ECTP Digital Built Environment Committee

Horizon Europe 2022-2027 POSITION PAPER

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Glossary

Big data: describes or relates to complex and large datasets, where advanced analytics methods are employed to extract information or value from data.

Building Information Modelling: process supported by various tools and technologies for creating and managing information on a construction project across the project lifecycle.

Dynamic built environment is meant as a built environment that is designed, built and operated within a dynamic relationship with citizens.

Green Public Procurements: Green Public Procurement (GPP) or green purchasing is a voluntary instrument whereby local authorities use their purchasing power to choose environmentally friendly goods, services and works to make an important contribution to sustainable consumption and production.

Industry 5.0: industry 5.0 provides a vision of industry that aims beyond efficiency and productivity as the sole goals, and reinforces the role and the contribution of industry to society[1]. It places the wellbeing of the worker at the centre of the production process and uses new technologies to provide prosperity beyond jobs and growth while respecting the production limits of the planet. It complements the existing "Industry 4.0" approach by specifically putting research and innovation at the service of the transition to a sustainable, human-centric and resilient European industry. Industry 4.0 refers to the concept of factories in which machines are automated and augmented with cyber-physical systems, the internet of things (IoT), cloud computing, cognitive computing and artificial intelligence, and connected to a system that can visualise the entire production line and control it.

Integrated Design and Delivery Solutions (IDDS): holistic approach of the construction process, relying on a combination of initiatives such as skill development, process re-engineering, responsive information technology, enhanced interoperability and integrating knowledge management, to reach a radical improvement of performances in the construction industries.

IoT: Internet of things: system of interrelated computing devices, mechanical and digital machines, objects, animals or people that are provided with unique identifiers (UIDs) and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction.

Servitisation: The servitisation of products describes the strategy of creating value by adding services to products or even replacing a product with a service.

Swarm robotics: research and development field to design groups of robots that operate without relying on any external infrastructure or on any form of centralised control. In a robot swarm, the collective behaviour of the robots results from local interactions between the robots and between the robots and the environment in which they act.

Twin transition: Twin green and digital transition providing a green productivity premium to discrete manufacturing, construction and energy-intensive industries, including process industries, according to the European Commission.

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1 https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/industry-50_en

List of acronyms

AI	Artificial Intelligence
AIOTI	Alliance for Internet of Things Innovation
ALIM	Asset Life Cycle Information Modelling
AMS	Asset Management System
AR	Augmented Reality
EED	Energy Efficient Directive
EPBD	Energy Performance of Buildings Directive
BEM	Building Energy Modelling
BEMS	Building Energy Management System
BIM	Building Information Modelling
CAD	Computer Aided Design
CCAM	Cooperative, Connected and Automated Mobility
CDW	Construction and Demolition Waste
DHW	Domestic Hot Water
DLT	Distributed Ledger Technologies
DRM	Digital Rights Management
DT	Digital Twin
EPBD	Energy Performance of Buildings Directive
GNSS	Global Navigation Satellite System
HLSI	High-Level Service Infrastructure
HVAC	Heating, Ventilation and Air Conditioning
GIS	Geographical Information System
ICT	Information and Communications Technology
IDDS	Integrated Design and Delivery Solutions
IFC	Industry Foundation Classes
IoT	Internet of Things
KET	Key Enabling Technologies
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCSA	Life-Cycle Sustainability Assessment
M2M	Machine-to-machine
MEP	Mechanical, Electrical and Plumbing engineering
ML	Machine Learning
MR	Mixed Reality
NZEB	Nearly Zero Energy Building
PED	Positive Energy Districts
RES	Renewable Energy Sources
RFID	Radio Frequency IDentification
R&I	Research & Innovation
SLCA	Social Life Cycle Assessment
SRI	Smart Readiness Indicator
TIIM	Transport Infrastructures Information Model
UAV	Unmanned Aerial Vehicle
VR	Virtual Reality

1. Introduction

1.1. Overall context

The Construction and Built environment sector represent 13% of the World's GDP and 9% of the European GDP. It is one of the major industries responsible for high levels of GHG emissions that contribute to climate change, with buildings accounting for 40% of total energy consumption and more than 75% of them being energy inefficient. This sector is therefore in the centre of attention of policymaking, innovation and research, the goal of the European Commission being to help it become more competitive, resource efficient and sustainable.

Digitalisation is a steppingstone to achieve the 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).
Though, **construction is one of the least digitised sectors in the EU, and digital technologies disrupt the traditional value chain**. Behind a few leaders (the UK, Scandinavia, Germany, and France) and some "beginners", many European countries have not yet initiated the digital transition in construction, still waiting for clear demonstrations of its tangible benefits[3].

The past years have consequently seen a particular focus on digitalisation, calling for a more comprehensive approach to enable a fully generalised digitalisation, with e.g., FIEC-EBC-CECE BIM manifesto, the current action of DG CONNECT supporting digital construction industrial platforms and the development of Digital innovation Hubs and Competence Centers by the European Commission, the importance of Digitalisation in the Horizon Europe programme, etc.

The aim of the Digital Built Environment Committee is to establish an exhaustive network, including the relevant stakeholders of the construction sector and of the surrounding technology and supply value chain (including customers) delivering a European-wide consensus around the Digital Transformation of the Construction sector.

1.2. Scope and approach

This position paper has been developed with the purpose of identifying challenges and objectives of the construction sector related to digitalisation and automated construction, and defining R&I priority areas and topics, to be included in the next Horizon Europe Working Programmes. Horizon Europe is indeed a great opportunity for improving the construction sector, and, through specific

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

[3] See State of BIM adoption across Europe: https://www.e-zigurat.com/blog/en/state-of-bim-adoption-europe/

subprogramme and topics, would permit to build an R&D ecosystem dedicated to the digital transformation of the construction sector.

This position paper aims at:

- Providing an overview of the latest innovations and technologies enabling the digitalisation of the built environment and the construction processes.
- Identifying research needs to drive the digitalisation of the construction sector and the built environment to the forefront of European research and innovation agendas.
- Raising awareness and communicating priorities to strategic stakeholders.
- Supporting research-funding proposals and partnerships.
- Advocating and sharing knowledge within and beyond the ECTP.

1.3. Trends and challenges

Digital challenges of the Built Environment

The Built Environment embraces buildings as well as infrastructures, both facing their own challenges when it comes to digitalisation.

For **buildings**, it is about the development and change of status of our European buildings towards smart buildings, as well as their smart readiness, which must characterise their capacity to smoothly integrate more intelligent components and deal with more and more IT-based systems and services. This encompasses the following elements (the list being not exhaustive), with some examples related to energy efficiency, but with potential for adaptation/generalisation to other fields (water, waste, etc.):

- Active/Communicating components (transition towards "connected objects / systems" / IoT): Besides their innovative functions (i.e., insulation, generating energy, storage, etc.), components need to exhibit an API – so as to be part in some "agnostic" way to any agent-based / event-based networks. This is a prerequisite to transform buildings in "smart-grid ready" even "smart-network ready" buildings (this also applies to high-level service infrastructure or HLSI). This may refer to improve the quality of the installation works too – through inbuilt data;
- Integration of the components in the buildings, both physically, but also "logically", i.e., scaling and parameterizing according building typologies, constraints, etc., providing compliant input data used to further issue an Energy Performance Certificate for a building or a multi-modal transport hub for instance. This requires a high level of "interoperability" among components, between components and their 'container'.
- Integration of the building components in **services**, according to users demands and expectations and constraints, and according to demands/requirements from the networks outside the buildings/HLSI, e.g., mobility systems, grids infrastructures, etc. This should allow to tangibly transform the buildings with communication interfaces between their own equipment and the surrounding infrastructures. This is linked with the "empowerment" objective of the Commission: "Put customer at the centre of the energy system".
- Systems that allow to optimize the structuring and sizing of the systems and the grids, electric & heating/cooling, with scaling-up considerations. Indeed, these systems are not part per se of the built environment, but may be supportive to decision-making systems and may play an

important role in investments (in renovation, maintenance, etc.), while guaranteeing a secure and stable access to decarbonised energy.

- More funding support towards any development related to the “interfacing” of the various energy components to improve the achievement and the flexibility of the “energy mix” in the sense of favouring the complementarities of the various energies;
- More funding around the buildings & districts energy profiles / audits, and awareness raising of (all types of) users;
- More commonly agreed standards and interoperability for the companies that comprise the construction sector; commonly agreed communications protocols for data exchange that allow a proper comparison and evaluation of the digital equipment performance;
- Huge amount of data to be further generated and managed, with issues related to security & privacy (adding quite some additional complexity at level of ICT tools).

For **infrastructures**, digitalisation means the true development of a Digital Era for Transport. Many tend to think that, when applied to transport, the word “Digital” refers mainly to the rolling stock (e.g. all smart vehicles, trains, ships or aircrafts) whereas it is obvious that we can see more profound changes, as advocated by ECTP:

- First, in the way transport infrastructures will be built using digital technologies, while the sector is still undergoing the digitalisation of its productive processes in an environment that is more complex than the one of manufacturing.
- Secondly, in the level of services to be provided by the infrastructures (referred as *High Level Transport Infrastructure*) to vehicles: for instance, the generation of infrastructure management data to provide positioning services in areas without GPS coverage, to deliver structural data about the road condition, to pinpoint fallen objects on the road or areas of damaged pavements, to make available information related to traffic restrictions or detours, to provide a better user experience in concessions or in public infrastructure, to provide a digital operational framework as a support to develop services and solutions for automated and connected vehicles, etc…
- Thirdly, in the way infrastructures are going to be managed and maintained in the future: technologies as IoT together with Artificial Intelligence can deliver more efficient management of the infrastructure and its maintenance. It should also serve to implement innovative maintenance methods based on actual infrastructure condition, less invasive and less traffic disrupting so automated traffic flow would not be disturbed.

Challenges for construction processes

The **construction process** also has potential to become more effective in terms of environmental, economic and social sustainability, including with the increase of its productivity. This productivity has largely increased in other sectors like manufacturing or services over the last 25 years, when Construction has not yet taken full advantages of digitalization, design-controlled prefabricated manufacturing and new lean production process. As such, there is a tremendous opportunity over the decade to come for the construction sector to increase its performance from design to decommissioning.

Design processes have dramatically changed in the last decades, under the influence of an increased complexity of construction projects which have 1) to comply with multiple and strengthened regulations, 2) to be designed and built in short times, 3) while achieving high performances with regard to material use or energy consumption. Nowadays, digitalisation is at the heart of designers’ everyday actions, enabling to handle this complexity, facilitating repetitive tasks and smoothing collaborative processes.

Notable innovation potential to the design tasks can be highlighted as follows:

- *Data-driven Design* refers to digitalised handling of design documentation and interoperability, as well as to analysis capability,
- *Performance-based Design* is associated with the anticipation and simulation of a given project quality, in various engineering fields including energy, sustainability, or acoustics,
- *Parametric Design* where especially in early design phases, parametric models link designers' inputs to geometric constraints and patterns, prefiguring future advanced design BIM models,
- *Generative Design* benefits from Artificial Intelligence techniques to generate project geometries according to simulation and optimization definitions, e.g. by including biomimicry principles or widened deployment of nature-based solutions.

The role of the sector has to more and more perceived as an integrating one, bringing together technological solutions and innovation with the needs and wishes of the customers (inhabitants, building owners, social housing, local authorities and municipalities, etc.) – along a complete value chain (as described in the next figure) that brings together new forms of client-centric or client-driven design, parametric concrete solutions brought by innovators, integration fully controlled along the off-site manufacturing line, the logistics process and the construction on site, and with new technologies and services for management, maintenance, improvement and demolition – all under a "ground" of digital interoperable model-based software and service (see Figure 1)

To do so, however, channels of dialogue need to be opened between the construction sector and the various other stakeholders, as well as knowledge gaps regarding innovative processes, products and services, technical solutions etc. need to be found and addressed. On the same time, ways to unlock private financing need to be found, that should facilitate the formation of progressive coalitions across the value chains, which would result in concrete pledges, actions and projects, ambitious innovation targets creating growth and competitiveness – supported by the EU industrial representatives and companies, innovative SMEs, cities, and regions.

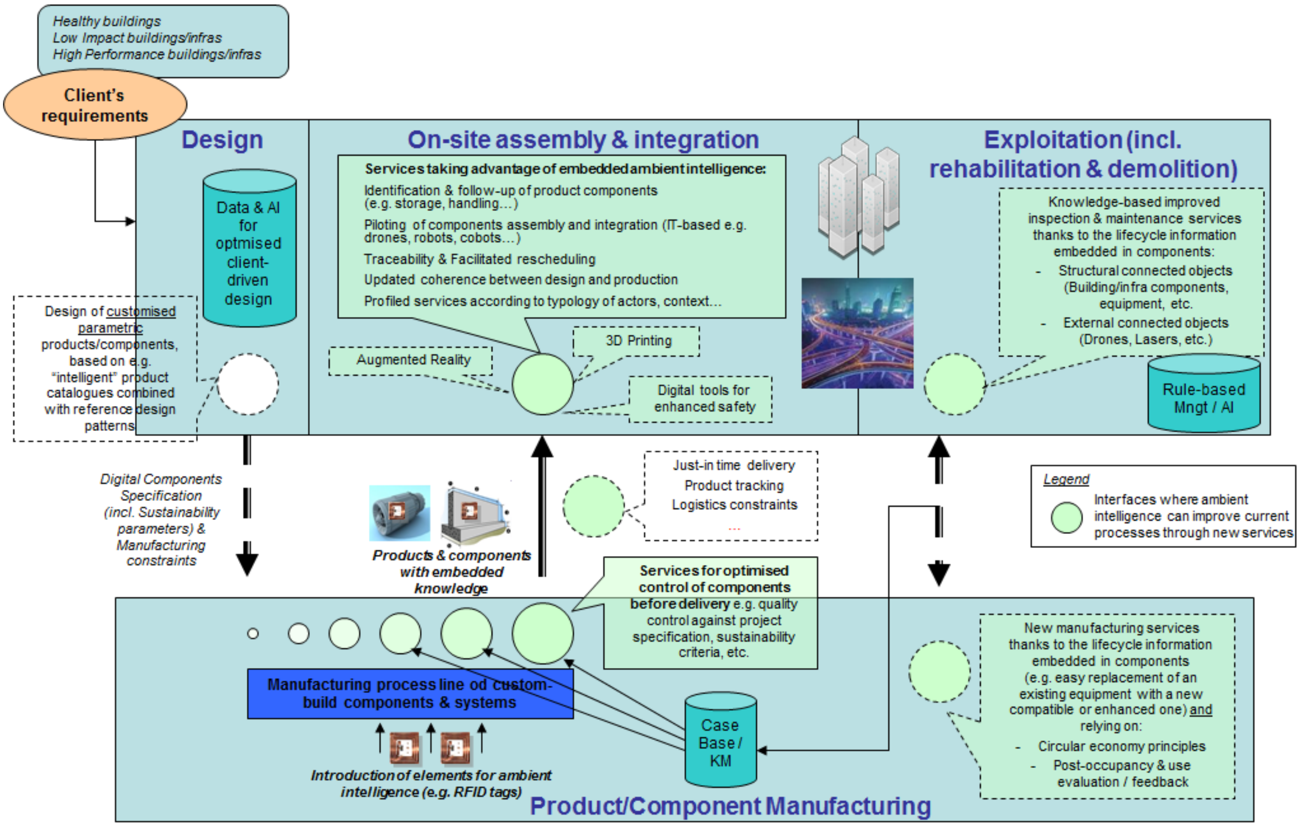

FIGURE 1: CONSTRUCTION 4.0 - AMBIENT SERVICES ALONG THE WHOLE VALUE CHAIN AND THE COMPLETE CONSTRUCTION LIFECYCLE

As exemplifying of such potential industrialisation for the Construction sector, one can consider 2 examples (among many others):

- Additive manufacturing (also referred as 3D printing), fabricates components in a layer fashion directly from a digital file. A large number of the today applications of additive manufacturing technologies are in the aerospace, automotive, and healthcare industries, but already several experimental applications of additive manufacturing in the construction sector have been achieved. Additive manufacturing for construction has the potential to decrease labour costs, reduce material waste, help in the quality control and eventually support customized complex geometries that are difficult to achieve using conventional construction techniques. There is a large range of potential applications for construction to exploit the rapidly maturing additive manufacturing technologies for a variety of material types, with still a required need for R&D regarding related methods of implementing additive manufacturing and potential advancements in applications of this technology. Examples of potential advancements include use of multi-materials (e.g., use of high-performance materials only in areas where they are needed), in-situ repair in locations that are difficult or dangerous for humans to access, disaster relief construction in areas with limited construction workforce and material resources, structural and non-structural elements with optimized topologies, and customized parts of high value. The future of additive manufacturing seems promising to the construction industry, but interdisciplinary research is still needed to provide new materials, new processes, faster printing, quality assurance, and data on mechanical properties before additive manufacturing can realize its full potential in building and infrastructure construction.

- IoT- and BIM-enabled platform for on-site assembly services in prefabricated construction: BIM can be a useful support tool in facilitating the on-site assembly services of prefabricated construction, thanks to the use of digital twins (functional digital presentations) it allows. But the use of BIM in the on-site assembly services of prefabricated construction requires a complete, accurate, and timely data exchange along with real-time visibility and traceability – which can be achieved through an appropriate mix of IoT and BIM technologies. Based on clients' requirements, other stakeholders expectations (e.g., low emissions, noise mitigation etc.) and construction site constraints, a full process can be put in place, relying on IT objects and gateways collecting real-time data throughout the working processes of on-site assembly of prefabricated construction using e.g. RFID technology, capturing data being uploaded to some cloud platform in real-time to process and analyse for decision support purposes to the benefits of the involved site managers and workers. BIM associated to AR/VR technologies can deliver visibility/traceability functions, allowing managers to supervise the construction progress and approximate cost information in a real-time manner. Such IoT and BIM-coupled platforms can provide various decision support tools and services to different stakeholders, for improving the efficiency and effectiveness of daily operations, decision making, collaboration, and supervision throughout on-site assembly processes of prefabricated construction.

Key enabling technologies for the transformation of the construction value chain

Construction 5.0 is to be made possible by the "multiplying" of innovative and proven materials, technologies (the so-called KETs - *Key Enabling Technologies*), and components, and their integration supported by enhanced data/knowledge management and ICT. It is also made possible by a deep integration of data management and ICT platforms and tools in all phases of the Construction process, placing the wellbeing of the worker at the centre of this process. In such consideration, the ECTP today advocates that the value-chain should drastically evolve from a *linear operational and economic model* into a transformed, fully integrated, human-centric Construction value chain, as depicted in Figure 2.

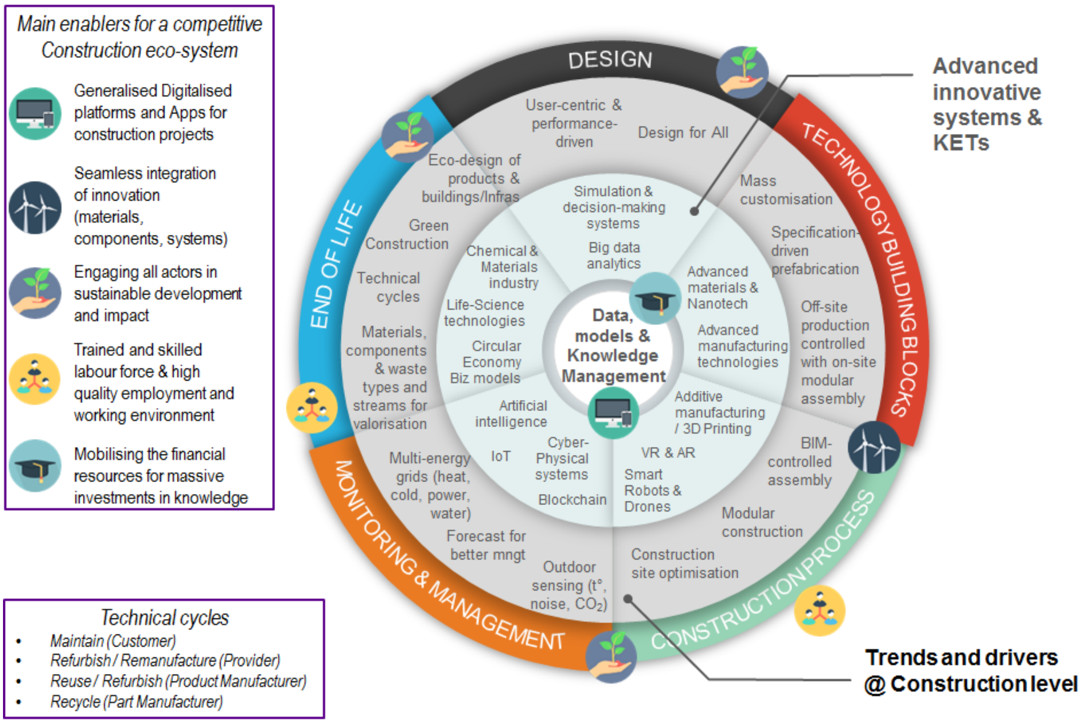

FIGURE 2: THE TRANSFORMED CONSTRUCTION VALUE CHAIN (AS CONSIDERED IN ECTP 2020-2030)

This transformed value chain has three main characteristics:

- At the core, the integration of **data, information and models**, that form the digital resources which will in the future feed and empower all activities related to the built environment processes (design, construction, operation & maintenance, etc.), relying on basic digital technologies such as BIM, IoT, Big Data, etc.;
- At a 2nd level, the **KETs and advanced innovative systems** are to provide with the key tools and components sustaining the necessary transformation of process in the whole construction industry value chain and built environment life-cycle – they all rely on the core data/information and their management in the 1st level;
- At a 3rd level, the large transformation of the various processes in the construction Industry and sector are fundamentally relying on those 2 previous levels, which provide the bricks to enhanced design, planning, and optimised coordination/execution and operation of construction sites, as well as prefabrication and mass-customisation, while optimising the 3-uple time-quality-costs to the benefit of clients and users and in a context of sustainable construction more and more linked in the future to circular economy. This value chain transformation is to be the grounding for achieving the main upcoming targets as exhibited in the previous Figure.

1.4. High-level objectives formalised by the DBE Committee

Based on the above-identified challenges and trends, the Committee has formalised 6 high-level objectives that are critical to enhance the digitalisation of the construction sector and the built environment by 2030, namely:

- **Objective 1: Twin transition for lifecycle approach with value chain integration**
- **Objective 2: Digitalised construction & renovation processes**
- **Objective 3: Smart operation and maintenance of buildings and infrastructures**
- **Objective 4: Data governance, data access & security**
- **Objective 5: Integration to the urban environment and to the grid**
- **Objective 6: Support people-centric approaches**

For each of these objectives, a set of priority areas are identified for the future research and innovation activities of the sector: they each correspond to specific challenges and are complemented by a list of focused R&I topics. The next diagram provides an overview of the priority areas identified for each objective.

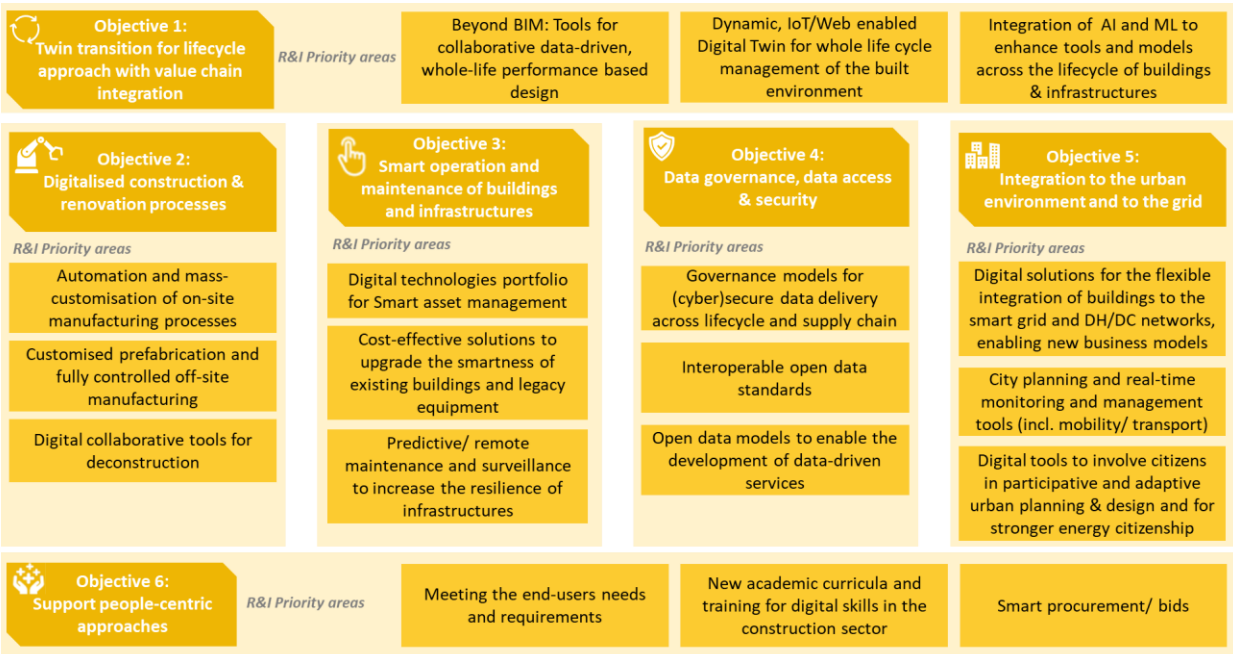

FIGURE 3: High-level objectives formalised by the Digital Built Environment Committee, and related priority areas for Research and Innovation

The next sections of this Position Paper detail these objectives and their respective R&I priority areas and topics.

2. Objective 1: Twin transition for life-cycle approach with value chain integration

Digital transformation in the built environment and the construction sector can boost sustainability, by enabling a whole-life cycle approach. This “twin green and digital transition”, or “twin transition”, may be the key to decarbonising the economy and adopting a circular development model, transforming the linear construction value chain into a fully integrated one.

Since the rise of Building Information Modelling (BIM) in early 2000s, there is an expectation that the building’s lifecycle data would be contained in a comprehensive three-dimensional (3D) virtual model which is developed and used by all stakeholders in a collaborative way. Such a BIM model would grow and evolve from the initial stage –where the virtual model contains the programme of requirements (PoR) for design, construction and occupation; through to the design, engineering and construction stages –where the architectural, structural, MEP and construction BIM models are generated; until the operation, maintenance and renovation stages –where the ‘as-built’ BIM model is enriched and updated by the data on the actual condition of the building.

While the latest BIM technologies are capable of achieving this expectation, in real practice there are a number of constraints for the use of BIM as the ‘central’ information holder in the building’s lifecycle. Among them there is an organisational constraint due to the rather conventional procurement and contractual arrangements between the stakeholders in the building’s value chain that hinder an integrated collaboration that is needed to use BIM optimally. Another reason is technical as it is difficult, if not impossible, to gather and contain all data across the building’s lifecycle stages in a BIM model. In real practice, the aggregated BIM model approach is used more frequently and effectively compared to the centralised approach relying on a single all-containing BIM model.

In order to progress beyond BIM, Asset Lifecycle Information Modelling (ALIM) should be considered to cope with the present and future demands, and to complement BIM and overcome the limitations of BIM with regard to building’s lifecycle data. ALIM underlines the integrated view in the ISO 19650, the international standard for managing information over the whole life cycle of a built asset using building information modelling. Combining Linked Data and Semantic Web technologies, it overcomes the need of oversized information models when the data from the whole building’s lifecycle is dealt with.

Taking BIM to the next level, the Digital Twin (DT) concept, an up-to-date full digital representation of a construction, is now at the heart of the digital transformation. It indeed facilitates monitoring of activities and comparison of relevant data against the design project, the initially agreed planning and construction methods. Applied to construction sites, it is considered as a set of digital information that captures the actual physical status of the building and the status of the construction processes. This information system has the ability to represent both the as-built product and the as-performed processes. Since the concepts contained in the DT relate, in full or in part, to BIM concepts representing the product as designed and the construction processes as planned, it becomes possible, through data analysis and visualization, to highlight differences in terms of progress, quality or work efficiency. It is then achievable to early implement appropriate corrective measures, to predict the outcomes of alternative scenarios, to anticipate future problems and to improve the general knowledge needed to plan the next actions of the current project in an informed manner. It is advisable to define specific key performance indicators to measure the performance of these processes in a quantitative manner.

Spanning from the design phase to the end-of-life of buildings and infrastructures, this objective is by definition a cross-cutting one, and includes tools, approaches and digital building blocks that take into account most of life stages (such as BIM and digital twins, enhanced by IoT, Artificial Intelligence and Machine Learning, etc.) and bring together the many stakeholders of the construction sector. *Tools that are more specific to a particular life cycle stage (e.g. construction, operation) are covered in Objectives 2 and 3*.

To enable the twin transition with a whole life-cycle approach and a fully integrated value chain, the upcoming R&I activities should focus on the following three priority areas:

- **Tools for collaborative data-driven, performance-based whole-life design (incl. BIM)**
- **Dynamic, IoT/Web enabled Digital Twin for whole life cycle management of the built environment, evolving towards the Semantic Construction Web of Things**
- **Integration of AI and ML to enhance tools and models across the lifecycle of buildings & infrastructures**

2.1. Beyond BIM: tools for collaborative data-driven, whole-life performance-based design

Digitalization implies major changes in design methods, technologies and tools. Beyond BIM, in the light of technology advancements and societal changes related to smart buildings in the Industry 5.0 era,. Digital technologies will no longer be treated as add-ons to the conventional architecture, and new design concepts will rise based on novel virtual and physical platforms to develop smart buildings. Due to the abundance of information, creative designing may no longer follow the traditional learning curve 'from rough to detailed'. While Artificial Intelligence and Predictive Design Modelling may be used for resolving technical design challenges, the creative power of designers would be optimized to invent user-centric solutions. A new design paradigm is envisioned that empowers end-users and design professionals alike to benefit from crowdsourcing of user preferences and behavioural information. Architects and engineers would commence with designing by investigating new physical and virtual usages of spaces and facilities. Changing societal trends (such as working from home and home schooling during the corona virus pandemic), and integration of smart materials, smart building elements and ICT as the backbone of smart buildings will become important considerations when designing the physical space layouts, building structures, and the connections between buildings and their surroundings.

For structural design, the benefits of Digital Twins will become more and more significant. A goal of Digital Twins related to structural design is to be able to assess the performance of the designed structural elements of buildings and civil infrastructures. The interactive design approach facilitated by Digital Twins will allow for a correct anticipation of the present and future demands for the designed structures, their responses to the structural loads, and the necessary countermeasures.

Furthermore, digitalization will imply new design methods involving topology optimization for additive manufacturing or 3D printing. Topology optimization is a powerful form of computation design, capable of generating high-performing optimized structural geometries without requiring the user to provide an initial concept. Based on mathematical optimization algorithms, it is a systematic yet also highly creative design method, with a wide variety of industrial applications. Topology optimization generates optimized designs in the form of material distributions in 2D/3D space[4]. An optimal design will minimize material and resource use without compromising the function and performance. Virtual material design, relying on multi-physics simulation and multi-scale modelling, has been investigated to determine how specific properties could be effectively designed into a 3D-printed object[5]. This innovation will find a way to building and structural design where topology optimization can be employed to reduce material use and weight without reducing the performance of a structure, and to provide designers with a larger freedom in creating forms and shapes.

In design projects, the production tasks and information exchange processes are now widely digitalised thanks to the introduction of BIM workflows and tools in the last decades, which itself followed the Computer Aided Design (CAD) revolution. Digitalised and interoperable workflows undoubtedly enable a strengthened collaboration amongst the design stakeholders, reinforce and facilitate the involvement of clients and owners in the decision-making processes, while also consolidating the information transmitted through the design cycles, including the shift from design to construction processes and the handover of design/construction data to facility management.

Still challenges remain when it comes to producing this information, sharing it with the other stakeholders or financing the additional costs when the added value is not fairly shared amongst design stakeholders and owners. In addition, strong digital link needs to be established amongst the deconstruction projects, dismantling components and materials, and the design/construction activities reusing it.

Research topics in this area include:

- Propose/Investigate new collaboration models within and amongst design consultancies, including new roles and skills to foster recognition of digital design leadership within architecture and engineering consultancies
- Propose standardised processes integrating software tools & platforms
- Develop methods to better link relevant standards in the data sharing workflow
- Develop and maintain common, standardized, up-to-date and reliable databases providing:
    - data on the material/ element up-supply chain at construction stage to support the demolition and end of life management (i.e. reuse, recycle the building elements)
    - best practices where dismantled components are reused in design, including their characteristics and traceability through material passports;
    - best practices associated with the design constraints to be formulated for construction processes relying on standardised prefabricated elements, or robotics;
- Widen Post-Occupancy Evaluation studies and data collection on existing NZEB buildings, to integrate learnings into new design patterns.
- Develop mechanisms to make use of Digital Twins in renovation, and design of new buildings based on data of existing buildings and neighbourhoods.
- Develop and share integration methods of contextual information (BIM data) and time series data (sensor collected) to enhance asset models

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[4] https://www.tudelft.nl/3me/over/afdelingen/precision-and-microsystems-engineering-pme/research/structural-optimization-and-mechanics-som/som-research/topology-optimization

[5] https://www.comsol.fr/story/download/309021/TNO_CN15.pdf

2.2. Dynamic, IoT/Web enabled Digital Twin for whole life cycle management of the built environment

BIM uses have extended to include lifecycle management of built assets. However, the current state of BIM is not compatible with IoT integration, specifically because of its legacy formats and standards which limits BIM usability and extensibility with a semantic web paradigm (Boje et al., 2020)[6].

The use of semantic web technologies (Semantic Web of Things) will make it is possible to transfer the BIM-based simulation to BIM-IoT real-time Digital Twin for monitoring construction, operation (including indoor air quality and energy performance), maintenance, renovation and demolition crossing whole life cycle of the built environment. The literature review shows that semantic web technologies have a 'key role to play in logic-based applications and applications that require information from multiple application areas (e.g., BIM + Infra + GIS + Energy).' [7] The data from operation stage will give the inputs to the more efficient operation, maintenance and renovation. As such, real-time Digital Twin can create more value (i.e., better indoor climate, lean construction, etc...) and contribute to less negative environmental impacts of built environment.

Although real-time Digital Twin technology have a huge potential to transform the construction sector in a more sustainable and efficient industry, there are several barriers to overcome:

- IoT data not at par with the monitoring requirements (Slow communication between IoT and Digital Twin platform, low accuracy, and frequency data from affordable IoT, or high-performance data with expensive IoT)
- Lack of close loop communication between IoT and BIM/Digital Twin platform, for example, the dual communication between construction machine and Digital Twin to reach the automatize/autonomous construction machine
- Digital Twin developed in different stages are fragmented and do not work as a comprehensive lifecycle management tool
- Lack of efficient and secured data communication between different stakeholders in Digital Twin, especially on the indoor climate monitoring as it will require occupants' behaviour, which will lead to the privacy concerns
- Most homes are not smart yet and even if they have potential computing capability, the lack of communications capability may hinder the twinning capabilities of any asset
- Lacking the distinct level Digital Twin, Digital Twin users' involvement and large-scale demonstration especially on infrastructures and public buildings (hospital, school, etc.)

Research topics in this area include:

- Understand the construction domains that can benefit from Digital Twin and investigate the conditions enabling the deployment of Construction Digital Twins, including the technological architectures enabling it

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[6] https://doi.org/10.1016/j.autcon.2020.103179

[7] https://doi.org/10.1016/j.autcon.2016.10.003

- Develop hybrid and innovative IoT solutions and communication technology to reach effective real-time communication between IoT and BIM
- Propose solutions to facilitate the adoption of semantic technologies and standardised format such as the Industry Foundation Classes (IFC) to structure data and provides better interoperability and reasoning capabilities, with common data spaces
- Develop methods to move from the static nature of information exchanges using the IFC format, to a more open, web linked data paradigm, ensuring that the right data is available at the right time
- Develop Digital Twin Environment coupling systemic simulations across the lifecycle of the asset with the time series coming from the real time monitoring (e.g. from Smart Connected Homes) to calculate key performance indicators and reduce the gap between performance and simulation. Current advances in ICT should allow real-time simulations and enhance this effect by the creation of simulation loops along the operation of the assets. This will support performance contracts and the deep renovation wave[8]
- Develop innovative solutions of Building Digital Twin with life cycle perspective, and scale it up from single building to the district level (e.g. A DT concept should integrate a functional mathematical model covering all phases of the building and incorporating human occupancy, weather and operating conditions of the building)
- Investigate the evolution of current digital infrastructures like 5G or the price of the available on-line storage, and their impact on the full integration and synchronization of information models in the cloud, in the shape of the future based Digital Twins
- Promote the publication of Digital Twins online: Development and dissemination of tools for building internet-accessible Digital Twins, together with adequate training
- Develop "DT compliant" new smart connected products: ease of physical connectivity (plug and play) to physical asset and ease of virtual connectivity to DT, with simple interfaces
- Define and deploy wireless communication systems in isolated or low connectivity environments
- Integration of BIM based platforms and tools for integrated Life-Cycle Sustainability Assessment (BIM-LCSA (LCA-LCC-SLCA))

2.3. Integration of AI and ML to enhance tools and models across the lifecycle of buildings & infrastructures

The current applications of Artificial Intelligence (AI) in the construction sector, and its forms, are embedded with its digital transformation strategies and need to be seen in two dimensions: (i) the design, construction and maintenance of buildings and infrastructures in one dimension, and (ii) the living environment as "host" of its inhabitant's life processes and interactions in the other dimension. Considering lifecycles and its complexity, all the AI forms are relevant at some phase or process. Machine learning (ML) and AI related robots are potentially impactful for the design stage and for the

[8] SPHERE White paper, 2021: FROM BIM REPRESENTATION TO FUNCTIONAL SIMULATION AND REAL TIME ADVANCED CONTROL

automation of construction process. Neural networks techniques can bring value to Buildings Energy Management Systems and its interconnectivity with district/city energy management systems.

Although AI technologies have a huge potential to transform construction sector in a more sustainable, efficient and user-centric industry, there are several barriers to overcome:

- As in other application areas, the impact of the different AI forms will depend on the available data quantity, quality and reliability. The Data capture, storage and sharing are key issues and it is one of the hardest to tackle from a business perspective.
- Social perception of AI as a threat. AI will impulse a disruptive transformation of buildings and civil infrastructures along their complete lifecycle and it can be perceived by the society as a threat. From the labour force point of view, the main concern will be about the suppression of jobs, but from the citizens one the main concern will be about the lack of privacy.

Research topics in this area include:

- Investigate Artificial Intelligence techniques to address and solve optimisation opportunities in the various impact fields associated with construction processes, and to enhance durability models and thereby service life of the built environment
- Propose agent-based simulations methods and machine learning on historical data to predict outcomes of design and plan alternatives
- Provide standardized methodologies for data management and processes, and consolidation of proprietary data formats and languages to implement AI
- Deploy pilot/demo cases and promote success stories in the adoption of AI technologies to facilitate the adoption of AI technologies and extend the market uptake
- Provide recommendations for regulatory and contractual liabilities considering the complexity of the projects and value-chains
- Provide solutions with less sensors but better quality and reliability: Improve and propose new sensors supported by human models, wearable's and smart home tracking and presence detection. In this context:
    - Develop and integrate human models in real time systems to propose an objective reference of health and comfort level and consider specific properties of non-standard occupants.
    - The hardware implementation of human interaction can be supported by wearables and smart sensors, and simulation will play a key role calculating in real time health and comfort parameters.
- Develop AI-based pattern recognition techniques and high-level reasoning to detect defects in surface and texture
- Develop blockchain approaches to have a full overview of the chain of production and other relevant procedures in which traceability can uptake the process
- Create generic tools that can support the industrialization and be used by many (clustering tools, automatic modularization, assembly optimization, etc.) instead of customs tools for every situation

3. Objective 2: Digitalised construction & renovation processes

According to the International Council for Research and Innovation in Building and Construction (CIB)[9] the Industrialisation in Construction is defined as: *"A rationalisation of the work processes in the industry to reach cost efficiency, higher productivity and quality. It involves a change of thinking and practice to improve the production of construction to produce a high quality, customised built environment, through an* ***integrated process, optimising standardisation, organisation, cost and value, mechanisation and automation"****.*

With labour productivity growing at around a quarter of the rate in manufacturing sectors (1% vs. 3.6% respectively), the construction sector is the poorest performer in terms of productivity[10]. Construction projects are notoriously late and commonly run over budget. A major root cause is the lack of production planning and production control, which leads to excessive waste of workers' time, inefficient use of equipment, waste of materials, rework costs, quality costs, etc. For example, several research studies[11] on labour have shown that, in general, only 35-45% of workers' time is spent on value-added activities. Commonly, tasks are delayed due to failure to address one or more of the prerequisites (design information, materials, space, labour, equipment, external conditions and preceding tasks). Besides, most of the companies in the supply chain are often implementing standard tasks which are human intensive and not knowledge and technology driven, thus leading to non-optimized processes. Although the unicity of each construction project is a concrete limitation to any optimisation ambitions, the extensive use of new technologies on construction sites paves the way for more productive, more secure, more resource-efficient, more environmentally friendly and less costly processes while improving the overall building quality.

Solutions exploiting robotics and automation in the construction processes, together with the adoption and massive use of digital technologies such as BIM, IoT, data analytics and artificial intelligence, must be developed and tested in order to demonstrate their profitability potential in the digitalization of construction sites. Moreover, such digitalized process enables stronger integration of the value-chain, enabling off-site and on-site synchronisation through adequate logistics planning, tracking and optimization. Accordingly, new services and processes must be developed for improved management, monitoring, planning, surveillance and safety of construction sites, and this should certainly go together with the adoption of new working practices by all concerned actors. Ultimately construction sites are required to be managed in a sustainable way, limiting their emissions while improving waste management towards circular economy.

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[9] "New Perspective in Industrialisation in Construction - A State of the Art Report". Working Commission 119 successor to the former CIB Task Group TG57 - Industrialisation in Construction; joint commission of CIB and IAARC - the International Association for Automation and Robotics in Construction. Edited by Prof.Dr.Ing. G. Girmscheid, http://www.irbnet.de/daten/iconda/CIB18177.pdf

[10] The Economist (2017). The construction industry's productivity problem.

[11] S. Sarhan, C. Pasquire, A. King, Institutional waste within the construction industry: an outline, in: 22nd Annual Conference of the International Group for Lean Construction, IGLC & Akademika forlag, Oslo, Norway, 2014: pp. 895–906.

Overall, the following impacts can be expected:

- 20% reduction in budgets and schedules,
- Equipment utilization rate of at least 90%,
- 40% reduction in emissions of the construction process,
- Reduction of the number of safety defects that cause hazardous situations by at least 20%.

Objective 2 focusses on the industrialisation enabled by digitalisation of the construction, renovation and deconstruction processes, both off-site and on-site.

To accelerate the digitalisation and automation of the construction and renovation processes, the upcoming R&I activities should focus on the following three priority areas:

- **Automation and mass-customisation of on-site manufacturing processes**
- **Customised prefabrication and fully controlled off-site manufacturing**
- **Digital collaborative tools for deconstruction**

These three R&I priorities are detailed in the next sections.

3.1. Automation and mass-customisation of on-site manufacturing processes

Numerous techniques are being developed to capture raw data on site, from scans (point clouds), images, videos, sensors, RFIDs, UAVs , even satellites and GNSS , can be used to provide some of this data. The raw data collected from multiple sources, however, must be interpreted in combination in order to produce meaningful information about the product and processes status. It is where AI-based solutions (data mining, machine learning…) can come into play by deriving added-value information from raw data. For instance, AI-based activity or scene recognition techniques can be used to automatically detect hazardous situations for site workers.

On another level, whether automation in construction has been already developed and deployed, an exciting use of certain on-site robotic techniques is emerging. For example, on-site 3D printing robots, controlled with BIM data, now make it possible to quickly erect relatively simple building structures. Moreover, as a consequence of the evolution of the prefabricated constructive systems, for example, their complexity regarding sizes, weights, joint systems, manufacturing and erection tolerances, … it is offered to the on-site robotic the opportunity to provide competitive automated processes, for example, for the architectural envelopes.

Research topics in this area include:

- Demonstrate how Digital Twin can be utilised to optimise on-site renovation processes: 3D Scan-to-BIM, BIM-to-BEM (Building Energy Modelling), BIM-to-Fabrication, BIM-to-3D Printing, real-time sensing, monitoring and control systems
- Implement Linked Data techniques in BIM and Digital Twin platform for creating high-level information & knowledge models and supporting semantic interoperability
- Automate the capture and semantisation of as-built geometry (e.g. through point clouds) and its registration into the BIM, automatically monitoring progress and detecting inconsistencies in the structure and systems

- Deploy the use of machine learning techniques with intelligent analytics and predictive control to detect risks and provide real-time warnings to workers (risk detection and prevention)
- Develop AI-based optimisation algorithms, using e.g. convolutional neural networks or reinforcement learning methods for scheduling and control of equipment use
- Test and validate the use of robotics controlled with BIM data to create complex structures
- Study the economic, legal/health and safety issues at local levels to foster the wide adoption of robotics on construction sites. New Business models are also necessary to accommodate to new ways and to properly exploit this hi-tech equipment in future construction sites
- Develop flexible and configurable construction robots that serve as on-site fabrication mini-factories to assemble, 3D print, manufacture, and customise different building elements and components
- Integration and development of different Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (XR or MR) tools to support a BIM common working environment
- Introduction of driver-assistance system and autonomous driving for the work construction site equipment to improve construction process and reduce physical workload on the construction site
- Test and validate the extended use of autonomous vehicles (excavators, bulldozers, etc.) to carry out construction work 24 hours a day, 7 days a week, rather than being limited to working hours

3.2. Customised prefabrication and fully controlled off-site manufacturing

Off-site processes for prefabricated structural constructive solutions[12,13,14] have been demonstrated and the remaining challenge is to provide higher added value solutions as, for example, **customised envelopes and integrated installations and active systems in adaptative components**[15].

The fabrication and delivery on-site of prefabricated standardised construction components is intrinsically linked to buildings design decisions and require fully digitalised information flows across the whole design/construction supply-chain down to the manufacturer. This trend visible in the product manufacturing and construction is spreading over the whole construction market, including the development and real-estate where Product-as-a-Service extends towards Building-as-a-Service model, where the usage-related and performance-based Service Level Agreements will redefine the ownership in the future. The end-user value and acceptance of such construction methods and ownership models relies significantly on the ability to customise the design, allowing flexible usage while enabling architectural expressiveness, e.g. in building morphology and appearance.

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[12] ANDECE, Spanish Association for Precast Concrete Industry, https://www.andece.org/

[13] CONSTRUCTALIA, ArcelorMittal, Steel based constructive solutions for building and infrastructures, https://constructalia.arcelormittal.com/

[14] CATALOGUE BOIS CONSTRUCTION by FCBA, https://catalogue-bois-construction.fr/

[15] Arup partners with WoHo to revolutionize building design and construction, catalyzed by $4.5 million in seed funding, https://www.arup.com/news-and-events/arup-partners-with-woho-to-revolutionize-building-design-and-construction

On the other hand, the objective for a highly customised prefabrication leads to a more flexible manufacturing processes but automated for a cost-effective approach to the market: 3D printing technologies can play a role to provide, for example, early prototypes, moulds or the functional product.

Research topics in this area include:

- Develop embedded sensors and IoT solutions for lifelong monitoring of prefabricated solutions
- Develop the next-generation digital construction machines and construction robots in the context of highly automated off-site and prefabricated construction processes
- Develop, test and scale up digital tools enabling new smart manufacturing processes, including modular off-site construction or prefabrication, pop-up factories, 3D printing, generative design, integrating Artificial Intelligence
- Develop Connected and autonomous plant and robots to be operated remotely in order to improve construction efficiency and undertake repetitive tasks autonomously.
- Design and implement an ethic assessment and impact assessment of the transition steps to construction 5.0 to make sure it brings benefit for workers and for society
- Apply digital twin to modular construction compatible to cultural heritage for a sustainable high comfort level

3.3. Digital collaborative tools for deconstruction

Construction and demolition waste (CDW) accounts for about 25%-30% of all waste generated in the EU[16]. CDW arises from activities such as the construction of buildings and civil infrastructure, total or partial demolition of buildings and civil infrastructure, road planning and maintenance.

One can consider that ca. 50% of this amount is currently recycled in most EU countries[17], however the majority of CDW is destined for backfilling and other low value applications (downcycling). For instance in North-West Europe countries, the reuse and high-quality recycling (and even upcycling) of CDW remains below 3%.

However numerous challenges prevent a broad adoption of such *deconstruction* practices. First, they are usually relatively costly, compared to usual demolition, and require more time. There is also a limited sharing of technical knowledge and best practices associated with deconstruction projects so far. Moreover, the professionals lack tangible information on the potential value of the deconstructed products, and the absence of (regional) markets for those products is a barrier. The limits associated with the current status of the construction products regulations, and their application for re-used, recycled or upcycled products, is another important challenge.

Regulations, certifications, and a poor digitalisation level of the construction sector are amongst the key factors hindering better exploitation of those existing construction products stocks.

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[16] https://ec.europa.eu/environment/waste/construction_demolition.htm

[17] Detailed figures per Member States in 2011 are available from https://ec.europa.eu/environment/waste/studies/pdf/CDW%20Statistics%202011.pdf (accessed Dec. 9th, 2020)

Digitalisation is a priority to unlock the barriers mentioned above, enabling the instantiation of the circular economy principles in the building sector through the vision of "buildings as (digital) material databank which gathers all information on materials (origin, volume, environmental data, etc.) used in a building from construction to disassembly".

Research topics in this area include:

- Develop digitalised rigorous and collaborative process to deconstruction management, where digital information management would underpin the whole process, from initial inspections, materials' inventories to deconstruction scenarios and execution towards the further storage and reuse in new design projects
- Define assessment methodologies and simulation models of the key environmental and financial indicators associated with the analysis of the deconstruction scenarios. In particular, Life-Cycle Assessment facilitated by BIM models can consider the emissions associated with the End-of-Life phase of the whole constructed assets down to their components/materials. This would directly inform the re-use / re-valorisation scenarios
- Develop digital inventory tools based on 3D-scanning technologies, enabling rapid data collection on existing buildings (including AI, computer vision applied to objects recognition) and accurate material audits before renovation or demolition
- Develop a digital platform based on BIM and integrating blockchain and IoT solutions for enhanced traceability of the building materials and their reuse, while ensuring data security.
- Develop digital marketplace platforms and open API, to enhance the trading of materials across all the markets, boost the market of recycled and secondary materials and enable circular deconstruction. In particular, develop and test national logistics management platforms for recycled materials both for certification needs and to verify local availability.
- Propose methods to secure economic transactions, relying on blockchain technologies and linked with the digital material passports
- Develop new tools that support "design for reuse": each building component/element must be "re-usable" and its disassembly, re-purposing, and re-assembly must be available in the form of a product data model/sheet to support ease of assembly, disassembly, re-purposing (if needed), and re-assembly

4. Objective 3: Smart operation and maintenance of buildings and infrastructures

The climate emergency calls for a deep change in the way buildings and infrastructures are operated and maintained over their full life cycle, so as to make them more sustainable and resilient.

Digital solutions are instrumental to ensure that the real, long-term performances of the built environment are in line with the designed ones (see Objective 1 on whole-life performance-based design) – or get improved to align with new regulations. A new holistic and systemic approach to asset management, making the best of digital tools, is needed to optimise and upgrade existing buildings and assets, increase their service life, make best use of them to reduce the need for new ones and to support relevant policy goals. In the current context of constrained finance, ageing facilities and rising demand, countries are indeed looking for strategies to maximise returns on infrastructure investment.

Buildings need to become smarter, with legacy equipment being upgraded or enhanced with active, communicating, interoperable components to enable an optimised operation. The Smart Readiness Indicator[18] currently being tested in some of the EU Member States, on a voluntary basis for now, provides a well-structured framework on how to make buildings smarter, more energy efficient and user-centred. Yet, the smartening of the existing building stock is not happening at the required pace.

For infrastructures, technologies as IoT together with Artificial Intelligence can deliver more efficient management and maintenance, for instance innovative maintenance methods based on actual infrastructure condition, less invasive and less traffic disrupting.

Objective 3 focusses on digital tools and services for the smart operation and maintenance of the built environment. Required R&I activities are structured into three priority areas:

- **Digital technologies portfolio for smart asset management**
- **Cost-effective solutions to upgrade the smartness of existing buildings and legacy equipment**
- **Predictive/ remote maintenance and surveillance to increase the resilience of infrastructures**

These three R&I priorities are detailed in the next sections.

4.1. Digital technologies portfolio for Smart asset management

The different stakeholders of the construction sector (European, State and Local Administration, Developers, construction companies, insurance companies and technicians) work within a legal framework that can be improved. The coordination of the different agents, the synthesis of the existing legislation and the technological capacity, makes possible the objective of increasing work

[18] https://smartreadinessindicator.eu/, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator_en

safety and health, mitigating the environmental impact and increasing efficiency in the exploitation phase.

The main challenges / opportunities to be addressed in smart asset management include: increase security by acting predictively and proactively; increase reliability and availability; optimize investment and operating costs, minimize environmental impacts.

Research topics in this area include:

- Develop and demonstrate artificial intelligence and advanced machine-to-machine interfaces(M2M) enabling Asset Management System (AMS) to take automated actions and decisions autonomously, including for emergency management
- Propose a digitization strategy of network asset management processes, through the adoption of key enabling technologies for the development of innovative approaches
- Develop predictive and deterioration models, implementing AI to define optimal intervention routes and to support the activity of operational staff for an optimised management of construction sites
- Develop decision-support tools based on digital twinning (Digital representation of physical asset), big data, artificial intelligence and risk assessment for transport infrastructure operation, scenario testing and improved asset life-cycle management processes
- Adopt BIM & Digital Twin for planned and existing assets for improved information on assets and as built information. Common object type libraries for digital representation of assets.
- Ensure interoperability between Digital Twin platform used for the management of CH assets and VR/AR/MR tools for valorisation
- Define and deploy scalable Big Data architectures to promote smart environment
- Develop and demonstrate in real environment, digital technologies for the operation and management of energy facilities in buildings taking into account occupant behaviours (deep learning solutions)
- Propose a certification system for office and tertiary buildings, to link the virtual model with real and virtual sensors, in order to have a more accurate forecast of the building's energy performance and a better management of it
- Demonstrate the benefits of automated solutions for facility management using a BIM-DT approach

4.2. Cost-effective solutions to upgrade the smartness of existing buildings and legacy equipment

The achievement of the EU Green Deal target calls for the transformation of the existing building stock into sustainable buildings in terms of energy efficiency and carbon neutrality. Energy efficient renovation, implemented in accordance with the Energy Performance of Buildings Directive (EPBD), usually involves a smartness upgrade of existing buildings – as reflected in the Smart Readiness Indicator (SRI) – to optimise the building performance during subsequent operation and maintenance stages. As such, high-impact, cost-effective and non-intrusive solutions are needed to upgrade the smartness and sustainability of the existing buildings and legacy equipment. In the smartness upgrade strategy, data interoperability should be ensured in relation with the architectural and civil engineering solutions and ICT technologies.

Research topics in this area include:

- Develop, demonstrate and commercialise cost-effective interoperable, cybersecure systems (with e.g., open APIs, AI and ML) to better monitor and control legacy equipment (in particular equipment such as HVAC and DHW systems with high costs of replacement and long lifecycles)
- Provide an open marketplace of accredited smart, plug & play solutions (software and hardware - IoT sensors, controls, etc) enabling the upgrade of building smartness, with indication of their respective contribution to increasing the SRI value
- Develop innovative upgrade systems to existing infrastructures that involve the development of new advances materials or technologies and incorporate smart infrastructure solutions (IOT, traffic/weather detection, etc.)
- Adapt Digital Twin Platform (BIM + IoT) to the cultural assets' context

4.3. Predictive/ remote maintenance and surveillance to increase the resilience of infrastructures

A well-maintained facility may retain its optimal operational performance (and its value) for a longer time. Yet, according to a G20 2021 report[19], the deferral of necessary maintenance remains common across countries and sectors, often due to challenges of non-technical nature, including, among others:

- asymmetry of information about asset's status and performance;
- mismatch between evolving demand patterns and the capacity of existing infrastructure;
- human resources with inadequate skills to perform effective maintenance over an asset's life-cycle.

There are a number of opportunities that can be exploited to make maintenance spending more efficient and to ensure that interventions are handled in the most timely, smart and least invasive way. Digitalization and data-driven advances in monitoring for instance enable "smarter", better targeted maintenance.

In particular, predictive maintenance (i.e., enabled by advanced analytical methods that predict the likelihood of damage) can potentially minimize costs over time and reduce potential failures. The use of sensors, drones and satellite imagery can lower maintenance costs in roads, water and energy infrastructures, remotely pinpoint damage to networks as well as enable faster and more targeted response to disasters. AI, cloud computing and machine learning can improve the information sharing and analytical tools for risk modelling or asset maintenance plans[19].

Research topics in this area include:

- Combine Digital Twins with what-if scenarios simulation to improve resilience against human threats, identify weak components of infrastructures to manage investments for the reinforcement of existing and new infrastructures weak points

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[19] G20 Policy Agenda on Infrastructure Maintenance Mending and regenerating our infrastructure systems, 2021

- Develop fully digital and automated infrastructure inspection methods, including distributed IoT and sensors, robotics and reality capture to assess the structures and for a continuous monitoring and surveillance and integrate it in asset management systems
- Develop cost-effective solutions to monitor assets behaviour and deterioration processes (including the supporting geostructures) and collect real time data for cost-efficient predictive maintenance (using IoT, AI, machine learning), moving from current prescriptive-based approach to condition-based up to preventive maintenance. Use weather patterns, to forecast the maintenance requirements and costs by infrastructure types and locations.
- Develop new effective solutions for better real time surveying for an adequate support of the site operation as well as the monitoring of the infrastructure resilience
- Using high performance data analytics and AI to create accurate predictive degradation models and algorithms for proper conservation and use of the built heritage
- Integrate the use of drones, sensors, IoT to develop new on-site processes and services, including safety, surveillance and quality control
- Provide recommendations to support small infrastructure providers, like mid-size cities, sharing a common AI/Sensor system for infrastructure maintenance and to then build a collective, predictive tool to extend infrastructure lifecycles
- Analyse ethical implications both on technological solutions and people implied on remote maintenance and surveillance systems

5. Objective 4: Data governance, data access & security

Digitalization will increase the amount of data generated in the whole building life cycle. Having access to such data will be crucial in improving overall construction processes as well as operation and maintenance. To achieve this goal, new agreements on data sharing will have to be introduced to fully harvest the benefits of data, while guaranteeing the quality of data and the security of citizens. Furthermore, digitalisation is also pushing companies in the sector to rethink the way they are doing business: in particular, business models are expected to change and new forms of collaboration as servitization will emerge because of the adoption of digital technologies.

Open standards for data are, therefore, needed to resolve fragmentation and liberate data from silos. The implications of new open standardisation with regards to Semantic web, ontologies and linked data include[20]:

- Ensuring data is Findable, Accessible, Interoperable, and Reusable (FAIR)
- Supporting data sharing and data modelling methods which are compliant to the anticipated open standard CEN TC 442/WG4/TG3 Semantic Modelling and Linking Standard (SMLS)
- Developing reference architecture for a digital platform for European construction industry that is compatible with the Semantic Linked Data requirements.

The Semantic Modelling and Linking Standard[21] (prEN17632) for data integration in the built environment is under approval and expected to be available in the coming year (2022). The scope of this standard includes:

- Modelling and linking of data sets and data models (like vocabularies, dictionaries, thesauri, classifications and ontologies) using W3C linked data/semantic web technology recommendations to facilitate data integration (like by data delivery or data sharing);
- Total life-cycle of assets and their supply chains involving projects and (catalogue) products in the built environment (covering buildings and civil infrastructures, and their systems, elements, components and materials);
- All relevant stakeholders including asset users, asset owners, asset managers, supply chain parties (related to projects and products) and related implementing software vendors.

To accelerate the development of a DT-based service market for construction site management, agreement must be reached on a standardized way to model data and relevant information. Indeed, the development of a standardisation framework for DT, in the same way that Open BIM has fostered the development of interoperable tools, is the key to rapid and cost-effective deployment of DT-based solutions for future smart construction sites. It is recognized today that a fully semantic data environment brings several benefits, allowing the design and construction supply chain to leverage web-based linked data.

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[20] DigiPLACE deliverable D5.2

[21] Semantic Modelling and Linking Standard

Besides, a true collaborative spirit has to get into construction teams. While LEAN management methods strongly rely on the involvement of each stakeholder, tools and devices are required to let them access the right information at the right time and in the right place.

Objective 4 covers all aspects of data governance, data access & security, for data related to the built environment or at the interface between the built environment and the "external" networks such as energy and transport.

To accelerate the digitalisation and automation of the construction and renovation processes, the upcoming R&I activities should focus on the following three priority areas:

- **Governance models for (cyber)secure data delivery across lifecycle and supply chain**
- **Interoperable open data standards**
- **Open data models to enable the development of data-driven services**

These three R&I priorities are detailed in the next sections.

5.1. Governance models for (cyber)secure data delivery across lifecycle and supply chain

To grant data providers that their data are going to be used as they expressed in policies is the main obstacle to data sharing. To prevent data leaks, the integration of privacy-preserving technologies such as homomorphic encryption or functional encryption are taking great relevance. These technologies do not make data usage possible if the consumer system does not have the corresponding temporary cryptographic key with which the data was encrypted, this approach limits the data usage.

To prevent the misuse of the data, trusted applications can be developed. Trusted applications are software components that guarantee compliance with the policies by limiting data usage. Even though they do not control data usage, they allow data usage for certain circumstances that always satisfy the policies. The trustworthiness of the application is guaranteed by a certification authority that verifies how the application works and that meets the agreed policies. This approach is typically used in Digital Rights Management (DRM) systems. Nevertheless, it presents huge challenges in terms of feasibility as the number and complexity of the policies expressed in high scale ecosystems are high.

Research topics in this area include:

- Develop novel methods to ensure data privacy and security in the Built Environment Digital Twin:
  - Implement new privacy management tools in order to comply with regulations but making possible data transactions and public reporting in controlled conditions
  - Provide solutions to manage and store historical/new data and statistics from building digital logbooks and ensure to have property, security and local control over the data collected
  - Consider a coordinated cooperation among all the stakeholders is needed to provide an Ethical approach to prevent the revelation of behaviours whenever inside homes, schools, working offices, etc.

- Develop standardized cyber-secured communications and integration technologies in order to guarantee interoperability of the adopted solutions between buildings and local energy systems
- Facilitate the implementation and deployment of the reference architecture proposed by the International Data Space Association (IDSA) by providing use cases, methodology and standards for communication and for the definition of usage control policies
- Provide solutions to guarantee access to data from User Information System, complying with data protection laws
- Develop trusted digital platforms (managed by a trusted third party) to ensure the safety and security of data and transactions
- Develop Trustworthy AI solutions taking into account stakeholders implied in the process and end-user who will be impacted, with algorithms to audit them

5.2. Interoperable open data standards

A digital platform for European construction industry should promote and facilitate data sharing based on Linked Data open standard. Moreover, to create "smart data" which is machine-interpretable (for instance for present and future use of Artificial Intelligence), data modelling on this platform should utilise the Semantic Web technology according to the topics that are covered by the CEN standard, i.e.

- Conceptual Meta Model (CMM) + Language Bindings to RDF + SKOS, RDFS, OWL & SHACL
- Conceptual Model (CM), including modelling patterns for: Top Level Taxonomy; Quantities & Units (reusing QUDT v2.1 by NASA/TQ); Enumerations; Decomposition; Complex Properties (attributes and relations modelled as individuals of classes to be able to attach meta-data)
- Data linking methods (weak and strong ways, on both concept and individual level)

Research topics in this area include:

- Develop a unified and shared EU ontology & semantics for devices, equipment and assets (e.g. "Dictionary" bringing together all relevant semantics and ontologies, with shared definitions)
- Support the roll-out and wide adoption of common, recognised open standards in the building industry thanks to digital dictionaries facilitating their interpretation and ease of use
- Develop communication protocols and propose standards for data exchange and information channels between multimodal facilities (how data from vehicles, trains, ships, airplanes can be used across modes and how it can be made available for users in clear and not confusing format)
- Develop protocols ensuring data interoperability between design (architectural, structural) and construction (modular assembly, renovation, etc) and ICT technologies to enable smartness upgrade of existing buildings

5.3. Open data models to enable the development of data-driven services

"Data is the new gold". Data has become an essential component of today's business foundation, as it can be used to provide new services. But, quoting Deloitte (2018)[22], benefiting from it will require settling the question of who controls the data. Both owner and user will legitimately claim the right to 'their' data.

'Walled garden' approaches, whereby equipment manufacturers offering data services in a vertically integrated cloud solution, with user data and equipment control being then fully captive to the manufacturer's solution, should be avoided. The new Data Governance Act (DGA), which aims to increase trust in data sharing, create new EU rules on the neutrality of data marketplaces and facilitate the reuse of certain data held by the public sector, should enable the secure access to data by (new) market players, while ensuring optimal governance and liability.

This complex regulatory and market framework needs to be taken into account when developing models enabling data-driven services.

Research topics in this area include:

- Develop novel Big Data platform(s) powered by energy-related data that effectively addresses the complexity of the energy/ electricity/building sectors value chain interactions and allows for the delivery of innovative Energy-as-a-Service offerings
- Develop new approaches and services to allow for the local storage of data and local execution of data operations, and at the same time permit the blending of external data sources to increase the added value of data-driven services
- Review/test and select different data sharing models to demonstrate and disseminate good practices, including all value chain stakeholders and users in the building lifetime and tailored to the building typology as data and value chain differ
- Set up a strategic data flexibility framework, which clearly states data rights and requirements for data quality and integrity, also defining the role of trusted third parties as warrant of cybersecurity and data privacy
- Open energy data for developers and start-ups to develop new Energy Efficiency services

[22] Deloitte (2018) Data is the new gold: The future of real estate service providers

6. Objective 5: Integration to the urban environment and to the grid

The city is expected to be sustainable, resilient and inclusive with citizens with an active participation in the governance modules and planning of their living environment. This will demand that cities provide, higher value novel services to citizens, tourists and visitors, and relevant stakeholders, aided by an increasingly digital context.

The actual and future applications of smart digital technologies in this area, hosting buildings, infrastructures and cities inhabitant's life and cultural heritage, will be instrumental to support the decarbonisation targets and an inclusive citizen-centric urban governance.

It is expected that connected and open smart buildings and infrastructures, will feed the ecosystem for these new integrated city services with data lakes, and new algorithms, to allow a full-fledged and open policy of sustainable urbanisation, transforming the public city space, enhancing the city and highlighting its architectural, cultural and natural heritage.

Generalising such connected and open built environment, feeding data from buildings, infrastructures, public networks, crowd-sourcing and crowd-sensing, will allow access to data to the users and all authorized stakeholders. Current and future players will be able to retrieve information in order to build solutions that will provide services for cities and buildings, and also for city stakeholders and urban planning processes, users, operators, and communities.

These will facilitate the spread and use of public services, with many dealing with the management and optimisation of city infrastructures and serving the citizens' quality of life. These can include services related to urban planning, energy and water networks, as well as of climate adaptation and safety risks, supporting services such as smart diagnostics (e.g. detect the risk of urban heat islands) and disaster management (due to heat waves, power shortcuts) or "perturbations" (public events, demonstrations), by sending targeted alerts to their citizens.

The integration of novel big data and AI technologies should allow to tangibly transform the urban environment with communication interfaces between buildings, and their own equipment, and the surrounding buildings and infrastructures and their interconnectivity with district/city management systems and personalized experience for the citizen.

Objective 5 goes beyond the building scale.

To improve the integration of buildings and infrastructures to the urban environment and to the grid, the upcoming R&I activities should focus on the following three priority areas:

- **Digital solutions for the flexible integration of buildings to the smart grid and DH/DC networks, enabling new business models**
- **City planning and real-time monitoring and management tools (incl. mobility and multi-modal transport hubs)**
- **Digital tools to involve citizens in participative and adaptive urban planning & design and for stronger energy citizenship**

These three R&I priorities are detailed in the next sections.

6.1. Digital solutions for the flexible integration of buildings to the smart grid and DH/DC networks, enabling new business models

The transition in the whole energy system brings a progressive shift from the traditional energy production model, where buildings are only passive consumption units, towards microgrid models and energy communities with optimised energy management. Digital technologies support the changes and the integration of buildings as active nodes in the energy system, creating flexibility while keeping comfort and creating fair, and clarified, conditions for the consumers.

Buildings and communities need to be integrated as an active part to the energy system to deliver flexibility and interoperability, in line with the regulatory framework. The challenge is to optimise the whole energy system of the building as an entity, including minimised and balanced energy use, on-site RES and energy storage, and the energy transactions to both buy and sell all energy forms (electricity, heat, cooling, and (bio)fuels). Smart building applications enable buildings to start acting as prosumers as an active part of the local energy systems. Standards, AI and easy implementation are the key requirements.

The building energy management system need to be integrated in standardised way, seamlessly and on a plug-and-play basis, with the smart grid and district heating and cooling systems. The main challenge is the interoperability. Further developments potential can be found from developing new (cloud based) EE services for buildings, which has challenges in data collection and sharing and their ownership, as well as to semantic interoperability. In relation to the development of the standardisation, linked challenges include deciding where to connect EV charging: whether EV charging should be included directly to the smart grid, or via the building energy system.

Often non-technical challenges are hindering the development even more than technical problems. To be able to utilise the full potential of buildings in supporting the carbon neutral performance of an energy system, the governance of the energy system and its business models, operation principles and agreements should be clarified among the network of partners who act and participate in the operation of the energy system. Also, barriers in legislation and city policies still exists that further hinder, and even restrain, buildings active participation in the energy system (these have been recently identified e.g. in H2020 EXCESS project).

Moreover, there is a need to integrate novel big data technologies, tools and libraries, with energy sector legacy systems and ICT-enabled assets and services to accelerate the data management and analysis cycle for powering and turning the 4 Big Data Values into Stakeholder Value. This will accelerate the penetration of advanced renovation support solutions for optimized and accurate energy-efficient design of buildings addressing key business viability requirements of ESCOs. This will optimize urban monitoring and planning functions through the collaboration of city authorities, facility managers and ESCOs. This will improve facility management and predictive maintenance and maximise self-consumption towards significantly reducing energy costs of consumers and facility/ building managers, while increasing their autonomy from the overlay grid and the capability of local communities and microgrids to operate in local energy islands. Introducing novel services for real-time building energy performance and smart readiness certification, will enable the offering of new services through the collaboration of various actors of building energy management ecosystem.

Research topics in this area include:

- Demonstrate the integration of Digital Twins into the microgrid (or Local Energy Communities) control to optimize its performance and supply information to complete the energy forecasting
- Develop solutions enabling a seamless and flexible integration of buildings into the energy grid as prosumers, taking into account the building users and occupants, and enabling energy transactions directly between prosumers
- Demonstrate the integration of communication and information infrastructures with optimised grid operation to support the development of technologies enabling demand response Develop frameworks for lean intervention on multiple buildings rather than implementing technologies on a single building, to improve building and grid performance
- Develop both standards and related solutions (hardware, software, related control systems, and interfaces) for seamless and easy plug-and-play cybersecure integration of buildings to the smart grid and district heating and cooling networks, to enable buildings act as prosumers without compromising the indoor conditions for building users and occupants
- Develop blockchain technologies to support communication and the decentralised energy trading (smart contracts), avoiding energy brokers as Distributed Ledger Technologies (DLT)
- Integrating novel big data technologies, analytics and algorithms with Building Energy legacy systems to support building renovation scenarios and proactive energy-wise maintenance support
- Developing novel collaborative business models driven by big data sharing and analytics services, benefiting the whole value chain of actors relevant to building energy management technological domains

6.2. City planning and real-time monitoring and management tools (incl. mobility and multi-management port hubs)

City planning is crucial for enabling cities to develop and thrive, while supporting the wellbeing of its citizens. Tools such as city information models and digital twins, fed with live data via IoT, can help planners and policy-makers to manage resources, enhance economic development, reduce ecological footprints and improve the overall quality of citizens' lives. Thanks to real-time data provided by sensor networks and intelligent systems, operations and maintenance of physical assets can be better optimised, as well as systems and daily processes of the city, from the integration of new constructions (taking into account their impacts on inhabitants) to mobility and traffic.

With regard to **urban planning**, high quality data (including real-time data) can be used to better inform decisions through decision support systems based on a quantitative approach, thereby providing support to architects and planners. Digital Twins allow cities to design buildings more accurately so as to avoid expensive modifications after the initial build, find more resilient ways to improve physical infrastructure to reduce the cost of emergency response and incorporate sustainable, holistic design choices to reduce the environmental impacts at city scale and increase its ability to adapt to climate change. This includes improving circularity, decarbonization, and the overall quality of urban living.

As for **mobility**, by 2050, European multimodal transport infrastructure network will ensure green, cost-efficient, inclusive, resilient and secure transport of goods and passengers through the High-Level Service Infrastructure (HLSI) concept spread out by urban mobility, multimodal hubs and long-distance corridors. Any transportation hub aim is to connect and centralize large, medium and short spokes in the most efficient way according to particular local constrains. Standardized regulations, interoperability codes and common KPIs can then help to optimise all activities along the lifecycle of those hubs. Under a common perspective, it is easier to share and implement best ideas for the next designs, optimising the whole Multi-Modal Transport Infrastructure Framework.

A transportation hub is also a data generator and a good mix between data management and geospatial distribution of different traffic flows. Investing on modelling the information that infrastructures hubs provide will enable to design and operate them in the most efficient manner. The use of BIM in the Transportation Infrastructures sector is growing rapidly, and we now speak of Transport Infrastructures Information Model (TIIM). A TIIM model acts as a geospatial virtual platform able to gather and process data through machine learning algorithms. It can contribute to the development of “info structures” leaning against physical HLSI, formed by an integrated set of information services for the passenger, providing a Facilities-Services continuum as well as ensuring quality of services for accessibility and affordability by all to high-quality services and HLSI.

It is easy to imagine how TIIM standardization and practices sharing would speed up the process of taking transportation hubs to a higher level of effectivity, i.e., High Level Service Infrastructure concept, to boost the economy by making all transportation processes more agile and effective.

Research topics in this area include:

Urban planning

- Develop city planning and real-time monitoring tools to enable added value services that satisfy emerging energy sector stakeholders needs and effectively contribute to the short-, mid- and long-term targets for a cleaner, more sustainable and more efficient building/district/city systems characterized by maximized RES integration, increased Energy Efficiency, enhanced Consumer Empowerment and Democratized Energy Markets
- Develop a decision support tool using high quality data for informed planning decisions
- Develop data analysis processes with Artificial Intelligence and Digital Twin, connecting buildings and personalised experience resource optimization (prosumers) to the city
- Design and test solutions for an interactive operation and management of city assets, using high quality data to support decision-making
- Deploy trust management platforms and services to ensure data security, anonymisation, secure (role-based) access, and compliance with GDPR and other data security standards and protocols

Mobility and multimodal transport hubs

- Develop advanced physical and digital infrastructure solutions as a support for new mobility services and solutions (cooperative, connected and automated mobility – CCAM)
- Develop Communication and Information Transport Systems using AI and ML for traffic management and monitoring systems in both urban and extra-urban areas
- Develop required communication infrastructure for real-time information and mobility services (e.g. in relation to network maintenance operations) to inform end-users on traffic

conditions, and suggest alternatives adapted to the mobility demands, based on co-modality principles

- Test construction alternatives and demonstrate how TIIM, used as a virtual environment, can help:
  - to improve new design (including underground and vertical design) and construction techniques for multimodal hubs,
  - to optimise the structure repair, maintenance and life extension processes
  - prefabrication and automatization processes
- Collect and share common practices on the use of TIIM models and the data collected, and provide benchmarking analysis and trainings to help to standardise their use among key national stakeholders, transportation operators, users and technology providers
- Propose new tools and trials to analyse whole-life/whole-system energy and carbon impacts, considering multimodal hubs as energy producer centres, to reduce energy use and carbon footprint
- Propose an adaptative design approach to provide flexibility services to reply to increasing demand of the population and climate change, and facilitate interoperability with other hubs
- Develop a scenario-based and modelling approach to assess the consequences of disruptive events, including preparedness, study of interdependencies, cascade effects
- Design and develop an easy to manage, practice-oriented tool for the identification and assessment of transport infrastructure vulnerabilities regarding man-made threats to strengthen the resilience of the European Transport Network against various man-made hazards
- Develop scenarios and propose methodologies and planning tools to increase resilience against terrorist attack in transit environments and station infrastructure (preparedness, prevention, mitigation, deterrence, robustness and recovery plans)
- Implement real-time data acquisition tool to prepare for disruption
- Develop fast & non-intrusive safety controls in accordance with ethics, health and privacy requirements: biometric identification, non-radioactive scanning and detection and identification of dangerous material

6.3. Digital tools to involve citizens in participative and adaptive urban planning & design and for stronger energy citizenship

When moving from smart buildings and infrastructures to smart districts and cities, interoperability and standardization are prerequisites for the integration of the Smart Buildings, and infrastructures, into their surrounding environments. While the technical solutions are ready to support this integration, critical challenges remain to overcome in privacy and data security as well as regarding European and local legislation, city policies and governance models. This requires holistic solutions beyond the technical ones and a multi-stakeholder dialogue. In short, how do we build trust and connect key stakeholders with services, built environment, and governance using secure digital technologies.

Research topics in this area include:

- Provide solutions for stronger democratic participation, energy citizenship and new energy communities
- Scaling up the use of digital systems to involve stakeholders and citizens in participative urban planning & design and to foster dynamic and participative urban planning for sustainable buildings. These should be tools fostering awareness, education and sense of belonging of citizens as members of the local community (including the accessibility to cultural heritage via virtual, augmented and mixed reality, and immersive technologies).
- Develop a new generation of digital tools, systems and applications to support new services for the citizen and the city (transport, health, car parks, waste management), with an enlarged involvement of stakeholders and citizens in monitoring and maintenance of the built assets

7. Objective 6: Support people-centric approaches

Digitalisation is a strong leverage for increased energy efficiency and sustainability in the built environment, improved quality of life for users and buildings occupants and added value for work performance, but only if smart solutions are correctly understood and adopted by the end users. While numerous smart solutions are being developed for the building sector, they are often designed following a technology-push approach, insufficiently taking into account the actual behaviours of users and buildings occupants, their expectations in terms of features and functionalities, but also their reluctance or fears related to Information technologies.

On another hand, the new digitalisation objectives require new skills, that are not usually found in current blue and white-collar staffs. This current lack of digital qualification in the workforce impedes the take up of digital technologies in the sector. There is a strong need to renew the full educational and professional pathway within the construction sector. A variety of EU funded projects is contributing to addressing the skills gap in construction industry, trying to up-skill the existing work force. However, the shortage of digitally skilled blue-collar construction workers, as well as high-trained IT experts should be tackled in the near future. Scientific profiles also need to be attracted. Solutions include making the professions safer and more attractive for youth and the female workforce, which potentially could close the gap of youth unemployment and inequality at the same time. The systematic identification of new roles and competencies, devised in a homogeneous EU-wide way as much as possible, will help to better define and integrate these new professionals.

Digital capabilities must be built, curricula and training techniques must be renewed, from state-of-the-art ICT tools (e.g. visualization, modelling) to historical building renovation. Life Cycle Thinking and asset management must be integrated in curricula through a cross-disciplinary approach. Beyond capacity building, all processes within the industry must initiate their transition towards more participative processes in order to retain workers and increase their commitments to quality and performance targets.

Objective 6 is transversal and a pre-requisite to the achievement of all objectives previously presented in this position paper. It covers the behaviours of building users and occupants, their expectations in terms of building features and functionalities but also the upskilling of the value chain in a holistic way: building up of digital skills, continuous improvement and self-learning as well as building more collaborative and participative way to work with clear commitments and responsibilities.

To support the upskilling of the value chain and the continuous improvement of the digital skills of all workers, the upcoming R&I activities should focus on the following three priority areas:

- **Meeting the end-users needs and requirements**
- **New academic curricula and training for digital skills in the construction sector**
- **Smart procurement/ bids**

These three R&I priorities are detailed in the next sections.

7.1. Meeting the end-users needs and requirements

Digital technologies allow interactions between the users and the built environment, either for an improved quality of life or for improved operation of the building and infrastructure. To maximise these effects, an iterative, human-centred approach must be employed, to understand the global challenges faced by society and the new end-users' behaviours (i.e., how people live, work and play) and to better engage with the end-users and provide services meeting their expectations. Such approach will help to foster the deployment and facilitate the market uptake of digital tools in the building sector.

Research topics in this area include:

- Define, combine and apply new methods and tools to design and deliver smart building systems ensuring the alignment between occupant-user needs and industry's perception of occupant-user needs
- Assess the impact of built environment intended functional use and design on occupants' needs
- Analyse the non-technical (legal and ethics) implications of integrating ICT technologies into smart home environments
- Co-design and test innovative solutions to promote occupational safety and health of construction workers
- Boost open and interoperable solutions to enable people to live independently in their own environment and to remain physically and mentally active as they age
- Redefine living environments and provide and test innovative tools and technologies to promote Out-of-Home Smart Mobility and Social Participation (aligned to New European Bauhaus initiative)
- Build the next level of perception, visualisation and interaction on smart buildings and users to enable users to take full advantage of the benefits that technology can offer, regardless of their age, race, gender or capabilities
- Integrate with building systems, solutions to collect human feedback on comfort perception all along the occupation phases in a non-disruptive manner
- Develop/upgrade tools and process to collect data on occupants' well-being: from non-intrusive sensors to smartphones and wearables, and upgraded post-occupancy evaluation framework
- Tackle human and data biases (race, gender, age, etc.) in AI technologies applied to smart buildings
- Deploy innovative systems to reduce power asymmetries on data management and citizen empowerment
- Co-design, test and deploy friendly interfaces and customised information systems to improve user experience and foster the use of user-centred tools.
- Co-design and test scenarios for healthy and active lives in public spaces and infrastructures
- Develop and validate digital solutions for participatory design, and operation of the built environment

7.2. New academic curricula and training for digital skills in the construction sector

A deep lack of digital qualification in the workforce impedes the take up of digital technologies in the sector: there is a strong need to renew the full educational and professional pathway within the construction sector, also to tackle the shortage of blue-collar construction while attracting scientific profiles. Solutions include making the professions safer and more attractive for youth and the female workforce, which potentially could close the gap of youth unemployment and inequality at the same time.

Digital capabilities must be built, curricula and training techniques must be renewed, including state-of-the-art ICT tools (e.g. visualization, modelling). Life Cycle Thinking and asset management must be integrated in curricula through a cross-disciplinary approach. Beyond capacity building, all processes within the industry must initiate their transition towards more participative processes in order to retain workers and increase their commitments to quality and performance targets.

Certification and accreditation schemes over the EU also need to recognise digital design leadership and encourage wide-range training of design construction workforce, to ensure that even the smallest design consultancies integrate such roles.

Research topics in this area include:

- Update or reinforce existing training schemes and platforms to take account of technical developments and innovation for the construction sector, including digitalization
- Develop new curricula with specific skills to tackle the cybersecurity and data privacy challenges
- Upgrade academic curricula in content (performance-based approach, new technologies for energy, health, resilience, LCA approach, asset management, BIM, smart construction, smart built environment, integrated approach to problem solving)
- Upgrade academic curricula in format, by integrating ICT tools (e.g. virtual reality to simulate situations and work on problem solving)
- Develop digital tools for self-learning and continuous improvement. For instance:
    - Develop virtual training environment for emergency response relying on DT-based hazard simulation and cascades effects
    - Digitalization of all construction processes (Data + AI) can give historic data to increase efficiency in all process in new job sites
    - Develop immersive capacitation with AR/VR tools to upskill the blue collars, train the workforce and improve safety
- Develop AI-based software solutions for Generative design to save design time on training and development and promote projects based on industrialised systems

7.3. Smart procurement/ bids

Procurement and tendering must be rethought and tested in the perspective of performance targets, proposing new ways of measuring or assessing performances. While the generalisation of BIM and other digital tools allows to implement more efficient management and procurement methods like Lean and IDDS (Integrated Design and Delivery Solutions[23]), these advances are still hindered by current rigid procurement mechanisms, very strictly regulated in most EU countries. Tendering processes should also:

- shift away from the systematic "lowest cost solution" priority and give more room to innovations with yet limited track records, contributing to accelerate their learning curve and reduce their cost,
- allow and encourage more participatory processes, engaging all the stakeholders in the production value chain at the very early stages of the design process.

Empowering early participation of technical and non-technical stakeholders across all lifecycle stages from design to operation via new procurement and tendering models will ensure common goals and shared benefits to be the drivers for collaborative and inclusive production of the built environment.

Research topics in this area include:

- Promote the use of data analytics and digital platform to facilitate tendering and construction processes
- Develop new approaches to improve the performance of public procurement process (speed of handling the process for instance with AI evaluation, increase quality, timing, efficiency).
- Demonstrate how digital innovation can support procurement and contracts: Micro-payments, automated payments with smart contracts, blockchain based platform/ marketplace
- Designing with the users: early integration of end-users in the design loop using ICT powered tools (BIM, Digital Twin) in new procurement processes (Integrated Design and Delivery Solutions)

[23] *See proposed definition in Glossary section*

8. Conclusion

8.1. Timing of the different R&I priorities

Members of the DBE Committee were asked about the most relevant scheduling for the above identified R&I activities, according to three time horizon: the next Horizon Europe's Work programme (2023-2025), the following one (2025-2027), or after the end of the current framework programme (beyond 2027).

The table below synthesises their views. The colour code is as follows:

>75% of votes	between 50 and 75% of votes	between 25 and 50% of votes	<25% of votes	No votes

Objective 1: Twin transition for life-cycle approach with value chain integration	2023-2025	2025-2027	Beyond 2027
Beyond BIM: tools for collaborative data-driven, whole-life performance-based design	>75% of votes	<25% of votes	<25% of votes
Dynamic, IoT/Web enabled Digital Twin for whole life cycle management of the built environment	between 50 and 75% of votes	between 25 and 50% of votes	No votes
Integration of AI and ML to enhance tools and models across the lifecycle of buildings & infrastructures	<25% of votes	between 25 and 50% of votes	between 25 and 50% of votes

Objective 2: Digitalised construction & renovation processes	2023-2025	2025-2027	Beyond 2027
Automation and mass-customisation of on-site manufacturing processes	between 25 and 50% of votes	between 25 and 50% of votes	between 25 and 50% of votes
Customised prefabrication and fully controlled off-site manufacturing	between 25 and 50% of votes	between 25 and 50% of votes	<25% of votes
Digital collaborative tools for deconstruction	between 25 and 50% of votes	between 25 and 50% of votes	<25% of votes

Objective 3: Smart operation and maintenance of buildings and infrastructures	2023-2025	2025-2027	Beyond 2027
Digital technologies portfolio for Smart asset management	>75% of votes	No votes	<25% of votes
Cost-effective solutions to upgrade the smartness of existing buildings and legacy equipment	between 50 and 75% of votes	<25% of votes	<25% of votes
Predictive/ remote maintenance and surveillance to increase the resilience of infrastructures	between 25 and 50% of votes	between 50 and 75% of votes	<25% of votes

Objective 4: Data governance, data access & security	2023-2025	2025-2027	Beyond 2027
Governance models for (cyber)secure data delivery across lifecycle and supply chain	between 25 and 50% of votes	between 25 and 50% of votes	<25% of votes
Interoperable open data standards	between 50 and 75% of votes	between 25 and 50% of votes	No votes
Open data models to enable the development of data-driven services	between 25 and 50% of votes	between 50 and 75% of votes	<25% of votes

Objective 5: Integration to the urban environment and to the grid	2023-2025	2025-2027	Beyond 2027
Digital solutions for the flexible integration of buildings to the smart grid and DH/DC networks, enabling new business models	between 50 and 75% of votes	between 25 and 50% of votes	No votes
City planning and real-time monitoring and management tools (incl. mobility and multi-modal transport hubs)	between 25 and 50% of votes	between 25 and 50% of votes	<25% of votes
Digital tools to involve citizens in participative and adaptive urban planning & design and for stronger energy citizenship	between 50 and 75% of votes	between 25 and 50% of votes	<25% of votes

Objective 6: Support people-centric approaches	2023-2025	2025-2027	Beyond 2027
Meeting the end-users needs and requirements	between 50 and 75% of votes	<25% of votes	<25% of votes
New academic curricula and training for digital skills in the construction sector	between 50 and 75% of votes	between 25 and 50% of votes	No votes
Smart procurement/ bids	<25% of votes	between 50 and 75% of votes	<25% of votes

8.2. Synergies between the DBE position papers and other ECTP committees

The digital transformation needs are embedded in all the dimensions of the construction and build environment processes. The DBE Committee is, in this sense, interlinking all related needs from other ECTP´s Committees and playing as a broker between ECTP and its Committees, on one side, and the ICT stakeholders, in particular interacting with AIOTI[24], the other manufacturing and ICT-oriented PPPs and other European ICT platforms. The DBE committee executive board and the dedicated working group assembled for this paper integrate stakeholders from all the other ECTP Committees aligning positions and articulating the different perspectives needs.

The main digitalisation needs, and priorities, identified by each of the ECTP committees in their position papers are summarised in Figure 4. In this paper, the DBE committee looks for the needed developments and adaptations of the digital technologies in order to fill these needs and priorities.

	Energy Efficient buildings	Digital built environment	Material & sustainability	Built4Life	Heritage & Regeneration	Infrastructure & mobility
Infrastructure & mobility	Climate mitigation Energy integration & management	Inclusiveness Asset management Skills & safety Strategic planning	Resilience & climate mitigation Circularity	Inclusiveness & accessibility	Cross-impact assessment	
Heritage & Regeneration	Retrofitting solutions & skills	Inclusiveness Digital preservation Retrofit & Maintenance	Resilience & climate mitigation Circularity	Comfort & accessibility Regeneration		
Built4Life	Quality of life Energy communities Biodiversity	Quality of life Inclusiveness & adaptation Smart places	Inclusiveness & adaptation Indoor env. quality Climate adaptation			
Material & sustainability	Retrofit, RES, CCUS Circularity	Construction & renovation processes, incl. circularity				
Digital built environment	Smart buildings Skills & safety					
Energy Efficient buildings						

Figure 4 Synergies between ECTP Committees

The use of digital technologies for smart operation and maintenance, performance monitoring, diagnostic and optimisation is seen as a priority for materials, infrastructures, energy efficiency in buildings as well as to preserve our cultural heritage.

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[24] AIOTI – Alliance for Internet of Things Innovation (https://aioti.eu/)

BIM- based-technologies, data and platforms are seen, by all committees, as critical enablers for the digital transition, facilitating not only information management but also stakeholder's dynamics along the value chain and performance-based contracting, as well as supporting inclusiveness of the built environment.

For the cultural heritage the development of dedicated digital technologies, for the restoration, maintenance and management projects, brings improvements of the conservation conditions, including for conservation works of inaccessible sites. In addition, these novel technologies can increase the interaction of citizens with the city parameters and cultural assets.

A smart management of transport infrastructure and the use of digital technologies for the integration with mobility services will increase safety / security, predict events, failure and cascade effects while increasing performance and user satisfaction.

8.2. Link with other initiatives

The topics proposed in this Position Papers are aligned with:

- The European Commission staff working document on Scenarios for a transition pathway for a resilient, greener and more digital construction ecosystem
- The Alliance for Internet of Things Innovation (AOITI)
- The High-Level Construction Forum (HFLC - working group on digital transition pathway for the EU construction industry ecosystem)
- The Building Digital Twin Association (BDTA)
- *The International Council for R&I in building and construction – W78 Information Technology for Construction (CIB W78)*