# Developing a Framework for Circular Economy Products and Processes within the Construction Industry

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*Abstract*— **This article presents a framework that will bring a new perspective to circular economy products and processes within the construction industry. The framework will utilize Federated Enterprise Architecture approach that is traditionally used in the aerospace, automotive, and oil and gas industries, for built environment needs. The framework will address 5 main objectives : i) to analyze and develop a decentralized Federated Framework for construction and renovation processes; ii) to optimize the re-usability and recycling of building materials and components; iii) to investigate the validation process for framework solutions across large-scale pilots in diverse contexts ; iv) to promote and implement innovative tools for stakeholder collaboration and green finance integration; and v) to provide guidance for policy, standardization, and stakeholder adoption. This article acts as prerequisite to prepare the construction industry for transition to Federated Enterprise Architecture practices.**

***Keywords – Federated Framework; interoperability; adaptability; re-use and deconstruction of buildings, life cycle assessment; construction and renovation, circular economy; pilot studies***

## I. Introduction

This article is a technical advancement of a published conference paper: ‘MODERN SYSTEMS 2025’ article "A Framework for Adaptability, re-use and Deconstruction of Buildings, Aligned with the Principles of Circular Economy"[1]. In this article the reader will understand how previous model representation projects supported the development of MBSE tools and techniques. Furthermore, the attributes of Federal Enterprise Architecture Framework (FEAF) is identified to demonstrate future architecture interface requirements, while also defining matrix criteria that aligns with the architecture types. Moreover, in this article the demonstrations are further developed and cross referenced to the case studies. In addition, this article presents the ‘Tools Evaluation and Holistic Impact Assessment’ platform that summarizes the what-if scenario analysis to meet the clients requirements.

It is estimated that half of the total $CO_2$ emissions of a building arise during the construction process and the production of the material components. Furthermore to reduce the construction industry’s contribution to global warming, its immediate decarbonisation is necessary and cannot only depend on incremental $CO_2$ savings over the life cycle of a building but must include the planning and construction process. There is growing acknowledgement for circular construction as a means to develop, use, and re-use buildings, sites and infrastructure without unnecessarily exploiting natural ressources, polluting the environment and damaging ecosystems [2]. Moreover, The European Environment Agency recognizes that “almost 75% of the building stock is currently energy inefficient and more than 85% of today's buildings are likely to still be in use in 2050. Energy renovation of buildings is ongoing but at a very slow rate”[3]. In addition, ‘Ecochain’ has identified that in many industries, the supply chain accounts for more than 80% of the environmental impact and in addition the supply chain managers that source from different suppliers contribute to a massive impact on their product footprint [4]. In 2018, ‘The European Commission’ led an intiative to focus on supporting regions and EU countries to develop national bioeconomy strategies that will enhance knowledge on biodiversity and ecosystems, monitor progress towards a sustainable bioeconomy, promote good practices to operate the bioeconomy and enhance the benefits of biodiversity. In order to unlock investments and markets, the commission mobilised stakeholders in developing sustainable biobased solutions while launching a €100 million circular bioeconomy thematic investment platform [5]. According to the World Economic Forum ‘Bioeconomy is emerging as a transformative force for sustainable development, leveraging biological resources and innovative technologies to address global environmental challenges [6]. Building upon these challenges and initiatives there is a growing need for solutions that extend the service life of buildings, support material reuse and recycling, and improve stakeholder collaboration through shared data and digital tools. This article outlines the development of a Federated Enterprise Architechure framework for developing solutions, methods and processes to meet the outlined objectives and align with the European Comission’s Built4People Partnership [7] contributing to : (1) Increased adaptability of buildings, (2) Reduction of Waste, (3) Support for local and regional economic development, and (4) Policy evolution. The article has three main sections covering the design of the framework (objectives etc.) in Section II, the methodology in Section III and Section IV highlights the potential demonstrations. The acknowledgement and conclusions close the article.

## II. Designing a Framework

The main goal of the framework is to deliver a comprehensive and sustainable framework for circular construction and renovation, ensuring adaptability, reuse, and deconstruction of building components while minimizing environmental impact and maximizing stakeholder value. The outcome is an innovative approach that integrates digital technologies, advanced processes, and novel materials into an interoperable and decentralized Federated Framework for (de)construction and renovation. This framework shifts away from monolithic, proprietary systems and creates an interconnected ecosystem where tools, platforms, and processes maintain autonomy while contributing to a unified, efficient workflow. The Federated Framework is designed to support decision-making across all stages of a building's life cycle from design and construction to reuse and deconstruction. Moreover, at the centre of the framework is Model-Based Systems Engineering (MBSE).

According to [8] MBSE is a paradigm that uses formalized representations of systems, known as models, to support and facilitate the performance of Systems Engineering [SE] tasks throughout a system's life cycle. In addition, [9] acknowledged that "Models are representations that are used to capture, analyze, and/or communicate information about a system or concept. They can vary in scope, purpose, and type, and can be utilized both individually as stand-alone entities as well as in concert with each other as part of an integrated set." [10] The CLARITY project is recognised for developing and structuring an international ecosystem to support open innovation in the domain of MBSE. Furthermore, the Capella open-source tool that was provided for the project was a Thales initiative that had been developed in house, and deployed in various Business Units. It was implemented as a key solution for complex systems design providing "technological breakthroughs for MBSE, methodological support and guidance for systems engineers through the underlying integrated methodology Arcadia." Since the CLARITY project in 2015, the Capella open-source tool and Arcadia methodology have advanced to be a global leader in defining, analysing, designing & valiadting System, Software, and Hardware Architecture.

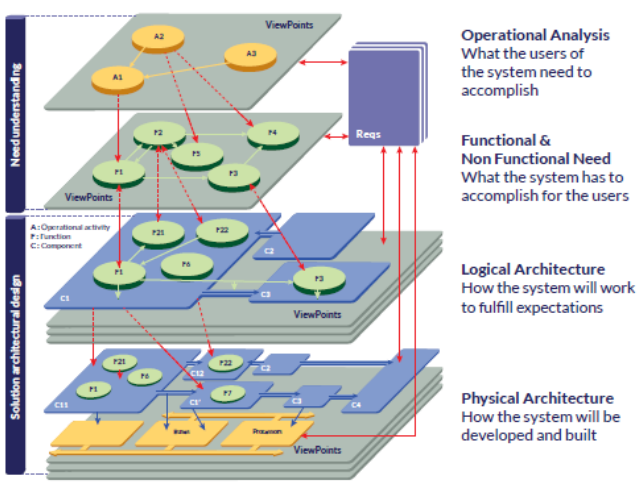


Figure 1. MBSE – The Arcadia Perspectives [11]

Figure 1 illustrates the operational needs and system needs analysis viewpoints against the 'need understanding', and the logical architecture and physical architecture against the solution architecture design. The Federated Enterprise Architecture approach will utilise the Capella open-source tool and Arcadia methodology to validate/justify solutions against operational needs, requirements and impact anaysis.

In reference to the foundation of Architecture Frameworks, in September 1999, the Federal CIO Council published the FEAF, Version 1.1. The purpose of Version 1.1 was for developing an Enterprise Architecture (EA) within any Federal Agency or for a system that transcends multiple inter-agency boundaries. Moreover, common business practices and designs were incorporated while providing standards for developing and documenting architecture descriptions of high-priority areas. Figure 2 shows the FEAF partitions as a given architecture into business, data, applications, and technology architectures. It was also acknowledged that the FEAF included the first three columns of the Zachman framework and the Spewak EA planning methodology [12].

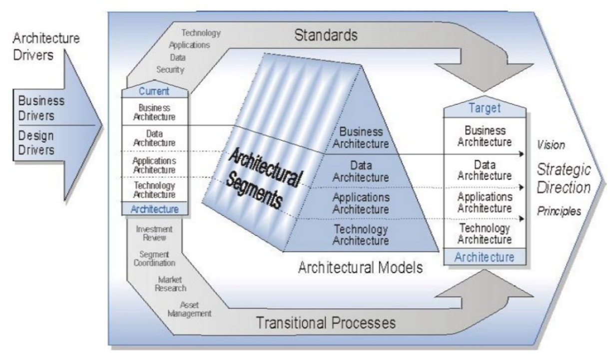


Figure 2. Structure of the FEAF Components

The goal of the Federal CIO Council was to "develop, maintain, and facilitate the implementation of a top-level EA predicated upon the FEAF". The objective of the architecture was to serve as a reference point to facilitate the efficient and effective coordination of common business processes, technology insertion, information flows, systems, and investments among Federal Agencies. Figure 3 illustrates the 3x5 matrix that graphically aligns with the architecture types (Data, Application, and Technology) on one axis of the matrix, and perspectives (Planner, Owner, Designer, Builder, and Subcontractor) on the other.

| | Data Architecture | Application Architecture | Technology Architecture |
|---|---|---|---|
| Planner Perspective | List of Business Objects | List of Business Processes | List of Business Locations |
| Owner Perspective | Semantic Model | Business Process Model | Business Logistics System |
| Designer Perspective | Logical Data Model | Application Architecture | System Geographic Deployment Architecture |
| Builder Perspective | Physical Data Model | Systems Design | Technology Architecture |
| Subcontractor Perspective | Data Dictionary | Programs | Network Architecture |

Figure 3. FEAF Architecture Matrix

In the authors' opinion, the FEAF cleared the way for future framework excellence such as The Modular Open System Archiecture ecosystem [13] that involves many areas in enegineering across the system life cycle, in particular acquisition program that considers : **plan** – the MOSA strategy with defined objectives ; **modularize** – by decomposing system capabilities into functional modules ; **specify interfaces** – by identifying connections between system building blocks ; **define interfaces** – specifications by capturing how functional modules interact ; and **standardise interfaces** – specifications to allow for opportunities of future mondernisation. It was these considerations that were acknowledged as best practices for this articles **Federated Enterprise Architecture.** The following sections address the overall components of the Federated Enterprise Architecture.

## A. *Objectives and Ambition*

The overall objective is to deliver a more sustainable framework for circular construction and renovation, ensuring adaptability, reuse, and deconstruction of building components while minimizing environmental impact and maximizing stakeholder value. The project proposal leverages cutting-edge digital technologies, advanced methodologies, and innovative materials to align with the European Union's goals for a sustainable, people-centric built environment. The framework adopts a holistic and decentralized approach, integrating federated architectures, life-cycle-based methods, and participatory design processes to address the challenges of resource efficiency, carbon reduction, and material circularity. This vision is realized through a suite of interoperable tools, validated across diverse geographical and climatic contexts. The Strategic Objectives (SO) that will enable the achievement of the framework are described below:

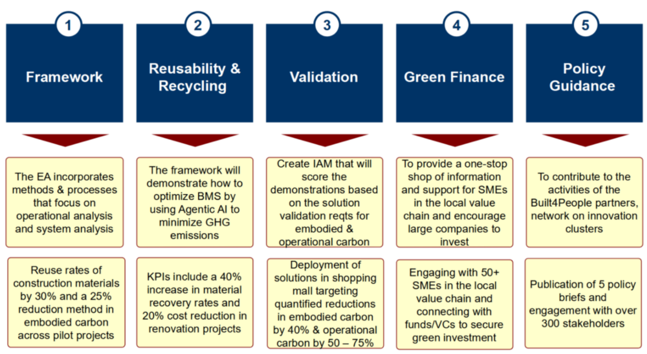


Figure 4. The Requirements and Measurements – 5 Objectives.

*a) To analyze and develop a decentralized Federated Framework for construction and renovation processes (objective 1):* This objective focuses on creating an interoperable architecture that integrates advanced digital solutions, such as graph technology, Digital Twins (DTs), and blockchain-based systems. The federated framework facilitates interoperability and information sharing between semi-autonomous de-centrally organized Line of Businesses (LOBs), in particular reference to AI & Agents.

*b) To optimize the re-usability and recycling of building materials and component (objective 2):* The framework will enhance the traceability and performance of sustainable materials, prioritizing bio-based, CO2-storing, and modular solutions such as, the use of waste wood, bio-based insulation, Supervisory Control and Data Acquisition (SCADA) controls, Heating, Ventilation, and Air Conditioning (HVAC) for energy management systems, and product inventories for supply chains. Through advanced Life Cycle Analysis (LCA) and predictive maintenance tools, the framework will establish best practices for disassembly and reuse, enabling a shift towards a circular construction model.

*c) To investigate the validation process of the Framework solutions across large-scale pilots in diverse context (objective 3):* Two pilot sites across Portugal and Slovenia, and one virtual pilot study (referring to test simulations for example interoperability issues of shared models) between Romania and Denmark, will perform the adaptability and performance analysis of the Federated Framework under real-life and close to real life conditions. These pilots will focus on delivering test solutions in residential and non-residential settings, enhancing adaptability, resource efficiency, and scalability.

*d) To promote and implement innovative tools for stakeholder collaboration and green finance integration (objective 4):* This objective involves creating a virtual living lab and green finance platform to connect investors with sustainable building initiatives. It integrates digital building logbooks and financial models to enhance the scalability and economic viability of circular practices. The outcome is to provide support and knowledge on investment opportunities, such as 'Growth and Income Fund' [14] and 'Feeder Fund' [15] as investment vehicles to provide capital from different investors and sources.

*e) To provide guidance for policy, standardization, and stakeholder adoption (objective 5):* The framework will deliver actionable recommendations for regulatory bodies, certification authorities, and industry stakeholders to support the standardization and scaling of circular construction practices. Moreover, the framework will engage in 6 key stewardship of activities such as: standard identification and monitoring; collaboration with standards and policy bodies; gap analysis and recommendations development; advisory policy framework working group; workshops and stakeholder engagement; and policy briefs and contributions, that will increase awareness on best practices for design, adaptability, reuse and deconstruction.

Table I explains the various challenges that will be applied to each objective and its evaluation defined through measurement.

TABLE I. REQUIREMENTS & MEASUREMENTS

| ***Evaluation*** | | |
|---|---|---|
| ***Objectives*** | ***Requirements*** | ***Measurable Key Performance Indicators (KPIs)*** |
| 1: Frame-work | The Enterprise Architecture incorporates methods and processes that focus on operational analysis – what the stakeholders need to accomplish and system analysis – what the system has to accomplish for the stakeholders. | KPIs include increased reuse rates of construction materials by 30% and a 25% reduction in embodied carbon across pilot projects. |
| 2: Re-usability & Recycling | The framework will demonstrate how to optimize Building Management Systems (BMS) by using Agentic AI to minimise GHG emissions during the full building operational life cycle that are essential for maintaining high levels of user comfort and well-being, which directly translate into high User QoE (Quality of Experience) KPIs. | The challenges that exist particularly for building systems is that electronic systems or products such as consumer products become obsolete long before the device wears out or fails and are simply discarded and sent to landfill. KPIs include a 40% increase in material recovery rates and a 20% cost reduction in renovation projects. |
| 3: Validation | After the demonstrations the framework will create Impact Assessment Methodology (IAM) that will score the demonstrations based on the solutions validation requirements for both embodied and operational carbon. | KPIs include successful deployment of solutions in a shopping mall in Portugal with a total area of ~200,000 m2 that hosts over 150 stores on 5 floors and a small site 40 m² of built space targeting quantified reductions in embodied carbon by 40% and operational carbon by 50 – 75% respectively. |
| 4: Green Finance | The overall objective for framework is to provide a one-stop shop [16] of information and support for SMEs in the local value chain but to also encourage larger companies to invest in disruptive technologies. | KPIs include engaging 50+ SMEs in local value chains and connecting them with funds/Venture Capitalists (VCs) to secure green investments. |
| 5: Policy Guidance | The framework will contribute to the activities of the Built4People partners and to the Built4People network on innovation clusters through the achievements of the demonstration. | KPIs include the publication of 5 policy briefs and engagement with over 300 stakeholders. |

## B. The Scope of the Framework

The Federated Framework consists of 16 interconnected modules that encompass key enabling tools, processes, and methods. These include advanced IT solutions such as graph technologies, digital twins, distributed ledger systems (blockchains), and Common Data Environments (CDEs), as well as methodologies like LCA, MBSE, and business process mapping. Each module addresses specific aspects of circular construction, such as material traceability, predictive maintenance, and user-centric design.

TABLE II. FRAMEWORK: INNOVATIVE TOOLS, PRODUCTS & TECHNIQUES, PROCESS & METHODS

| **Framework** | | |
|---|---|---|
| ***Innovative Tools (INNT)*** | ***Products and Techniques (P&T)*** | ***Process and Methods (P&M)*** |
| INNT1) AI, IoT and Agents for BMS | P&T1) Digital Building Logbooks including DPP, BRP and MP | P&M1) Buinsess Process Mapping |
| INNT2) Graph Technology | P&T2) Security Transactions including Data Encryption, and Payments Certs (eIDAS) etc. | P&M2) Life Cycle Analysis including SCBA |
| INNT3) Large Language Models including LangChain - GenAI, and Chat models | P&T3) Open Source: Open LCA and Open API | P&M3) Federated Architectures including Linked Data CDE |
| INNT)4 Digital Twins, BIM and GIS Platform | P&T4) Semantic Analysis Techniques, RAG and Indexes | P&M4) MBSE |
| INNT)5 Distributed Ledger Technologies / Blockchains | | P&M5) ETL Data Integration |
| INNT6) Preventative and Predictive Maintenance - RAM | | P&M6) Real-Time Linked Data Space |

a. Legends (Digital Product Passport – DPP; Building Renovation Passport – BRP; Material Passport – MP)

The semi-autonomous federated systems architecture will support State of the Art LOBs that uniquely provide solutions and by integrating them with products, techniques, processes and methods they will pioneer co-creation (see Table II). Furthermore, the pilot studies will transition the Use Cases (see Table IV), which are bundle of selected technology advancements, products, techniques and methods & processes from Table II at the demonstrations initial conceptual stage to an advanced operational development stage based on constant evolution and learning. Moreover, using the Federated Architecture will present simulations of the decentralized platforms' abilities to connect with each other in a “common data-space” of open collaboration pooling of information. At pilot level, the framework will encapsulate three very different pilot studies, for which two of them are very much real-life scenarios representing residential (Slovenia) and non-residential projects (Portugal). The other Pilot study comprises of two countries (Denmark and Romania) working on virtual models to test their CDE platforms and interoperability. The impact of these Pilot studies will be evaluated at city council level in the Ukraine to provide added value to the project circular economy results.

# III. METHODOLOGY

The methdology section comprises of four sections addressing an exploratory research stage; i) the framework vision, ii) the process, iii) the phases, and iv) the use cases.

## A. The Frameworks Vision

The framework’s vision is the development of products/materials/services including those that contribute to disassembled and reused, and CO2-storing materials etc. and also the cyphering of materials via Graph Technology. Moreover Graph Technology (ISO/IEC 39075:2024) Information Technology, Database Languages and GQL defines data structures [17]. The framework will provide structured and unstructured data from existing Relational Database and web services such as ECO Building Materials Suppliers Catalogs, deconstruction – reuse warehouse of materials, certified environmental product declaration catalogs and product environmental profiles in compliance with ISO 14025 standard [18], community engagement platforms, European circular economy stakeholder platforms, and environmental monitoring and IoT platforms.The integrating advances of bio-based materials manufacturing technology for example Ceramics and Glass and the use of digital solutions (AI, property and Knowledge Graphs (KG), Large Language Models (LLMs), Retrieval-Augmented Generation (RAG), LangChain) with economy principles, i.e., targeting VCs, Angel funds to provide investment opportunities to enterprises that develop and reuse, deconstruction materials in a life-cycle optimization and circular economy perspective, will offer solutions that not only mitigate environmental impacts, but also drive economic growth and societal well-being.

## B. *The Process*

The goal of the framework is to bring a new perspective to circular economy products and processes. However, fostering strategies and roadmaps is not enough and the framework will utilize Federated Enterprise Architecture approach that is traditionally used in the aerospace, automotive, and oil gas industries, for built environment needs.

Figure 5 illustrates the use of MBSE, which is a process offered in the framework to define the solution design. The pilot studies will transition from the initial conceptual stage (pilot study demonstrators original assumptions) to an advanced operational development stage based on constant evolution and learning. In the context of the framework, Figure 5 defines the solutions need analysis, it is an integrated systems open architecture identifying components (e.g., material providers), functions (e.g., supply chain), and exchange items (CO2 carbon content, policies, predictive & preventive maintenance, etc.) pooling of information.

In comparison to traditional architectures that highlight connections of how various components such as ontologies are used and interchanged with semantic platforms and where over ambitious proposals identify lots of connected applications, the framework project builds on a system design approach. It will promote iteration to accommodate the pilot studies' ever changing needs. In addition, new knowledge through the project's evolving research techniques can be implemented and tested to provide better practices and recursion to reach a level to finalize market readiness. Such analysis captures opportunities for disruptive and innovative solutions, processes and methods.

Furthermore, the Market Key Results Investment Platform, New Business Models, and Policy Recommendations will build upon private investments initiatives such as SMEs involvement in the project. Their presence shall extend contribution measures to local and

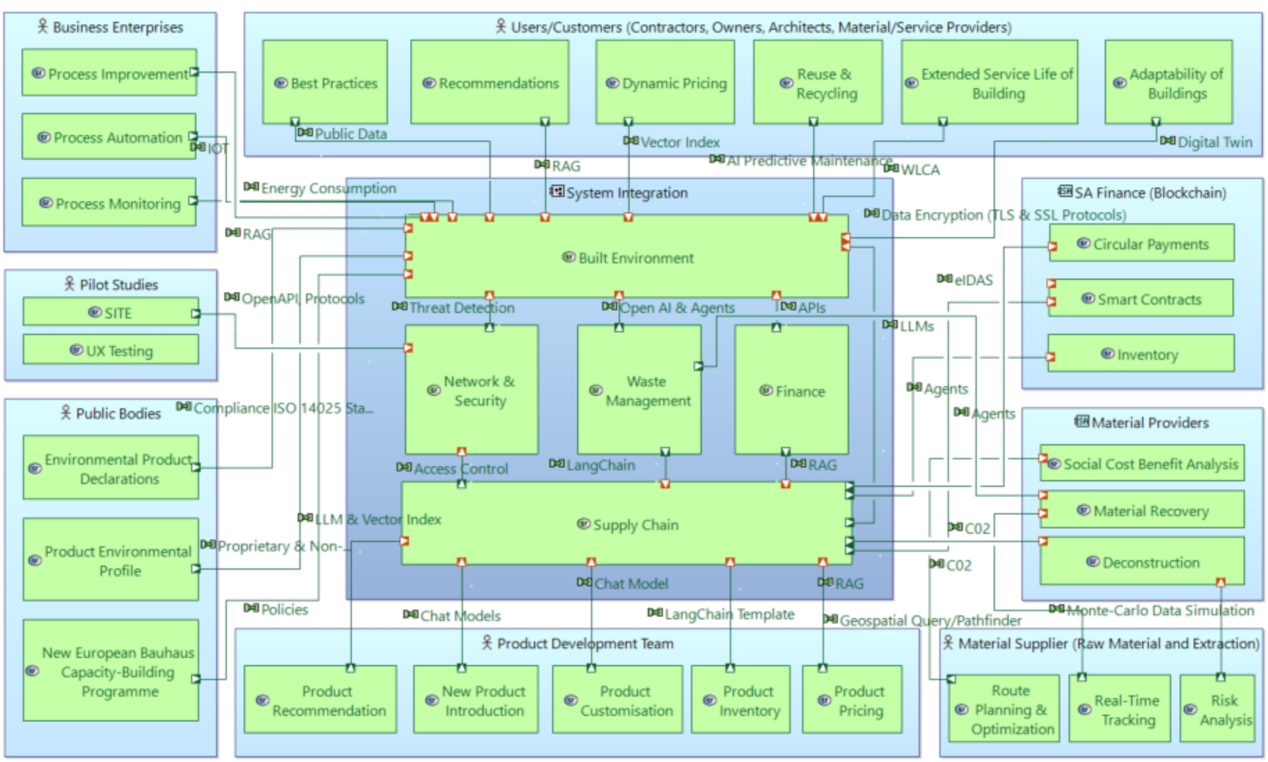


Figure 5. The Framework MBSE for Federated Enterprise Architecture.

regional value chain approaches, in order to increase innovation buy-in from users. This initiative has driven the proposal to focus on leveraging green finance investment and creating Scale & De-Risk Accelerators for bio-based materials and products (financial simulations). The impact is to not only provide sustainability, standardization, and governance but to also deliver a shared digital connected infrastructure for supporting decision makers with real monetary opportunities 'Bankability' reflecting and helping the circular economy.

### C. *The Phases*

To successfully demonstrate this concept and enable a posterior replication of the results obtained within such a project, a clear and well-defined methodology has been defined, which consist in the following 5 phases: Operational Analysis – Define Stakeholder Needs and Environment; Solution Analysis – formalize solutions requirements; logical architecture – develop solutions logical architecture; physical architecture – develop solutions physical architecture; and End Product Breakdown Structure (EPBS) – formalize solutions component requirements. The process of the 5 phases are captured visually in Figure 6 and explained in more detail via the following text.

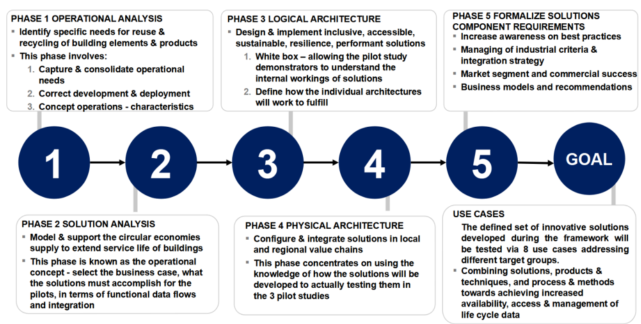


Figure 6. The Five Phases.

*a) Phase 1:* Identify specific needs for reuse & recycling of building elements and products (Operational Analysis) - this phase involves establishing the project's base-line while capturing and consolidating operational needs from the stakeholders for correct development and later deployment of the solutions. Moreover, it can be related to "Concept operations" where assumptions on the characteristics of the pilot studies have been made.

*b) Phase 2:* Model and support the circular economies supply to extend service life of buildings (Solution Analysis) - the data from P1 will contribute to P2 development of a Federated Architecture framework enabling the adoption/adaption of the existing methods and processes by identifying the boundary of the solutions, processes and consolidate the requirements. This phase can be referred to as the "operational concept" stage. The progress is more precise for individual pilots such as defining the business case, what the solutions must accomplish for the users, while also modeling functional data flows and dynamic behavior for integration approaches aligned with federated CDE and innovative tools. Whereas the previous phase investigates the overall intent of the pilot studies, OpsCon identifies what they will do (ISO/IEC/IEEE29148) [19].

*c) Phase 3:* Design and implement inclusive, accessible, sustainable, resilience, performant (energy, cost, etc) solutions for the built environment (Logical Architecture) - P3 represents a "white box" where models, methods are designed to be transparent, allowing the pilot study demonstrators to understand the internal workings of solutions. This phase built upon the information of P1 and the process and architecture of P2, will provide visibility into the pilot studies decision-making process, making it easier to identify the key features and rules contributing to their development. Moreover, P3 will define how the individual architectures will work to fulfill expectations such as the successful deployment of solutions to prove their capability.

*d) Phase 4:* Configure and integrate solutions in local and regional value chains (Physical Architecture) - P4 concentrates on using the knowledge of how the solutions will be developed to actually testing them in the 3 pilot studies. These 3 pilot studies consist of collecting real data from the field and deploying the practices to be replicated solutions, products, techniques, methods and processes based on platform assessment in the Ukraine (similar to the DAREED platform [20]). All specifications of interfaces deployment configurations, trade-off analysis of the integrated solutions is tested and evaluated.

*e) Phase 5:* Increase awareness on best practices for design for adaptability, reuse and deconstruction – the managing of the industrial criteria and integration strategy based on the impact outcomes of the pilot studies are assessed for market segment and commercial success. In addition, the outreach of solutions are analysed and considered to propose business models and recommendations to legislators.

### D. *Use Cases*

The defined set of innovative solutions developed during the framework will be tested via 8 use cases addressing different target groups. Use cases will represent an already proven concept for the viability of combining these solutions, products & techniques, and process & methods towards achieving increased availability, access, and management of lifecycle data in the built environment. These use cases are one of the cornerstones of the project, as its conception fosters replication, bringing framework to a larger public and set of users.

Table III maps and aligns with Table II Framework: Innovative Tools, Products and Techniques, Process and Methods, including Markets where the 8 Use Cases provide a combination of the frameworks modules for selection during the pilot studies, i.e., several modules can be applied to each UC.

TABLE III. SET OF INNOVATIVE SOLUTIONS DEVELOPED & TESTED

| Use Cases | | Innovation Tools | | | | | | Products and Techniques | | | | Process and Methods | | | | | | Markets | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | P&T1 | P&T2 | P&T3 | P&T4 | P&M1 | P&M2 | P&M3 | P&M4 | P&M5 | P&M6 | M1 | M2 | M3 |
| **UC1** | Circular Construction and Reuse Framework | | X | | X | | | | | | X | X | X | | | | | | X | X |
| **UC2** | Digital Platform | | X | | X | | | | X | | | | | X | | X | X | | | |
| **UC3** | Real-Time Linked Data-Space | | X | | X | | | X | | | | | | | | | X | | | |
| **UC4** | RAM Knowledge Platform | X | | | | | X | X | | | | | X | | | | | | | |
| **UC5** | Cybersecurity and Supply Chain Transparency | | | | | X | | | X | | | | | | | | | | | |
| **UC6** | LCA Models for Renovation Planning and Design | | X | X | X | | X | X | X | X | | | X | X | X | | X | | | |
| **UC7** | Operational Carbon Management Systems | X | X | | X | | X | X | | X | | | | X | X | | X | | | |
| **UC8** | Accelerator for Green Finance Investments | | X | | X | X | | X | X | | X | X | | | | | | X | X | X |

According to the American psychology Professor Howard Gardner of Harvard University, the brain functions using mutiple intelligences and as we are living in the Age of Intelligence, in which multiple intelligences rule, in order to perform effectively and productively in life as well as business we need to pay heed to this and develop 'intelligent strategies' [21]. Figure 7 is an all-embracing visual and graphic thinking strategy that is complementary to both Table III and chosen UC Tables V to VII. It expresses the UCs in a chronological order and harnesses the main business practices, problem solutions and strategies addressed in their descriptions. In essence it is a 'visual summary' of these Tables, created as a technique to help the thought process pertaining to the UCs.

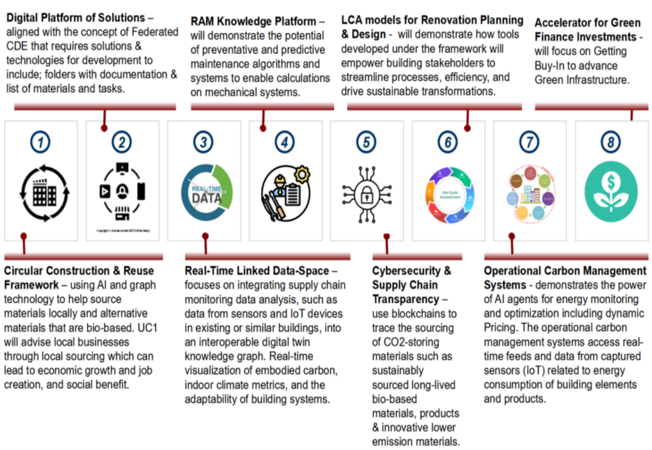


Figure 7. The proposed Solutions, Products & Techniques, and Process & Methods.

Table V provides compartmentalized descriptions of the 8 UCs aligned to Figure 7. The pilot studies will choose the most appropriate UCs to meet their require requirements. The process is similar to an inventory management system but each UC is a unified process containing the proposed Solutions, Products & Techniques, and Process & Methods where the users can bundle the attributes of several UCs in order to achieve the best results for their demonstrations.

TABLE IV. EIGHT USE CASES

| A Combination of Framework Modules | |
|---|---|
| ***Use Cases*** | ***Proposed Solutions, Products & Techniques, and Process & Methods*** |
| UC1 | *Circular Construction and Reuse Framework*: demonstrates different circular and sustainable building solutions to make building and infrastructure better, e.g., following circular and sustainability requirements such as design for adaptability, re-use, and durability. Using AI and graph technology (tracking) UC1 will help source materials locally that travel shorter distances, consuming less fuels and fewer carbon emissions. The preference will be to source reused materials or alternatively materials that are bio-based. UC1 will advise supporting local businesses through local sourcing which, can lead to economic growth and job creation, and social benefit. In addition, the sourcing of financing mechanisms, green insurance and micro-credit for sustainable development via Carbon Platform will provide enterprises with incentive to adapt to greener solutions connected to green finance thus providing a win-win situation. |
| UC2 | *Digital Platform of Solutions*: aligned with CDE to improve collaboration, planning, management and automation within construction projects. The concept of Federated CDE is connected to the project's overall methodology of Federated Architecture Approach. The platform functionality for the framework requires solutions and technologies for development to include: i) folders with documentation, ii) a platform providing a list of materials and tasks, while also mapping to standards where all materials and tasks are awaiting for implementation in the early phases such as selected bills of materials and structures by assemblies. In addition, functions that can provide business intelligence reporting of sales and inventory while also connecting the quantified data with processes that have been identified as a bottleneck. |
| UC3 | *Real-Time Linked Data-Space* [22] [23]: use case focuses on integrating supply chain monitoring data analysis, such as data from sensors and IoT devices in existing or similar buildings, into an interoperable digital twin knowledge graph. This integration supports real-time visualization of embodied carbon, indoor climate metrics, and the adaptability of building systems. The focus of this approach is on optimizing supply chain processes to align with circular economy objectives. Knowledge graphs further enhance this system by linking data on materials, supply chains, environmental performance, and stakeholder roles, thereby enabling informed decision-making. Financial tools, such as agents for circular payments, product pricing, and commercial contracts, ensure that supply chain operations align with circular economy principles. |
| UC4 | *RAM Knowledge Platform* [24]: will demonstrate the potential of preventative and predictive maintenance algorithms and systems to enable calculations on mechanical systems incurred by wear from the moment they are activated. The RAM knowledge platform identifies the useful service life of a system, product, or service by applying real-time monitoring against the preventative and predictive models, extended by proactive, Just-in-Time (JIT) sequence of preventive and corrective maintenance actions and upgrades. The RAM knowledge platform supports information/calculations on system configuration identification elements such as existing, internally developed, reusable components that may consist of Commercial Off-the-Shelf (COTS) products, and Non-Development Items (NDP – hardware and software configuration). Such processes are aligned with early defects detection "Poka-Yoke" [25] and reduce electronic and mechanical materials sent to landfills. |
| UC5 | *Cybersecurity and Supply Chain Transparency*: use case reflects how blockchains will trace the sourcing of CO2-storing materials such as sustainably sourced long-lived bio-based materials and products and innovative lower emission materials/aggregates. In fact each transaction or exchange of |

| A Combination of Framework Modules | |
|---|---|
| ***Use Cases*** | ***Proposed Solutions, Products & Techniques, and Process & Methods*** |
| | information is recorded in a "block", which is then validated by network members before being added to the existing chain. Once validated, information becomes immutable and traceable. This technology offers unique guarantees in terms of security, transparency and traceability of exchanges, without the need for a centralized trusted intermediary. In UC5 Blockchains will create digital "product passports", containing all the information on a product's composition, manufacture and use. Furthermore according to [26] the concept of "decentralized AI" (DeAI) envisions open source, transparent AI through several blockchain technologies. Decentralized storage and distributed computing networks enhance data integrity, while smart contracts ensure transparent model access and tracking. |
| UC6 | *LCA models for Renovation Planning and Design*: use case will demonstrate how tools developed under the framework will empower building stakeholders to streamline processes, enhance efficiency, and drive sustainable transformations. CO2 studies can be directly imported into openLCA [27] and standard LCA repositories, enabling UC6 users to assess flows and processes in their impact evaluations. UC6 will store all relevant data on a platform incorporating Digital Building Logbooks, which include Building Renovation Passports, BIM-based information, DPP, MP and GIS data. This integrated approach facilitates informed decision-making while ensuring compliance with the Corporate Sustainability Reporting Directive (CSRD). To advance beyond standard LCA principles, UC6 will adopt MBSE. The Carbon platform will generate life cycle inventories and evaluate the environmental impacts of material choices through comprehensive life cycle assessments. |
| UC7 | *Operational Carbon Management Systems*: demonstrates the power of AI agents for energy monitoring and optimization including dynamic Pricing. The operational carbon management systems access real-time feeds and data from captured sensors (IoT) related to energy consumption of building elements and products. The introduction of AI agents and graph technology enhances IoT capabilities and across diverse energy systems. The approach applied to smart buildings is reliant on AI agents for controlling lighting and optimizing energy consumption as they are programmed to learn from their environment and improve over time. The framework will analyse patterns of electricity usage and optimize it such as turning off lights in unoccupied rooms or adjust the HVAC systems based on current occupancy, thus providing Occupant well-being. Furthermore, it will facilitate environmental sustainability by tracking energy performance, carbon emissions, and environmental impact. |
| UC8 | *Accelerator for Green Finance Investments*: Green finance appears to be one of the leading technology solutions which, will further promote the increase in regulating environmental impact activities [28]. Therefore, the asset holders, bondholders, and issuers, among others, will have to refocus their efforts to guarantee that green finance is more useful, significant, inclusive, and environmentally protection oriented. UC8 will focus on Getting Buy-In to advance Green Infrastructure – Creative solutions for green infrastructure are only as viable as those who back them. |

## IV. DEMONSTRATIONS

To test these innovations and use cases, the demonstrations will cover a spectrum of many items included in the EU policy and market trends regarding data management in the built environment. This broad coverage aims to ensure that the proposed solutions offer high replication potential thanks to a demonstration plan. In this sense, the framework UCs will be tested by scenarios of different building typologies, energy grids and data architectures, via the involvement of a living lab (TRL6) and 2 large-scale pilots (TRL7-8) covering a variety of use cases and target users and 1 virtual pilot that will act as 'Development, Test and Evaluation (DT&E)' before the 2 large-pilots regarding 'Operational, Test & Evaluation' (OT&E) [29]. In addition, ISO 31000 Risk Management Plan will also be used to monitor the project progress [30].

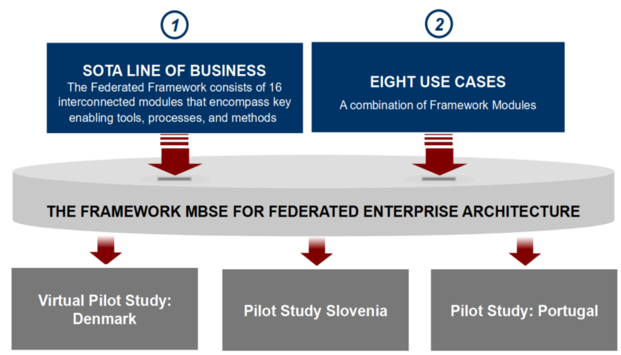


Figure 8. The Demonstrations Architecture

Figure 8 architecture illustrates the process of selecting the best technologies and UCs to be integrated & tested, including UX features, during the project's demonstrations. The three levels of interoperability are **the foundational level,** which refers to the ability of one information system to exchange data with another. The system receiving data must not interpret any information; the data must be system-agnostic. For software tools to be system agnostic, they must operate independently of any specific software environment or platform. This flexibility allows the tool to integrate seamlessly with various systems, making it adaptable to different technological landscapes. **Structural interoperability** is the second level and defines the data structures for information shared between systems. By standardising the message formatting, data is both preserved and unaltered. Data is immediately ready for use in the new system. In a **semantic model**, data is available in cloud formats (storage, platform) for any system to access, regardless of the internal systems in use [31]. Identifying standards for file formats, exchanges, and protocols will support the solutions selected for the project's demonstration. Each of the pilot studies is described in detail in the following sections. The results of the pilot studies will be a major part of providing the data source for widespread dissemination to EU-funded projects, testing facilities addressed and overall knowledge provided from the measured results.

### A. *Virtual Pilot Study: Denmark & Romania*

The Danish & Romanian virtual pilot (UCN, Brisk Group & ICI) will focus on a fully digital demonstration, leveraging advanced DT technology and BIM tools to address challenges in interoperability, circular construction, and supply chain integrity. This pilot aligns with the proposals objectives by simulating circular economy principles in construction and renovation processes. The virtual demonstrator will integrate open standards (Industry Foundation Classes ISO 16739-1:2024) [32], Information Container for linked Document Delivery under ISO 21597-2:2020 [33], Cybersecurity measures (courtsey of ICI Bucharest), and lifecycle optimization methodologies to showcase adaptability, reuse, and practices focused on carbon emission reduction. The primary aim of this pilot is to establish effective systems for sourcing materials locally, enabling businesses to develop robust recycling and reuse frameworks. This approach reduces reliance on resource-intensive production processes, minimizes waste generation, and fosters sustainable practices. Local sourcing is encouraged by transparency and decision-making capabilities enabled by the platform. The Carbon platform, equipped with graph technology conforming to ISO/IEC 39075:2024, will enable precise tracking and sourcing of materials, prioritizing reused materials and bio-based alternatives.

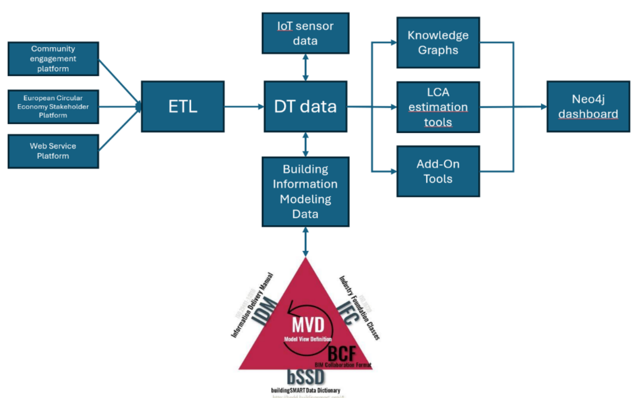


Figure 9. The Virtual Pilot

The Virtual Pilot scenario is focused on pulling data from various data bases via Extract, Transfer, Load (ETL) data processes, into a DT that also feeds from IoT and BIM data (elements of the building). The DT data is queried in real-time by Knowledge Graphs (see UC3) and LCA applied where the results are to be published on the Neo4j dashboards for analysis.

Table V identifies the five chosen UCs for the Virtual Pilot. The outcomes of this demonstration is to achieve the following key elements:

- Interoperability testing – ensuring seamless data integration using BIM, open standards, and federated architecture for decentralised Lines of Business (LOBs);
- Lifecycle optimization – simulating adaptability, disassembly, and reuse scenarios for building elements;
- Cybersecurity enhancements – securing the integrity of supply chains through advanced measures;
- Data-Driven collaboration – utilizing real-time linked data spaces and graph technology to support decision making across stakeholders;
- Real-world data – will be used from material performance and life cycle analysis will be utilized to validate the demonstrator's interoperability and accuracy.

TABLE V. VIRTUAL PILOT CHOSEN USE CASES

| N° | Use Cases |
|---|---|
| UC1 | Circular Construction & Reuse Framework (AI enabled tracking on a Carbon platform). |
| UC2 | Digital Platform (interoperability via Digital Twin Integartion). |
| UC3 | Real-Time Linked Data-Space (Environmental Data Integration). |
| UC5 | Cybersecurity & Supply Chain Transparency (through blockchains based products passports). |
| UC8 | Green Financing Accelerator (access to green subsidies & ESG investments). |

### B. *Pilot Study Slovenia*

The demonstration planned for Cirkulane (Slovenia), is a prefabricated, residential wooden house, addressing the challenges of Build4People topics, including circularity and sustainability. The demonstrator 'GORSKO' aims to focus on:

- Development of ecological modular walls designed for sound and thermal insulation.
- Reduce the carbon footprint and resources by using wood as a main structural material, including the use of waste wood, bio-based (wood, wood fibres, wood chips, straw, clay, sheep wool) insulation, also insulation based on waste textile, and focusing on providing locally produced materials and products.
- Extend the prefabrication processes: In addition to the wooden elements, there is designs to implement a BIM connection to automated production with CNC machines of insulation panels (wood fibre-based).
- Source products inventory and identification to optimize transport and installation.
- Optimisation of preparation and installation process: 3D scanning, e-site, AR/VR use for installation/supervision.
- Developing a smart building (IoT, Digital twin) and setting up smart management and maintenance as a service.

TABLE VI. PILOT STUDY SLOVENIA

| N° | Use Cases |
|---|---|
| UC1 | Circular Construction & Reuse Framework |
| UC2 | Digital Platform |
| UC3 | Real-Time Linked Data-Space |
| UC5 | Cybersecurity & Supply Chain Transparency |
| UC6 | LCA models for Renovation and Planning |
| UC7 | Operational Carbon Management Systems |
| UC8 | Green Financing Accelerator |

Table VI identifies the seven chosen UCs for the Pilot Study Slovenia. The expected outcomes planned are related to improve:

- Adapability of building design and solutions for different uses;
- Increased reuse of buildings components and increasing the end-of-life value;
- Extend services life by smart maintenance services and;
- Increase awareness and deploy best services in the demonstrators supply chain.

### C. *Pilot Study: Portugal*

The Portuguese demonstration will concentrate on the Mechanical and Electrical (M&E) components that contribute to operation costs. The challenges relate to current SCADA systems that collect and manage data from a building's Command & Control infrastructure, which oversees major energy systems such as lighting, HVAC, and power distribution. These systems operate in an event-based manner, meaning that human operators manually analyses data, respond to alarms, and make real-time decisions based on detected anomalies, incidents, or diverse operational needs. While this approach allows for direct human oversight and control, it also is reactive, and carries low efficiency, leading to potential delays in optimizing energy usage and system performance.

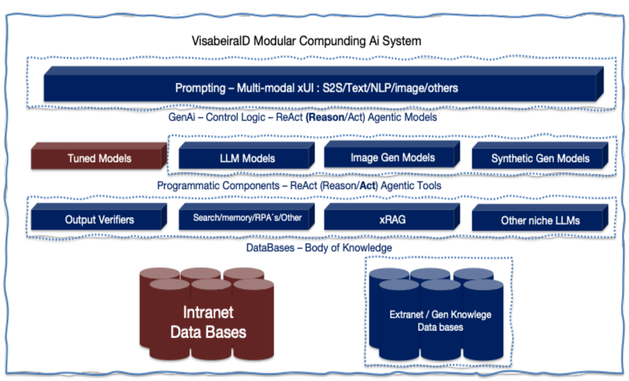


Figure 10. The 'Palacio de Gelo shopping mall' Pilot Study

The architecture of the 'Palacio de Gelo shopping mall' Pilot Study (Portugal) is illustrated in Figure 10. Moreover, the architecture reflects the selected SOTA from the framework and the chosen UCs to support the the scenario. In this To-Be scenario, new energy analytics services will be implemented, such as load forecasting, energy sourcing classifications, anomaly detection, and virtual consumption dis-aggregation to generate meaningful data & insights to be fed into the vertically embedded Agentic AI that will orchestrate building management system. The AI-driven system will utilize endogenous building information extracted from the internal active building management systems, as well as exogenous energy grid information incoming from the local energy Transmission System Operator/Distribution System Operator.

TABLE VII. PILOT STUDY PORTUGAL

| N° | Use Cases |
|---|---|
| UC2 | Digital Platform (Building systems' originated data, capturing real-time and historical building operations). |
| UC3 | Real-Time Linked Data-Space (SCADA systems data used as soucring, for creating an integarted digital twin of the building). |
| UC4 | RAM Knowledge Platform (include: I) prompting module, ii) AI ReAct (Reason/Act) Agent Models, a set of GenAI models, following the ReAct paradigm (Reasoning + Acting), will be deployed; iii) Progammatic Agentic Tool Components). |
| UC6 | LCA models for Renovation and Planning (enhance operational processes by integrating a systemic Agentic system approach that will enable energy optimization). |
| UC7 | Operational Carbon Management Systems (environmental impacts and GHG emissions due to large-scale electricity consumption for lighting, climate control, and other energy intensive systems). |

Table VII identifies the five chosen UCs for the Pilot Study Portugal. The outcomes of The 'Palacio de Gelo shopping mall' Pilot Study focuses on the following:

- Lifecycle optimization – Agentic AI will be embedded within the building management plan;
- Data-Driven Collaboration – The Portuguese use case focuses on maintaining present user QoE KPIs while lowering the current GHG building emissions footprint;
- The Pilot Study will address circular economy goals while adapting to local/regional sourcing of products and materials to increase replication.

## V. TOOLS EVALUATION AND HOLISTIC IMPACT ASSESSMENT

Neo-Eco | Circular Economy Consultancy (France) is the partner assigned to coordinate and manage the "tools evaluation and holistic impact assessment" platform for the Ukrainian test-bed. The overall concept is to pull the best practices, processes, and methods obtained from the three previous demonstrations into a beta stage dashboard. The business analytics of the dashboard will point the city officials to the frameworks best suited tech-powered solutions that can support the Dnipropetrovsk region's sustainable reconstruction needs. The beta stage dashboard will be developed to showcase how the frameworks's suite of solutions were deployed in the previous demonstrations.

In addition, a scorecard feature will be developed to indicate each tool's level of applicability and usefulness to the selected region based on the needs inputs it provides.

The Ukraine is purposely chosen as the project's validator due to its heavy (re)construction needs and potentially large availability of recyclable rubble and materials, in addition to its energy efficiency investment needs. The result of the project validation exercise will be a diagnostic and prescriptive tool that any city government can use to (1) identify the most relevant and impactful aspects of market building and coordination it should invest in to create a more sustainable construction industry, and (2) become acquainted with the tools that can make this happen. For example; if the selected city administration completes the tool's diagnostic survey and indicates its desire to reduce its built environment's embodied and operational carbon footprint in order to unlock further international donor support, then the dashboard will highlight the solution (tools, products, technique, processes and methods) that engages with its local construction industry accordingly.

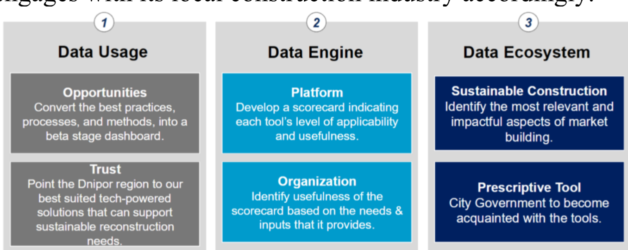


Figure 11. The Toolkit Impact Assessment Platform

Figure 11 addresses the 3 principal components of theToolkit Impact Assessment Platform : (1) Data usage, (2) Data Engine, and (3) Data Ecosystem for the planned validation of the Fedearted Framework for Adaptability, re-use and Deconstruction of Buildings, Aligned with the Principles of Circular Economy.

## VI. Conclusion and Future Work

This paper focused on a Federated Enterprise Architecture approach to integrate digital technologies, via advanced processes, with novel materials into a decentralised Framework for (de)construction and renovation. The existing challenges of non-interconnected frameworks associated with monolithic, proprietary system provided the initiative to design an interoperable ecosystem for tools, platforms, and processes that maintained autonomy. The article outlines 5 objectives and their potential requirements and measurable KPIs. The methodology examines in detail the use of MBSE as a process offered in the framework to define the solution design. Furthermore, the methodology describes the evaluation of research methods and their philosophical assumptions in five phases, where each is aligned to MBSE.

The concept of the pilot studies is to facilitate the transition of the selected UCs bundle from the initial conceptual stage to an advanced operational development stage based on constant evolution and learning. The framework's adaptive process will be measurable based on the outcomes of the demonstrations. Furthermore, the anticipated results of the process will provide a long lasting impact on our understanding of how an efficient design for adaptability, re-use and deconstruction of buildings should be approached, as well as to support EU regulation on those issues. Within the context of the paper's output it has identified how to increase adaptability of buildings and the reduction of waste via the Federated Enterprise Architecture, while analyzing supporting structures such as leveraging green finance investment for local and regional economic development, and moreover providing sustainability, standardization, and governance towards the circular economy policy evolution.

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