistency with other tools.

One interesting finding is that **both BRP and DBL should be fed automatically by EPC data** without any user interference, enabling the possibility of providing **dynamic roadmaps/BRPs** (i.e. updating renovation roadmap with the current occupant needs and specific situation to balance cost/comfort and sustainability) and tailored renovation proposals.

In 2021, the EU has published a Study on the development of a European Union framework for digital building logbooks[4]. According to the report, three priority actions are recommended to support the efficient implementation of DBL:

- The development of a standardised approach for data collection, data management and interoperability and its legal framework;
- Development of guidelines for linking existing databases;
- The launch of public funded R&I projects to further explore the Digital Building Logbook concept and its implementation.

The study aimed to support a harmonised use of DBL across Europe with contribution to other initiatives including the 'Strategy for a Sustainable Built Environment', the 'European Green Deal', the Circular Economy Action Plan, but also the Smart Readiness Indicator, the Level(s) framework, BRPs and EPCs.

Regarding the **Smart Readiness Indicator (SRI)**, many of its characteristics make it highly complementary to the EPC. The SRI is a European assessment scheme to evaluate the readiness of a building to provide services to the occupants of the building, its smart operation and maintenance, and its interactions with the grid.

A combined EPC-SRI approach could contribute to an increase in the use of EPCs and improve their accuracy. Nevertheless, implementing a combined EPC-SRI assessment presents many practical challenges such as a potential increase of the assessment costs or the need for additional training. The ePANACEA project has investigated how relevant aspects of the Smart Readiness Indicator (SRI) could best be integrated within the available national Energy Performance Certificate (EPC) schemes in the ePANACEA countries.

Overall, the remaining challenges and barriers to foster the adoption of EPCs, BRPs, DBL and SRI schemes could be overcome by further digitalisation, supporting the development of structured databases, providing baseline data and simplifying calculation methods.

In the BEYOND project, a blockchain-powered engine enables to build an environment where creating, signing and validating smart multi-party data contracts in an immutable manner is possible while **remunerating the involved stakeholders**. The BEYOND platform eases the curation, mapping and linking of private data assets with external data based on a Common Information Model. It supports searching, locating/matchmaking, understanding, exploring and preparing energy-related data for analytics. By saving time and being renumerated for the data generated, a stakeholder could optimise its investments.

3.2. Lessons learnt from Horizon 2020 projects

3.2.1. Overview

Many H2020 projects have reviewed, developed and/or demonstrated tools and approaches to optimise building costs: some of them are pictured in Figure 8. Although it is likely that this list is not exhaustive, it covers the projects represented (or mentioned) in the task force. Key lessons learnt or conclusions from some of these projects have already been presented in the state of the art.

[4] Study on the development of a European Union framework for digital building logbooks.

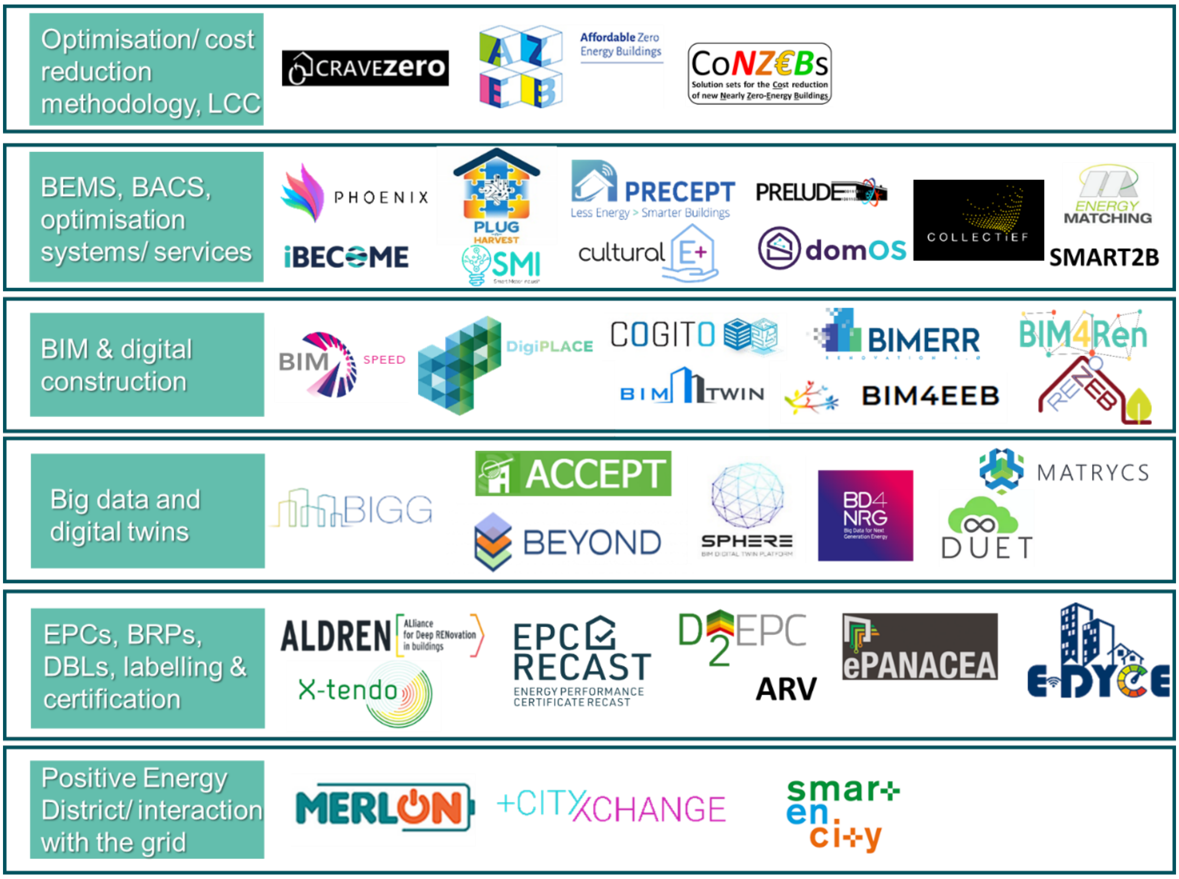

Figure 8: Relevant H2020 projects identified by the Task Force members

Below are presented some lessons learnt that have been provided by Phoenix, BIMSPEED, BD4NRG and SmartEnCity projects.

3.2.1. Lessons learnt from the PHOENIX project

The aspiration of the PHOENIX project is to change the role of buildings from unorganized energy consumers to active agents orchestrating and optimizing their energy consumption, production and storage, with the goal of increasing energy performance, maximizing occupants' benefit, and facilitating grid operation. It tackles various automation processes that elevate the building smartness and reduce its costs such as predictive maintenance, self-consumption optimization and flexibility optimization through predictive control as well as automated calculations of SRI and EPC.

Main conclusions:

The regulatory framework is in most countries supportive towards the increase in the building energy performance, including the general framework regarding GDPR and the directions posed by the European Green Deal. Moreover, a market analysis can give optimistic results, since solutions including the implementation of energy analytics, new energy services targeting the equipment upgrade and predictive maintenance and the increase in energy efficiency on the demand-side can prove profitable for both business stakeholders and consumers.

Despite the overarching goal to decarbonize energy systems, there is still a lot to be done in this direction, and for this vision to be realized, a fundamental prerequisite is to ensure user acceptance. The surveys revealed that consumers at large have a positive attitude to the smart building concept and are prone to engage with smart technology and services. Nevertheless, concerns are raised as to the protection of their privacy, the high cost of smart technology and the complexity of the concept. These constitute important barriers to the adoption of the smart building concept. The key outcome highlighted from the findings, however, is that financial gains from the upgrade of their existing building, protection of their personal data and reducing concept complexity, are main appeals for the consumers' side.

The PHOENIX Smartness Hub supports the smart building transformation initiative by establishing a direct connection between the data recorded from a number of IoT sensors and the energy services delivered to the PHOENIX main beneficiaries. The key stakeholders responsible for optimizing the building costs are the facility managers with a key interest in the overall building energy performance, the building smartness indicators, any opportunities to replace legacy equipment with smart equipment and any aspects of predictive maintenance regarding to the building equipment. So, services related to predictive maintenance, SRI and EPC evaluation are also designed and integrated into the PHOENIX Smartness Hub. An intuitive dashboard is also delivered in the scope of the PHOENIX project that visualizes appropriately all aforementioned information.

Key lessons learnt relevant to the optimisation of building costs include:

- The EPC and SRI automatic evaluations increase users' (building managers) awareness and allow for immediate understanding of the strengths and weaknesses of the building as well as its potential for upgrades.
- The data collected from the sensors within building spaces and from the building services will allow for the real time monitoring of the equipment, the prediction for parts replacement and the production of alerts in case of equipment malfunction.
- The optimization of demand response through the exploitation of data and analytics can further lower energy bills without mitigating the building comfort.
- Building automations through controlling assets that contribute to the self-consumption and grid flexibility can reduce the energy footprint of the building.

3.2.2. Lessons learnt from the BIMSPEED project

BIMSPEED aims to enable all stakeholders to adopt BIM to reduce the time spent on deep renovation projects. This is based on the use of an affordable BIM cloud platform, a set of tools based on the latest techniques and standardised procedures to ensure the comfort of the inhabitants through adapted renovation solutions that improve energy performance.

Main conclusions

Most of the existing BIM tools are applied and used for new buildings and there is a lack of application for renovation projects. Specific challenges of associated existing buildings need to be carefully analysed, starting with building modelling, to performance simulation of potential renovation options or even occupant engagement. Since a transdisciplinary approach is necessary for renovation, BIMSPEED is committed to having cost-effective, flexible and modular solutions for the different stakeholders involved in the chain.

Key lessons learnt relevant to the optimisation of building costs include:

The integration of new dimensions to BIM models for energy analysis, scheduling, quality control, costs, comfort assessment, regulation and big data applications offer new possibilities to manage building data in a harmonized way and accelerate the process for deep renovation. On the other hand, the potential of machine-learning had not been previously explored for renovation practices, and its application demonstrates that the time to find renovation solutions can be significantly reduced and hence that the costs can be reduced by supporting stakeholders with non-expert knowledge.

3.2.3. Lessons learnt from the BD4NRG project

The main objective of BD4NRG is to unlock and exploit the economic potential of big data and provide stakeholders in the energy sector with the opportunity to improve the operational performance of their business. Through an ecosystem powered by incremental decentralized energy data and powered by collaborative data sovereignty, a distributed big data analytics framework is provided to address emerging challenges in the sector, improve decision making, and open new market opportunities.

Main conclusions

New techniques can help de-risk investments in energy efficiency measures and increase the efficiency and comfort of buildings. In this sense, the BD4NRG project investigates first the use of predictive and prescriptive analytics to improve the reliability of Energy Performance Certificates, based on the integration of large amounts of data in a harmonized way through scalable Big Data mechanisms, helping to remove the barriers that are hindering the high potential of EPCs to achieve significant energy efficiency in the construction sector. Secondly, building thermal comfort predictions are used to help the public administration to implement building energy retrofit actions at the district/city level. The latest type of predictive analytics for energy efficiency de-risking, based on past action analytics, provides key performance indicators for projects, thereby reducing uncertainty related to lack of relevant skills and capabilities to assess investments.

Key lessons learnt relevant to the optimisation of building costs include:

The combination of different building indicators makes it possible to bridge the gap between controllable building parameters and thermal comfort. On the other hand, the use of historical data of the main market segments can encourage more investments in energy efficiency and reduce the risk of investments: the exploration of the past and the future through relevant indicators contributes to the measurement and evaluation of risk.

Many users would like to carry out energy rehabilitation of their homes and, in this sense, the EPCs have a key role. Member States should provide better information on the purpose and objectives of EPCs, possible energy efficiency measures and supporting financial instruments. EPCs could become powerful in providing recommendations for optimal cost-effective interventions and setting the picture on the energy performance of the building stock in any location, so that the impact of energy policies can also be assessed.

3.2.4. Lessons learnt from the SmartEnCity project

SmartEnCity aims to develop a systemic approach for transforming European cities into sustainable, smart and resource-efficient urban environments in Europe. Within this approach, strategies to reduce energy demand and maximise renewable energy supply are included in order to obtain improved energy performance of buildings at time of maintaining comfort constraints.

Main conclusions:

SmartEnCity, through the implementation of the Smart City Data Platform, is acquiring data from the different and various building assets, including the building demand and district heating generation. Insulation to obtain better performance buildings and high-efficient district heating facilities aim at transforming the building stock, as well as enhancing end-user comfort.

Nevertheless, improved performance requires quantification and analysis. In this sense, data becomes pivotal for extracting lessons learnt and continuous commissioning strategies. Within SmartEnCity, detailed monitoring programmes have been prepared with the ultimate goal of collecting high quality data that can drive to better analytics. In this sense, the involvement of the stakeholders is necessary, which is not trivial and sometimes neglected. Co-creation and co-design strategies demonstrate successful results.

Additionally, the definition of evaluation methodologies that can bring standard procedures to calculate analytics (or KPIs) to better understand the energy demand and consumption, therefore, being capable of optimising costs both at generation and demand side, should be considered. The application of Artificial Intelligence techniques verifies, on the one hand, the real behaviour and operation of the energy assets and, on the other hand, provides prediction methods to support decision-makers.

Within these approaches, enhanced assessment metrics are feasible to reduce uncertainties in the energy management. The accuracy in the KPI calculation also provides capabilities to extract dynamic indicators to certify buildings, such as the EPCs, according to the real energy use and continuous updates in the facilities performance.

Key lessons learnt relevant to the optimisation of building costs include:

- Data collection is a fundamental aspect that should be considered and, although improving steadily, there is still progress to be made on this side.
- Data interoperability is a must in the optimisation techniques, where data coming from different assets should be analysed together.
- Analytics should be defined at the start: establishing clear, trustworthy and feasible indicators to determine building performance.
- Implementation of AI techniques based on real data helps decision-makers to take more informed decisions in order to optimise building costs.

3.3. Other initiatives related to optimised building costs

Name of initiative	Relevant inputs
VLOCA	VLOCA proposes an Open City Architecture program aiming to consolidate European and international practices and standards into an open I(C)T architecture to boost the interoperability and openness of data and technology within cities and communities in the Flemish landscape.
DITUR **Digital twin concept for upscaled retrofits**	Supported by Flux50, the DITUR project aims to stimulate group renovations (i.e. mass renovation approach) using a digital twin and a user engagement proof of concept. The digital twin will be enriched by incorporating different data streams such as open data, consumption data and new-to-acquire data about the building characteristics, dimensions, installations and user behaviour and co -benefits (comfort, increased building value). As such, the digital twin will provide insights on recommended renovations in order to increase energy efficiency on a city level or portfolio level. The project aims for an accuracy of 5-10% of the recommended renovation bundles and 5-10% accuracy of the cost estimate of the renovation (compared to individual audits). Also, DITUR wants to proof that 60% of the dwellings in cities are eligible for an energy-based renovation and that 30 to 40% of the concerned dwellings can be renovated by means of a mass renovation approach, achieving a cost reduction of 20 to 25% compared to an individual renovation.
Optimised Retrofit Wales	The Optimised Retrofit project aims to make 1724 homes across Wales more energy efficient. The retrofitting process will enable the trial and refinement of the digital tools required to enable the decarbonisation of homes across Wales, as well as help build the skills and training needed to underpin this. Among the tools, the Pathway to Zero approach supports incremental home upgrades for less cost by aligning with the upcoming decarbonization of the energy grids.

Cross-cutting initiatives	
RETE ITALIANA LCA working group on buildings and energy	The working group aims to define the possible areas of application of the LCA method in the building sector: decision support tool for the design of construction products and buildings, tool for identifying industrial ecology or eco-design strategies in the production of buildings, environmental assessment tool for the certification of products and buildings, tool for defining environmental indicators to be included in construction standards or regulations, etc.
IEA EBC Annex 75	Cost-effective Building Renovation at District Level Combining Energy Efficiency & Renewables Annex 75 aims to investigate cost-effective strategies for reducing greenhouse gas emissions and energy use in buildings in cities at district level, combining both energy efficiency measures and renewable energy measures. The objective is to provide guidance to policy makers, companies working in the field of the energy transition, as well as building owners for transforming cost-effectively the city's energy use in the existing building stock towards low emission and low energy solutions.
CEN/TC	CEN/TC 247: Building Automation, Controls and Building Management CEN/TC 371 – Energy Performance of Buildings CEN/TC 442 - Building Information Modelling (BIM)
Green Building Certification	
BREEAM	BREEAM (Building Research Establishment Environmental Assessment Method) is an international scheme that provides independent third-party certification of the assessment of the sustainability performance of individual buildings, communities and infrastructure projects. BREEAM rated developments are more sustainable environments that enhance the well-being of the people who live and work in them, help protect natural resources and make more attractive property investments.
LEED	The Leadership in Energy and Environmental Design (LEED) rating system provides a framework for healthy, highly efficient and cost saving green buildings. It is for all building types and all building phases including new construction, interior fit outs, operations and maintenance and core and shell
DGNB	DGNB certification for buildings, districts and interiors. DGNB quality throughout the entire life cycle: planning, construction, operation, renovation and end-of-life. Market leader in Germany but also international.

4. Barriers and drivers

4.1. Barriers

Barriers to the market uptake of smart buildings related to the optimisation of building costs were reviewed and prioritised by the task force. The top barriers are highlighted below.

VALUE CHAIN	Decision-makers giving the preference to construction costs in the planning stage, i.e. targeting the lowest CAPEX instead of optimising the life cycle costs
	Construction companies working in silo with no overall guarantee of performance
	Mismatch between lowest bid costing and actual delivered cost (changes in cost from project approval to project delivery)
REGULATION	Regulatory framework for optimisation not simple enough for non-specialist end-users
SOCIAL	Lack of trust in digital solutions and security concerns from users, fear of loosing privacy
	Lack of user involvement limiting the optimisation potential and hindering the decision to invest
	Lack of knowledge on savings opportunities to guide decision-making and then the operation
ECONOMIC	Long payback period, as externalities such as CO2 and co-benefits are not considered
	Lack of clear and easy-to-understand data-driven business models (e.g. Energy Performance Contracts and other ESCO-based business models)
	Lack of tools to assess/ optimise investments and address uncertainty, especially in future energy prices
	Split incentives (owner/tenant or builder/owner)
TECHNICAL	Low smart readiness of the building stock and lack of interoperability between active systems and software
	Complex costs, rapidly changing (depending on location and time), without any common up-to-date database providing realistic costs for materials/ equipment over the whole life-cycle

Top barriers according to the Task Force

4.2. Drivers

The drivers identified by the Task Force are as illustrated below.

VALUE CHAIN	New tools to support decision-making (new technologies for the construction sector + co-design methodologies)
	Evidence of reduction of O&M costs through Energy Performance Contracts and ESCOs
REGULATION & STANDARDS	Push from EU Regulation: EPBD, SRI, Digital Logbook, Fit for 55 package, etc.
SOCIAL	Increased awareness and transparency thanks to open comparison with peers or supported by manufacturers and trade associations
	Opportunity to go beyond the building scale by mobilising (energy) communities
	Digital natives more open to digital concepts
ECONOMIC	New business opportunities arise with new technologies and services
	Evidence of increase in property value thanks to increased energy efficiency & smartness
	Incentives and new financing opportunities thanks to the Recovery Plan
TECHNICAL	Reduced cost of digital tools: digitalisation becoming ubiquitous and more affordable
	Standard data models and semantics for data interoperability

Top drivers according to the Task Force

5. Gaps

Various activities required to overcome the barriers and leverage the drivers related to the optimisation of building costs were suggested and prioritised by the task Force members and are presented in Table 1. The priority ones according to the task force are in bold.

Table 1: Suggested R&I activities

<table>
<tr><th>Type of activity</th><th>Activities</th></tr>
<tr><td>R&I</td><td>- Develop affordable and intuitive digital platforms, covering all stages of a building's life, for co-construction with all stakeholders, collaboration and communication, user involvement and decision-making (including simulation functionalities, gamification, etc.)
- Develop methods to better link relevant (open) standards in the data sharing workflow to support the optimisation of costs
- Develop harmonised tools and approaches for life cycle costing to enable a paradigm shift from targeting lowest CAPEX to optimising life cycle costs
▪ Including co-benefits and externalities in the optimisation equation as well as validated models of occupant behaviour
▪ Supported by an uncertainty analysis to assess the influence of various parameters
- Develop low-cost and plug&play sensors for energy and comfort monitoring as well as innovative solutions to interface with legacy equipment and upgrade smartness /optimise the operation and maintenance of buildings
- Develop and maintain common, up-to-date and reliable databases providing costs for materials and equipment over the whole life cycle (similar to LCA databases)</td></tr>
<tr><td>Demo</td><td>- Create a programme ("demo spaces") that support the trials and demonstration of technical/social R&D actions in privileged conditions (early access, reduce licencing costs etc) for SMEs and other construction actors:
▪ with experimental facilities and test beds as well as real buildings involving all stakeholders of the built environment
▪ promoting the involvement of potential early adopters
▪ with key metrics to quantify user involvement
▪ with a strong focus on data sharing to enable the optimisation of costs
- Implement an SRI pilot project in every Member State at least in one public building with calculation of costs and (wider) benefits</td></tr>
<tr><td>Regulation & legal framework</td><td>- Update buildings regulations to make them easier to understand and comply with, imposing a minimum level of smartness for new and renovated buildings (as well as rented dwellings), with a minimum set of parameters to be measured to monitor building performance (e.g. energy efficiency, IEQ)
- Encourage Member States to set clear long-term objectives and corresponding requirements for buildings (including for building codes) and invest in their implementation</td></tr>
</table>

Certification & standardisation	- **Make sure the digital platforms developed to enable the optimisation of building costs over the different life stages are GDPR compliant and give control and security to the data owners, and use harmonised data exchange standards** - Include the SRI rating in all building digital certificates, e.g. EPC, Digital Building Logbook, Building Renovation passport - Encourage the use of standardised methodologies for building life cycle management
Scaling up & industrialisation	- Implement specific programmes to attract investors to finance innovation and technology transfer for new solutions enabling the optimisation of building costs - Set up smart modular platform strategies[5] to address the complexity of innovation in buildings, reduce direct costs and shorten project lead times

[5] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-smart-platforms-can-crack-the-complexity-challenge-in-project-industries

6. Conclusion

This document formalises the collaborative work performed by the members of SmartBuilt4EU task force 2, on a voluntary basis, during the period October 2021- May 2022. It also integrates the feedback collected during 1) a peer review conducted by VITO in March 2022, and 2) an open consultation process during in April-May 2022.
Based on an analysis of the state of the art and the identification of barriers and drivers, the main objective of this paper is to detect some research and innovation gaps that still need to be addressed in the coming years in order to optimise the building costs with a life cycle approach.
This white paper will feed the elaboration of the Strategic Research and Innovation Agenda that the SmartBuilt4EU consortium will present to the European Commission.

Task Force 2 will investigate one more topic during 2022: next topic, starting in May 2022, will focus on **Smartness to reduce building's environmental impacts,** i.e. Integrating tools to reduce the environmental impact over the full life cycle (paying attention to the carbon footprint of smart solutions); resource efficiency; environmental impact management; Integration of renewable energies (incl. direct current building).

If you have some expertise to share on this topic, you are invited to join the task force and contribute to the next white paper (contact detail below).

To receive the updates on the SmartBuil4EU task forces, white papers and events, please register here: https://smartbuilt4eu.eu/join-our-community/

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8. Annex 1: list of H2020 projects reviewed

Table 2: list of relevant EU projects

Project	Status	Contact in TF	Weblink	Relevant inputs
ACCEPT	Ended	Ismini Dimitriadou	https://www.accept-project.com	Digital Twins / SRI
ALDREN	Ended	Graziano Salvalai (poliMI)	https://aldren.eu/	BRP+Renovation roadmap
ARV	starting	Mohamed Hamdy (NTNU)	https://cordis.europa.eu/project/id/101036723	Automated use of LCA, digital logbooks and material banks
BIM4Ren	ongoing	/	https://bim4ren.eu/	exploitation of BIM potential for the energy renovation of existing buildings for the whole construction value chain
BIM SPEED	ongoing	Sofía Mulero (CARTIF)	https://www.bim-speed.eu/en	BIM integration and BIM passports for renovation scenarios
BD4 NRG Big Data for Next Generation Energy	Ongoing	Sofía Mulero (CARTIF)	https://www.bd4nrg.eu/	Big Data solutions for increasing the efficiency and comfort of buildings, and de-risking investments in energy efficiency

BIM TWIN	Ongoing	/	https://bim2twin.eu/	Digital Building Twin (DBT) platform for construction management implementing lean principles to reduce operational waste, shortening schedules, reducing costs, enhancing quality and safety and reducing carbon footprint.
BIM4EEB	Ongoing	/	https://www.bim4eeb-project.eu/	BIM4EEB develops a BIM-based toolset – BIMMS - which offers a set of functionalities that meet the stakeholders' needs during the renovation work. BIMMS can integrate tools and enable the data interoperability through data exchange services.
BIMERR	ongoing	/	https://bimerr.eu/	Seamless BIM creation and information exchange among the three phases of the AEC/ renovation value chain.
BIGG	ongoing	/	https://www.bigg-project.eu/	Building Information aGGregation, harmonization and analytics platform
BEYOND	ongoing	John Avramidis	https://beyond-h2020.eu	BEYOND introduces a reference big data platform implementation for collecting, processing and analyzing building data, while transforming them into a tradeable commodity through the development of appropriate data sharing mechanisms for data sharing between different stakeholders.
+CITYxCHANGE	ongoing	/	https://cityxchange.eu/	Positive energy blocks and districts with balancing and optimisation of energy in the PEB
COGITO	ongoing	Giorgos Giannakis	https://cogito-project.eu/	digitalisation of Construction Phase using Digital Twin Digital Construction 4.0 toolbox that harmonises Digital Twins with the Building Information Model concept
COLLECTiEF	ongoing	NTNU-Mohamed Hamdy	https://collectief-project.eu/	Implement an interoperable and scalable energy management system to smart up buildings and their legacy equipment on large scale
CRAVEzero	Ended	/	https://cravezero.eu/	Approaches to reduce costs and improve nZEBs at all stages of the life cycle.
cultural E+	ongoing	EURAC + ADVANTICSYS	https://www.cultural-e.eu/	IoT+ML+cloud for positive energy buildings LCC tool
D2EPC	Ongoing	/	https://www.d2epc.eu/	Development of dynamic EPCs
DigiPLACE	Ongoing	Alexis David	www.digiplaceproject.eu	DigiPLACE is a framework allowing the development of future digital platforms as common ecosystems of digital services that will support innovation, commerce, etc. It will define a Reference Architecture Framework for digital construction platform involving a large community of stakeholders.
domOS	ongoing	Dominique Gabioud	http://www.domos-project.eu/	Operating System for smart building: Any in-building infrastructure available for any

				monitoring / control / optimisation application, if permitted
DUET	ongoing	/	https://www.digitalurbantwins.com/	Developing and validating the use of Digital Twins for better policy making
E-DYCE	ongoing		https://edyce.eu/	EDYCE provides Energy flexible DYnamic building Certification. It aims to create a technology-neutral methodology for dynamic labelling, based on maximizing the free running potential of the building and promoting the use of passive and low-cost solutions, instead of mechanical systems.
ENERGY MATCHING	ongoing	/	https://www.energymatching.eu/project/	Developing and demonstrating cost-effective active building skin solutions as part of an optimised building energy system, being connected into local energy grid and managed by a district energy hub implementing optimised control strategies within a comprehensive economic rationale balancing objectives
ePANACEA	ongoing			ePANACEA develops a holistic methodology for energy performance assessment and certification of buildings. Its platform makes use of the most advanced techniques in dynamic and automated simulation modelling, big data analysis and machine learning, inverse modelling for the estimation of potential energy savings and economic viability check.
EPC RECAST ENERGY PERFORMANCE CERTIFICATE RECAST	ongoing	Graziano Salvalai (PoliMI)	https://epcrecast.wordpress.com/ https://epc-recast.eu/	New generation of EPCS. House owners' considerations about usefulness of the EPC are central as owners decide whether to implement energy conservation opportunities provided by the EPC. EPC RECAST is a decisive decision-supporting tool for tenants and potential buyers. It provides guidance on cost-optimal building renovation for building owners, covering as well IEQ, wellbeing and smartness.
iBECOME	ongoing	/	https://ibecome-project.eu/	In small enough so as to not be equipped with BMS, the deployment of the iBECOME solution will allow essential energy savings and comfort improvements at very low cost but also provide the ability to tap into the emerging markets of additional services.
MATRYCS	ongoing	Sofía Mulero	https://matrycs.eu/	AI-powered framework for decision-support models, data analytics and visualisations in real-life applications
MERLON	ongoing	Katerina Valalaki	https://www.merlon-project.eu	optimisation at different levels / optimal interaction of buildings with the grid / optimal flexibility valorisation
PHOENIX	ongoing	Dimitra Georgakaki	https://eu-phoenix.eu/	The aspiration of PHOENIX project is to change the role of buildings from unorganized energy consumers to active agents orchestrating and optimizing their energy consumption, production and storage, with the goal of increasing energy performance, maximizing

				occupants' benefit, and facilitating grid operation.
PRECEPT Less Energy > Smarter Buildings	Ongoing	/	https://www.precept-project.eu	Proactive and Predictive Building Management System (PP-BMS) based on devices/systems interoperability and innovative technologies such as digital twins, artificial intelligence, etc.
PRELUDE	Ongoing	/	https://prelude-project.eu/	The project is focused on assessing the right level of smartness necessary for any given household and then providing the optimal tools according to the needs of the user. Combination of smart and low cost solutions into a proactive optimization service.
RENOZEB	ended	Focchi - a.pracucci@focchi.it	https://renozeb.eu/	RenoZEB aims to unlock the nearly Zero Energy Building (nZEB) renovation market by increasing property value through a new systemic approach to retrofitting. A more collaborative environment through a Building Information Modeling (BIM) based collaboration platform
SMART2B	ongoing		https://cordis.europa.eu/project/id/101023666	SMART2B project will upgrade the capacity of existing buildings by developing non-intrusive Internet of Things sensors and actuators to control equipment, while improving indoor comfort and energy efficiency. The project will allow for coordinated control of legacy equipment and smart appliances and integrate two existing cloud-based platforms into a single building management platform.
smart en city	ongoing	José L. Hernández (CARTIF)	https://smartencity.eu/	Smart Cities project where AI techniques are applied for energy forecasting and cost prediction of energy resources for heating
SMI	ongoing	/	https://www.smi.uha.fr/en/	Artificial intelligence to support the proactive management of energy consumption by end users
SPHERE BIM DIGITAL TWIN PLATFORM	Ongoing		https://sphere-project.eu/	Digital Twins + ICT Systems of Systems infrastructure based on Platform as a Service (PaaS) service to allow large scale data, information and knowledge integration and synchronization, to improve energy efficiency across buildings' entire lifecycle
X-tendo	Ongoing		https://x-tendo.eu/	X-tendo and its toolbox introduce ten features of the next generation of energy performance certificates. It aims to Ensure that the developed features and overall guidelines for improving EPCs are in line with four cross-cutting criteria: more reliable and high quality EPCs, user friendliness, economic feasibility of EPCs, and consistency with CEN/ISO standards.