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RINNO: Towards an Open Renovation Platform for Integrated Design and Delivery of Deep Renovation Projects

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Abstract: The building stock accounts for a significant portion of worldwide energy consumption and greenhouse gas emissions. While the majority of the existing building stock has poor energy performance, deep renovation efforts are stymied by a wide range of human, technological, organisational and external environment factors across the value chain. A key challenge is integrating appropriate human resources, materials, fabrication, information and automation systems and knowledge management in a proper manner to achieve the required outcomes and meet the relevant regulatory standards, while satisfying a wide range of stakeholders with differing, often conflicting, motivations. RINNO is a Horizon 2020 project that aims to deliver a set of processes that, when working together, provide a system, repository, marketplace and enabling workflow process for managing deep renovation projects from inception to implementation. This paper presents a roadmap for an open renovation platform for managing and delivering deep renovation projects for residential buildings based on seven design principles. We illustrate a preliminary stepwise framework for applying the platform across the full-lifecycle of a deep renovation project. Based on this work, RINNO will develop a new open renovation software platform that will be implemented and evaluated at four pilot sites with varying construction, regulatory, market and climate contexts.

1. Introduction

Energy decarbonisation and sustainable development are key strategic priorities for nations worldwide as recognised in the UN Sustainable Development Goals (SDGs) and the Paris Climate Agreement [1,2]. In response to calls for greater alignment with these initiatives [3], the EU 2030 Climate and Energy Framework sets out aggressive targets for cutting greenhouse gas (GHG) emissions, increasing the share of renewable energy and improving energy efficiency [4]. Its ambition is evidenced in its recent commitment to review the target to be reached by 2030 to a binding 32.5% at the EU level [5]. The EU building stock accounts for 40% of the EU's energy consumption and 36% of its green house gas (GHG) emissions [6]; meeting the 2030 targets requires reductions of up to 14% and 60%, respectively [7]. This challenge is not insignificant. The European Commission (EC) estimates that up to 75% of the EU's existing building stock has poor energy performance, 85–95% of which will be in use in 2050. The key action for energy efficiency in buildings

is reducing the demand for heating and cooling via renovation of the building envelope, using new low-energy-consuming equipment in general (and specifically, using more energy-efficient heating equipment), increasing the uptake and use of renewable solutions, as well as the adoption of "smart buildings" [6]. Recent research suggests that renovation efforts are adversely impacted across the value chain by a number of human, organisational, technological and market factors [8–11]. To address these issues, a combination of the greater use of ICTs in construction, renovation and maintenance and novel solutions for incentivising and financing renovation, promoting and driving demand for renovation and transforming the construction sector is needed [7].

RINNO is a Horizon 2020 project that aims to deliver a set of processes that when working together provide a system, repository, marketplace and enabling workflow process for managing deep renovation projects from inception to implementation. The ultimate objective of RINNO is to contribute to accelerating the rate of deep renovation in the EU by reducing the time, effort and cost of deep renovation while improving energy performance and stakeholder satisfaction. This paper presents a roadmap for an open renovation platform for managing and delivering deep renovation projects for residential buildings from planning and design, through to retrofitting, operation and monitoring based on seven design principles. We illustrate a preliminary stepwise framework for applying the platform across the full-lifecycle of a deep renovation project. Given the complexity and size of deep renovation projects, a scalable, modular, multi-stakeholder, full-lifecycle approach is required to support both open collaboration and new algorithmic analytics techniques. At the same time, given the wide range of stakeholders with varying backgrounds and skill levels, the platform and tools need to be easy to install, configure and use. Based on the work presented in this conceptual paper, the RINNO project will develop a new open renovation software platform that will be implemented at four different European pilot sites with different construction, regulatory, market and climate contexts.

The remainder of this paper is organised as follows. Section 2 defines deep renovation and the rationale for the deep renovation of residential buildings, elaborates on the challenges in deep renovation projects across the lifecycle of such projects and summarises related work to develop integrated design and delivery solutions for deep renovation within the EU. Section 3 summarises the design principles used to guide the high-level conceptual platform design presented in Section 4. This is followed by a brief overview of the application of the RINNO stepwise renovation framework in Section 5. Section 6 provides a brief overview of the pilot sites and evaluation metrics for RINNO before concluding.

2. Background

2.1. Deep Renovation

While widely used in legislation, academic literature and practice, there is significant variation in the definition and use of the term *deep renovation* (sometimes referred to as deep energy renovation). In their review of international definitions of deep renovation, Shnapp et al. [12] noted that there is significant local, regional and international variation in the definition. Different terms are often used interchangeably with respect to deep renovation, but such terms can have significant implications for renovation projects. These definitions of deep renovation can be largely categorised as "broad" and "narrow".

The broad definition treats deep renovation with respect to its integrative characteristics. From this perspective, deep renovation refers to the combination of several simultaneous renovation measures into one integrated strategy acting upon the building envelope and installation system, rather than discrete independent measures [13]. In contrast, although not in a mutually exclusive way, the narrow definition of deep renovation relates to performance. Indeed, this is the approach taken by the EU's Energy Efficiency Directive 2012/27/EU. Recital 16 defines deep renovations as renovations *"[...] which lead to a refurbishment that reduces both the delivered and the final energy consumption of a building by a significant percentage compared with the pre-renovation levels leading to a very high energy performance."* It is noteworthy that since its introduction, the exact quantitative performance

reference value has remained ambiguous [10]. For example, a 2012 European Parliament proposal suggested a level of 80% [12], while the recent Renovation Wave Communication refers to a level of 60% [8]. Shnapp et al. [12] proposed an integrative definition:

> Deep Renovation or Deep Energy Renovation is a term for a renovation that captures the full economic energy efficiency potential of improvement works, with a main focus on the building shell, of existing buildings that leads to a very high energy performance. The renovated buildings energy reductions are 75% or more compared to the status of the existing buildings before the renovation. The primary energy consumption after renovation, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting after the deep renovation of an existing building is less than 60 kWh per m^2 per year.

In general terms, this definition captures both perspectives, although the limiting of effective performance to specific reference values opens up such definitions to debate. For example, on-site renewable energy contribution towards nearly zero energy buildings (NZEBs) is not considered explicitly, nor does the definition differentiate between different climate zones. For the purposes of the RINNO project, deep renovation is a renovation that captures the full economic energy efficiency potential of all improvement works to existing residential buildings that leads to a very high energy performance and significant energy savings. By being inclusive of all improvement works and not enumerating specific thresholds for energy performance and consumption, this definition avoids potential temporal, location, design and technological sensitivity. This is not to say RINNO has not set performance targets. For RINNO, improved energy performance must be in excess of 60% and energy savings must be greater than 30%, compared to the status of the existing buildings before the renovation. Such performance expectations are in line with current EU communications [8]. It is agnostic of the specific renovation measure used, while focusing on the dual objectives of improved energy performance post-renovation and the associated energy savings. The latter is particularly important as it is linked to stakeholder adoption and satisfaction [10,14]. Furthermore, this definition accounts for idiosyncrasies in legacy building design and residential dwellings located in a wide range of climate contexts. In these scenarios, there may be lower boundaries to the upper limit of energy performance and/or savings. The evaluation criteria for RINNO are discussed in more detail in Section 6.

Deep renovation assumes the use and combination of multiple simultaneous renovation measures [13]. While specific measures may evolve with the state-of-the-art, three categories of measures are common, i.e., technologies for retrofitting (i) energy efficiency, (ii) renewable energy sources (RESs) and (iii) connecting to district heating systems and other more sustainable energy supply systems [15], as summarised in Table 1 below. For each of these measures, advances in the state-of-the-art improve the overall energy performance, as well as various aspects of the renovation process. For example, advances in additive manufacturing (including 3D printing), materials and integrated RES harvesting significantly reduce the time, effort and cost of deep renovation, while increasing energy performance, in particular when using pre-fabricated off-site solutions [10]. Deep renovation projects may be combined with more traditional technology solutions or include industrialised and prefabricated approaches [10]. This notwithstanding, what distinguishes deep renovations from other energy efficient retrofits is the integrated renovation approach.

Table 1. Deep renovation categories and example measures [15].

Measures	Examples
Energy efficiency	Fabric measures, windows, heating, ventilation and air conditioning (HVAC) plant, air infiltration, lighting and appliances.
Renewable energy	Solar hot water, solar photovoltaic (PV), passive solar, shading, wind, heat pumps and biomass and biogas.
Community energy	Cogeneration and district heating systems.

The literature suggests a variety of rationales and benefits associated with deep renovation:

1. Economic: Deep renovation may act as an economic stimulus across the deep renovation value chain contributing to area revitalisation, direct and indirect employment, the gross domestic product (GDP), property values, competitiveness, export growth and public finances, while reducing energy costs, exposure to price fluctuations and import costs [8,10,15–17];
2. Societal: Deep renovation may help citizens participate in a more resilient, greener and digitalised society and function more fully in society by reducing fuel poverty, improving health and contributing to a higher quality of life through increased personal well-being, comfort and productivity [8,15–17];
3. Environmental sustainability: Deep renovation may contribute to mitigating adverse environmental impacts and building a resilient habitat for existing and future residents through higher energy performance, lower demolition and waste production, lower GHG emissions and lower air and noise pollution [15–18];
4. Energy system: Deep renovation may contribute to greater energy security by reducing reliance on energy imports, avoiding investment in new energy generation capacity and reducing peak loads [15].
5. Opportunistic: Deep renovation may differentiate a building and may make it a more attractive place to live, work or visit, when compared to other buildings [15];
6. Catalytic: Deep renovation may act as a catalyst for other innovations, substitute technologies or processes and improved control techniques in direct and indirect sectors, including policy- and competition-induced technical progress in conventional technologies and processes [16,17,19];
7. Accessibility: Deep renovation may contribute to improved accessibility by accommodating the most vulnerable in society including those with disabilities and elderly people, and improving social integration [16].
8. Quality: Deep renovation may contribute to (i) improved building quality through improvements to building physics, aesthetics and architectural integration, useful building areas, safety and ease-of-use and control by users [17,19] and (ii) increased range, quality and efficiency of service delivery including public, community and commercial services through improved pre- and post-renovation human-centric smart home monitoring [16,19–21].

2.2. Barriers to Deep Renovation

Non-adoption of energy management best practices in general, and specifically in relation to the specific climate in which a building is located, can result in under-performance against expectations and unnecessarily high energy use levels and related emissions [19]. While a wider discussion on deep renovation (non-)adoption is beyond the scope of this paper, it is important to note that the adoption of deep renovation technologies is impacted both by adopter-centred factors, technology-related factors, organisational factors and external environmental factors.

2.2.1. Human Barriers to Deep Renovation Adoption and Use

In the context of deep renovation and related technologies, and RINNO specifically, consumer adoption largely relates to owners, occupants and other users of residential buildings. For clarity, human factors related to the supply chain are dealt within Section 2.2.3 below. Research suggests a wide range of factors may act as barriers to the acceptance, support and adoption of energy-efficient behaviours and deep renovation technologies and projects. These include social norms (and habits), a lack of information about the implication of alternative actions on the environment, split incentives, a lack of instruction on how to use new technologies, a lack of information on energy consumption and energy saving opportunities, short-termism and disturbance of daily routines including hygiene factors [7,14,22–29]. It should be noted that there is evidence that household characteristics impact the adoption of energy-efficient technologies including education, age and house-

hold composition, and these factors vary across European countries [14]. These findings highlight the importance of emphasising different messages to different cohorts, but also the importance of education in the context of the adoption and use of technologies such as those inherent in deep renovation projects.

2.2.2. Technological Barriers to Deep Renovation Adoption and Use

While D'Oca et al. [10] noted that much of the extant literature focuses on the feasibility or technical suitability of specific technologies for deep renovation, in recent years, the focus has shifted to the integration of various energy-efficient technologies. This reflects what one might consider to be the primary technological challenge in deep renovation, namely the technical viability of integrating appropriate context-aware deep renovation technologies in a proper manner to achieve the required outcomes and meet the relevant regulatory standards [30]. In this respect, it implies that many of the challenges are more technical than technological and that they may more correctly be categorised as human-related factors, e.g., (i) awareness, (ii) availability (iii) and the ability to select and implement the most appropriate technologies [9,31]. These factors result in quality-related issues and sub-optimal performance, leading to dissatisfaction with renovation technologies as a whole. This is not to suggest that there are no further advancements in the state-of-the-art or quality issues, but rather that there is sufficient evidence that the existing deep renovation technology base can meet the needs of the most challenging requirements, e.g., the the Passive House Standard, if sufficiently planned [30].

Deep renovation is a multi-domain area with multiple inbound and outbound linkages to a wide variety of stakeholders and systems. Interoperability can generate significant value in construction and deep renovation projects through improved communication, coordination, cooperation, collaboration and distribution [32]. This creates substantial interoperability issues, which adversely impact data flows and thus impair value generation [33,34]. Linking data across the lifecycle of a renovation project presents a number of challenges, e.g., identifying and reconciling different representations at both the schema and object levels, mismatches among sources, incompatible levels of abstraction or sector-specific data taxonomies and, obviously, data quality issues [35]. While there have been a number of attempts by both industry and the academic community to address these issues (e.g., [33,35–38]), not the least being ISO 29481 [39], the primary focus was on a limited number of specific sub-systems, the planning and design phase and supply-side stakeholders [31].

One of the by-products of the increased implementation of increasingly smart/connected products and smart energy monitoring and control systems is higher data volumes, something that will be exacerbated by the increasing adoption of the Internet of Things. In particular, smart building and smart home technologies assume massive increases in heterogeneous end-points with varying computational capabilities, intermittent connectivity and a wide variety of potentially conflicting data requirements, decision criticalities and priorities. It is important to note that the adoption and use of new software-enabled, and specifically cloud-enabled, solutions has been hampered in the wider construction industry by poor on-site connectivity and latency, integration across the supply chains, data flows and skills [40,41].

2.2.3. Organisational Barriers to Deep Renovation Adoption and Use

In the context of deep renovation, there is a wide range of stakeholders involved in the supply chain including architects, construction contractors and building owners, to name but a few. These are enumerated in further detail in Section 3.2. As discussed above, organisations are comprised of workers, and thus, the adequacy of existing resources, technical competence and the personal innovativeness of both management and operators are important considerations in the adoption of innovative technologies [42]. Successful deep renovation requires adequate resources including top management commitment, ample time, investment, competent people and fit-for-purpose technology infrastructure.

In the context of deep renovation, recent research suggests that the lack of properly trained energy efficiency professionals and construction workers, locally and in general, in the proper selection and installation of new constructional technologies is a significant barrier to adoption, both directly and indirectly [9–11,30]. For public sector organisations, procurement policies that favour price over quality can have a negative impact on deep renovation [43]. Consequently, consumer trust in both the construction sector, and in deep renovation projects themselves, may be undermined due to project delays and the associated disruptions, sub-optimal energy performance and failure to achieve anticipated cost savings [10]. From an organisational perspective, financial barriers are amongst the most highly cited in the literature [44,45]. These include high upfront investment costs [46], the availability and access to funding in acceptable terms [8,10,43,47,48] and the duration and payback period [10,45]. Financing, and decision-making in general, is particularly complicated in the deep renovation of multi-dwelling residential buildings, including social housing and other fragmented ownership models [10].

2.2.4. External Environment Barriers to Deep Renovation Adoption and Use

The external environment, in particular building and environmental standards, policies and regulations, heavily impact the deep renovation sector. Legislation and regulation related to deep renovation can be seen as complex or unclear, as well as time consuming [43]. For social housing, the limited borrowing capacity of the public sector, complex financial schemes favouring large investments and unfavourable accounting rules are viewed as specific problems for local authorities [43]. The impact of market barriers including some regulatory barriers, a lack of information and either poorly-designed incentives (e.g., split incentives) or a lack of incentives for the deep renovation of buildings, as well as the need for policy intervention is specifically cited in the EC Impact Assessment on the 2030 strategy [6]. Even where supports are available, it is important to note that some stakeholders, for example local authorities, may find the process of applying for and drawing down these supports complex and that their staff are not equipped with the technical skills to fully leverage these supports [43].

2.3. Towards Integrated Design and Delivery Solutions for Deep Renovation

As discussed above, deep renovation is distinguished by its combinatory and integrated approach. Consequently, a lack of integration, compatibility and poor management across the lifecycle of projects are seen as the primary contributory factors to the failure or under-performance of deep renovation projects. For over a decade, there has been a call for integrated design and delivery solutions (IDDSs) in building and construction to produce, collaborate, share knowledge and add whole-life value [49]. The International Council for Research and Innovation in Building and Construction (CIB) defines IDDS as the use of "collaborative work processes and enhanced skills, with integrated data, information, and knowledge management to minimize structural and process inefficiencies and to enhance the value delivered during design, build, and operation, and across projects" [50]. IDDS involves integrated planning, design and supply chain [50]. In addition to enhanced skills and multi-stakeholder collaboration across all phases, IDDS requires integrated information and automation systems, as well as knowledge management [49,50]. As discussed earlier, the building and construction value chain, and specifically the deep renovation value chain, is fragmented and optimised around individual components. IDDS requires high degrees of system interoperability including BIM, procurement, fabrication, construction, collaboration and communication technologies, building energy management systems (BEMSs) and wider building automation and control systems (BACSs), amongst others.

There has been a significant investment in research to integrate across the deep renovation lifecycle. Many of these projects have a primary focus on plug-and-play construction technologies for specific renovation scenarios (e.g., in areas with above-average seismic activity—Pro-Get-One), innovation for one aspect of deep renovation (e.g., multifunctional building envelope elements—BRESAER [51], EASEE [52], MEEFS [53], PLUG-

N-HARVEST [54]) or a particular outcome (e.g., heating and cooling—BuildHeat [55]). As discussed previously, some are very BIM-centric (e.g., IMPRESS [56]), and others seek to offer one-stop-shop (OSS) solutions to one or a subset of stakeholders (e.g., RE-FURB [57]). The former may exclude the totality of integration needed for full IDDS in deep renovation, while the latter pose their own challenges, not the least of which is bias, a potential lack of supplier and solution choice, scalability and a lack of evidence of market performance [58,59]. However, in their 2018 review of EU deep renovation projects, D'Oca et al. [10] noted that the primary barriers are not related to specific deep renovation technical problems, but rather, consistent with Owen et al. [50], relate to knowledge, skills and cost, and therefore, efficient and effective tools for managing deep renovation projects from cradle to grave are necessary.

A number of EU projects have and are exploring IDDS for deep renovation. The NewTrend project [60] developed new integrated design methods including software and design tools for energy-efficient building and district retrofit. These tools include a data manager, an energy efficiency technology library, a collaborative design platform, an interoperable data exchange server and a simulation and design hub. Similarly, 4RinEU [61] seeks to support stakeholders along the whole renovation process through four main strands of work—a cost-optimal energy audit, an investor and building user-oriented design platform based on BIM, technologies and methodologies that improve productivity within the construction processes and a cost-effectiveness rating system. D'Oca et al. [10] noted that feedback from 4RinEU suggested that integration and a lack of data are key challenges [10]. It is unclear from the documentation whether NewTrend and 4RinEU are truly full-lifecycle, as this implies that both projects take the view that the project lifecycle ends upon implementation rather than ongoing operation and end-of-life. P2ENDURE addresses this potential shortfall by developing a modular process using a stepwise approach for planning and implementing deep renovation, followed by monitoring of the resulting performance improvements. P2ENDURE [62] conceives of the deep renovation process as an iterative loop of mapping, modelling, making and monitoring (the 4 M process) and includes elements for knowledge management, skill development (via augmented reality (AR) and virtual reality (VR)), procurement (via a marketplace) and fabrication (including additive manufacturing). While P2ENDURE features many of the elements of IDDS, residential buildings are not its exclusive focus, and it is unclear whether all solutions were implemented at each demonstration site. They noted access to knowledge artefacts and data, compatibility and interoperability as key challenges [10]. MORE-CONNECT [63] seeks to apply a holistic approach to deep renovation including product and process innovation including advanced geomatics, ICT-enabled decision tools linking building characteristics, building (energy) potentials, end-user requirements, technical solutions, component combinations in concepts, production automation, BIM integration and remote diagnostics to support an energy cost and performance guarantee. As REFURB, MORE-CONNECT also seeks to offer its solution as an OSS and, as 4RinEU, is BIM-centric, thus potentially suffering from these limitations. For example, MORE-CONNECT specifically cites interoperability with BIM as a specific ongoing challenge and barrier to adoption [10]. Although NZEB-specific, REZBUILD [64] is a new project that seeks to address interoperability problems by building on an agile project management (APM) platform optimised for interconnected systems and interoperability including BEMS, BIM and other renovation-related tools. It is noteworthy that many of these projects cite poor financial results for their projects [10]. Few of these projects explore advanced machine learning-based analysis and decision-making or address the end-of-life phase in a comprehensive manner.

3. Design Principles

Deep renovation is an increasingly complex feature space. It is complicated by the number and heterogeneity of regulations, designs, elements, materials, processes, tools and data and a dynamic operational environment [32]. Multiple stakeholders, often with conflicting interests and motivations, exacerbate complexity in the design of a full-

lifecycle solution for deep renovation. As such, the needs of different stakeholders must be addressed in the design of RINNO. Tiwana et al. [65] defined digital platforms as *"software-based external platforms consisting of the extensible codebase of a software-based system that provides core functionality shared by the modules that interoperate with it and the interfaces through which they interoperate."* This implies that any such system is modular, open and interoperable. Given the complexity, volumes, velocity and variety of the data generated and required to support next-generation deep renovation projects, algorithmic approaches to data analysis, security, actuation and scalability to meet the required quality of service (QoS) and quality of experience (QoE) are needed. The remainder of this section discusses each of these design principles in more detail.

3.1. Full-Lifecycle (P1)

While deep renovation is, in one sense, part of a wider building lifecycle, within the deep renovation process, there are four clear phases—(i) planning and design, (ii) retrofitting, (iii) operation and monitoring and (iv) end-of-life. At its core, a lifecycle approach suggests that the best available technological solutions and construction practices should be implemented in every step of the renovation activities across the renovation project lifecycle [50,66]. It is widely acknowledged that deep renovation plans are rarely made from a lifecycle perspective [67–69]. The opportunistic nature of deep renovation practice results in short-termism both in terms of planning and payback to the detriment of implementation quality, living standards and energy performance [68]. In contrast, economic modelling suggests that a full-lifecycle approach to deep renovation results in substantial energy savings, while avoiding adverse effects [68]. Indeed, Mainali et al. [66] suggested that encouraging systematically planned stepwise deep renovation through single-source platforms with associated linkages to appropriate finance mechanisms could attract owner support for deep renovation. From a strategic perspective, developing an architecture from a full-cycle perspective allows stakeholders at each step in the lifecycle leverage and share the benefits of the architecture (including associated data flows), as well as introduce network effects into the economics of the ICT platform, in this case RINNO [70].

3.2. Multiple Stakeholder (P2)

In line with Rozanski and Woods [71], stakeholders in the context of the RINNO system architecture are an individual, team, organization or classes thereof, having an interest in the realization of the system. In this respect, a useful stakeholder is informed, committed, authorized and represented [71]. As such, a large number of stakeholders are involved in deep renovation projects. These include (i) building owners, occupants and other users (e.g., facility managers), (ii) housing development and construction firms, (iii) architects, consulting engineers and other (sub)contractors, (iv) energy solution providers, construction technology providers and other related independent software vendors (ISVs), (v) construction finance companies and crowdfunding platforms and (vi) policy-makers, regulators and funding bodies, amongst others [72,73]. Liang et al. [73] suggested that the stakeholder relationship in retrofit projects, such as deep renovation projects, is more complex than in new building projects due to the number and type of relationships involved. Each of these stakeholders may have different requirements across the lifecycle of a deep renovation project. Critically, despite the importance of occupier cooperation and participation in both the deep renovation process and the achievement of target energy savings, deep renovation projects often under-prioritise their needs [73]. To ensure that the needs of all stakeholders are met, a multi-stakeholder approach is required. As such and to maximise user acceptance and impact, RINNO will not only be designed to take into account using multiple concurrent views, each from the perspective of representative stakeholders in line with ISO 42011 (a revision of IEEE Standard 1471) [74], but the technical proficiency of user types. Regarding the latter, ease-of-use relative to the expectations of a given stakeholder is a key consideration in RINNO.

3.3. Modular (P3)

Modularity refers to the design of systems composed of units (or modules) that are designed independently, but still function as an integrated whole [75]. Modular design is an adaptive strategy suitable for evolving markets and where end-users have diverse and fluid customer preferences [76]. As discussed, deep renovation is characterised by increasing complexity, rapid technological change and stakeholders with varying, and often conflicting, requirements and motivations [73,77,78]. For example, many stakeholders in the supply chain may have legacy software tools that they have invested in and wish to use. In the context of RINNO, there are significant advancements emerging from industry, but also other EU projects, that modularisation will allow both RINNO and its future users to exploit over the lifetime of the project and rapidly respond to feedback from stakeholders and pilot sites.

3.4. Open Collaboration (P4)

Levine and Prietula [79] defined open collaboration as *"any system of innovation or production that relies on goal-oriented yet loosely coordinated participants, who interact to create a product (or service) of economic value, which they make available to contributors and non-contributors alike."* It is important to note that it is not limited to data. Specifically, *open renovation* is a platform-based approach in which data, processes and renovation-specific functionalities are made available in an ecosystem of building stakeholders. Interoperability and application programming interfaces (APIs) are central to our conceptualisation of an open renovation platform. In the context of open renovation, APIs play an important role in the interoperability among all systems across the project lifecycle from BIMs to residential smart devices and other end-points and the exchange of data. A key characteristic of APIs is their abstraction from systems and infrastructure, thus allowing third parties to build new applications and services that consume APIs. In this way, RINNO can generate network effects in that the more add-on applications built for the RINNO platform, the more end-users the platform is likely to attract, and so on; a virtuous circle is enabled. Such platform ecosystems may evolve in to B2B, B2C and B2B2C marketplaces where developers and end-users can buy, sell and/or exchange applications and/or APIs (or API capacity) [80,81]. As such, interoperability is a key enabler of the RINNO vision of open renovation.

3.5. Algorithmic (P5)

Given the complexity of the deep renovation feature space, the high dimensionality, and the scale of the data envisaged, traditional analytical tools may not provide sufficiently accurate or timely insights, and as a consequence, smart buildings require increasingly sophisticated tools to learn, predict and make intelligent decisions [82]. This includes the use of machine learning and other more general algorithmic approaches' knowledge representation and reasoning, e.g., ontologies and rules to represent devices and building services, human activity recognition, distributed intelligence, semantic interoperability, as well as planning, intelligent control, adaptive interfaces and optimization for efficient management of resources and services [82]. RINNO intends to embed the RINNO architecture with what "*augmented building intelligence*". Again, this is a full-cycle approach that (i) uses machine learning and other more general algorithmic approaches coupled with data generated from buildings, and various users, to augment human intelligence through dynamic decision support in the planning/design and retrofitting stages, as well as the optimisation of building performance during the building operation and (ii) the enhanced cognition of each component of the building ecosystem. In this way, RINNO will leverage the improved data flows across the deep renovation lifecycle to support decision-making across the entire system, and within specific components and modules.

3.6. Scalable (P6)

Delivering RINNO's vision, and in particular a full-cycle multi-stakeholder design, requires accommodating a massive range of data structure types, algorithms and communication mechanisms [83]. For RINNO, scalability is a significant issue in all its forms including load, space and structural scalability [84]. The benefits of cloud computing in general terms and specifically to maintain QoS and QoE through auto-scaling are well established [85–87]. Furthermore, many of the key enabling technologies envisioned by RINNO for an open renovation platform are baked into the cloud computing model and ecosystem including support for APIs, security, fog and edge computing, application marketplaces, and so on. Recognising the specific human, computational and connectivity challenges inherent in many construction environments, RINNO must be cognisant of the need to accommodate fog and edge computing paradigms, and in particular intermittent connectivity, as well as make onboarding and use relatively easy and frictionless. As a final note on cloud computing, a goal of RINNO is to help meet EU energy efficiency targets. In architecting the RINNO platform, green cloud computing will be considered both in terms of the selection of the underlying cloud providers and resource management [88].

3.7. Secure (P7)

The modern built environment is increasingly dependent on cyber–physical infrastructure. As discussed in the Introduction, EU policy envisages greater use of ICTs in deep renovation projects to achieve its 2030 and 2050 goals [6,8]. While sensor-based networks, advanced building and energy design and management software, new cloud-to-edge computing paradigms and computational intelligence techniques provide significant benefits, they also introduce new vulnerabilities [89,90]. Such vulnerabilities can result in service disruption, increased energy costs, physical destruction and harm, as well as enabling wire fraud, burglary and data theft, amongst others [91]. Security is significantly more complicated in an open, modular and full-lifecycle platform such as that proposed by RINNO. Ciholas et al. [91] noted that there are few papers that explore research across the lifecycle of smart buildings, let alone the extended value chain in deep renovation; they only identified one paper in their review, an analysis by Mundt et al. [92] on building automation analysis. Given the criticality and sensitivity of the building and human activity data generated in deep renovation projects, security considerations must be integrated into all aspects of an open renovation platform from the cloud to the edge.

4. The RINNO Open Renovation Platform

Figure 1 below presents a high-level overview of the main components in the RINNO Open Renovation Platform based on the six design principles discussed above—full-lifecycle, multi-stakeholder, modularity, open and interoperable, algorithmic and scalable. The intention of Figure 1 is to facilitate an understanding of the way RINNO views how full-lifecycle platform-based renovation might operate. Please note that this is not an exhaustive list of all components.

Firstly, cloud computing infrastructure-as-a-service (IaaS) *(1)* is included as a core component to enable scalability *(P6)* and support algorithmic approaches *(P5)*. In particular, the hyperscale cloud service providers (CSPs), e.g., Amazon Web Services (AWS), Microsoft Azure, Google Cloud, Alibaba Cloud and IBM, provide a built-in and unified approach to security from the cloud to the edge, suitable for the deep renovation context *(P7)*. The core RINNO Operational Platform will sit on this IaaS layer. The cloud configuration will adhere as much as possible to green cloud computing principles to support the underlying ethos of the RINNO project. In addition, the hyperscale CSPs support common enterprise applications used in architecture and construction services (including data analytics, energy management information systems and BIM) in their cloud application marketplaces *(2)*, thereby reducing implementation times dramatically and supporting modularity *(P3)* and open collaboration *(P4)*.
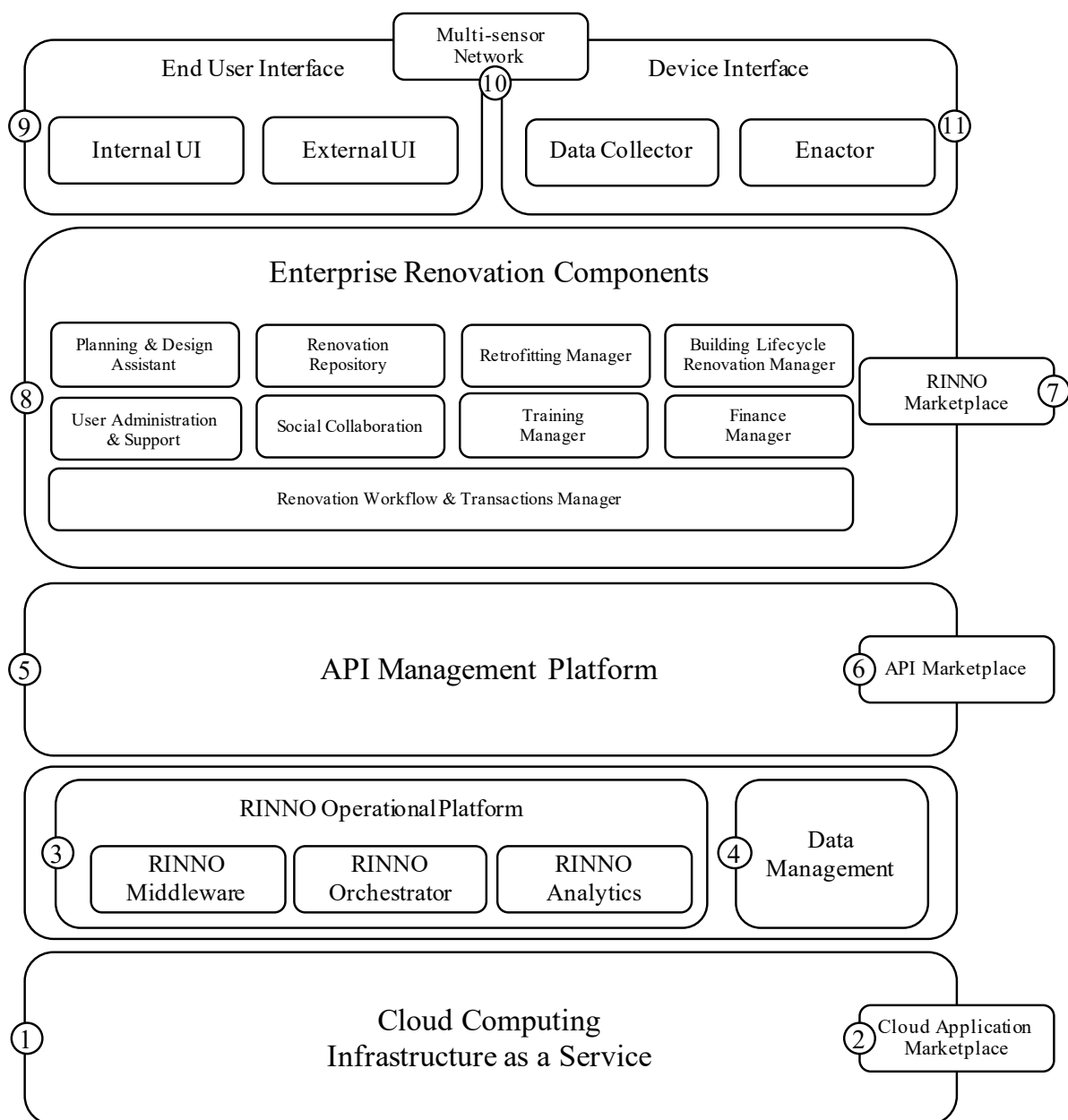
Figure 1. High-level conceptual RINNO Open Renovation Platform with illustrative components.

The Core RINNO Operational Platform *(3)* provides the primary underlying platform architecture, middleware, orchestration and analytics systems upon which the platform operates. The middleware connects the underlying architecture, the various components, modules and end-points collecting data within RINNO and enables integrated data flows and exchanges. The orchestrator provides blueprints, models and templates to support the design of business processes and functionality including mappings to integrated APIs and the abilities to add new APIs through the API Management Platform *(5)*. The analytics component includes the processing and analytics engines to support the core enterprise renovation components. Data management *(4)* includes the systems for storing and managing all the underlying system, customer, building and transaction data. These may be part of the core operational platform, a specialist add-on component or, due to the sensitivity of some projects, managed independently.

The API Management Platform *(4)* supports designing, securing, publishing, monitoring, analysing, consuming and monetising APIs. Again, this supports open collaboration *(P4)*. The API Management Platform plays an important role in data exchange by

providing a standard way to integrate proprietary, legacy and third-party applications, services and systems. API Marketplaces *(5)* allows users to discover and connect to APIs, thereby supporting both extensibility and open collaboration *(P3)*.

On top of the underlying infrastructure sits a number of renovation-specific components, which may comprise one or more modules. The initial deployment includes ten high-level components *(P3)* that support the full-lifecycle of a renovation project *(P1)*:

1. The **Renovation Repository** is an open standards-based repository of building data including products, materials, services, processes, elements, discrete and combinatory renovation measures and other related data that can better inform full-cycle renovation decision0making;

2. The **Planning & Design Assistant** is a component that helps to make proper and justified decisions based on optimum renovation solutions and inform the planning and design of a given building's renovation. It will leverage performance simulations and a detailed assessment based on relevant key performance indicators (KPIs);

3. The **Retrofitting Manager** is a component that supports the execution, analysis, monitoring and management of the renovation process. It will be based on and informed by best practice construction strategies, process industrialisation and optimisation techniques including off-site construction and on-site automation;

4. The **Building Lifecycle Renovation Manager** extends beyond the initial renovation process through to the full-lifecycle by supporting users during the renovation process and beyond by monitoring various aspects of building operation and performance including occupant comfort. This component will be sufficiently intelligent to accommodate updated information models, updated technologies, standards and KPIs over time, to identify any potential deviations in the design and actual building performance and support present and actuate revised optimal strategies to maximise energy efficiency, if supported by the installed equipment;

5. The **Renovation Workflow & Transactions Manager** is a module that acts as an enabling workflow for the entire renovation value chain and organises the data exchange among the various components, providing verification libraries for the automated quality assurance of processes and ensuring the transparency of quality assurance, certifications, transaction contracts and overall data provenance.

6. **User Administration & Support** are mechanisms to add, manage, support and terminate subscriptions, accounts, users and roles, as well as to perform service-specific maintenance and administration tasks;

7. The **Social Collaboration Platform** provides mechanisms and incentives (including gamified elements) to support information and knowledge exchange among stakeholders including results, best practices, case studies, etc.;

8. The **Training Manager** provides electronic productivity support systems to facilitate asynchronous and synchronous learning including on-the-job in-field training using AR/VR, as well as conventional e-learning;

9. The **Finance Manager** provides mechanisms for sourcing and managing funding for deep renovation projects including support for crowdfunding and smart contract-enabled contract execution;

10. The **RINNO Marketplace** will leverage the **Renovation Repository** to bring suppliers and customers of renovation-related products and services together. Aggregation is a core business value of the **Renovation Repository** and **RINNO Marketplace**. Stakeholders can search for suitable renovation products and services by either browsing through standard categories suggested by the **Renovation Repository** and the **RINNO Marketplace** or search through product and service descriptions, which accompany every solution listed in the Renovation Repository.

Additional components can be integrated to deliver the business functionality required in deep renovation projects over time through the RINNO Marketplace *(6)* or the underlying IAAS cloud application marketplace *(2)* where components have been pre-integrated through interoperable APIs, ensuring quick and easy implementation.

Users interact with the various components and modules through responsive end-user interfaces *(9)* to take into account that many stakeholders may be working on site and accessing RINNO through mobile devices. The RINNO platform recognises that there is a need for internal platform administration interfaces and separate interfaces for end-users *(P2)*. A critical component for the RINNO platform is the interface between the RINNO platform (and its components and modules) and the physical environment of the building. The platform will achieve this, primarily, through a multi-sensor network *(10)* comprising heterogeneous devices (e.g., energy smart meters, environmental sensors, etc.) that interact with the physical world and provide building-related information to the RINNO platform. These data are collected through standards-based interfaces with the various sensing end-points deployed by those involved in the renovation project *(11)*. Similarly, optimised energy management strategies may be actuated based on these data *(11)*. To maintain QoS and QoE, RINNO will need to support a range of different scenarios for data collection and actuation from the cloud to the edge including the fog and edge computing paradigms *(P6)*.

Finally, it is critical to emphasise that machine learning and general algorithmic approaches will be implemented throughout the platform for both optimising system performance and renovation process outcomes *(P5)*.

5. The RINNO Stepwise Renovation Framework

To support a full-lifecycle approach, RINNO can be used in a stepwise manner. Figure 2 outlines the components in the RINNO platform and shows a stepwise process flow across the lifecycle of a renovation project. In the following description, figures in brackets indicate the relevant component shown diagrammatically in Figure 2.

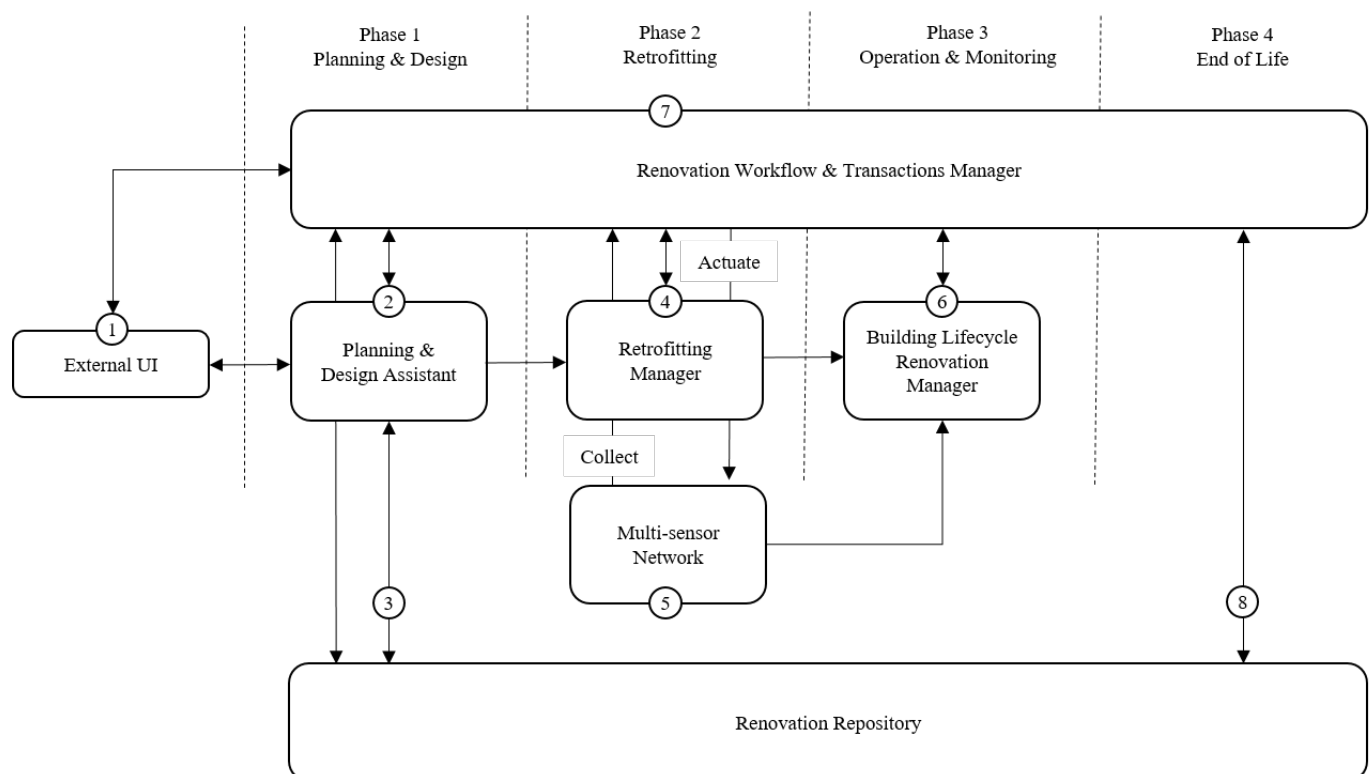**Figure 2.** RINNO stepwise renovation framework.

In Phase 1, stakeholders and their needs are defined and collated in the context of the specific building renovation projects including relevant environmental and architectural details *(1)*. These data are input into the Planning & Design Assistant to formulate the renovation end-scope with due consideration of appropriately selected and quantified

KPIs *(2)*. With the help of the **Renovation Repository**, the system provides a set of renovation options that can meet the pre-defined requirements of the stakeholders and projects based on the selected criteria including cost, time and performance *(3)*. It is important to note that the **Renovation Repository** can play an important role across the lifecycle of deep renovation projects including the end-of-life phase *8*.

Next, the **Planning & Design Assistant** prepares a virtual digital representation of the building (a digital twin), within which a range of applicable renovation scenarios based on options from the **Renovation Repository** are generated. Different renovation scenarios are subsequently simulated on the basis of the building and its system's digital twin to quantify their impact in terms of various KPIs. Based on these quantified KPIs, the **Planning & Design Assistant** facilitates the relevant stakeholder to select the optimum scenario(s). Once selected, a subordinate module generates the optimised workflow for the realisation of the selected renovation scenario, thus simplifying the design process for the selection of the optimum scenario and the optimum workflow.

In Phase 2, the RINNO system offers a variety of tools and methods for reducing the implementation time and potential occupant disturbance including on-site and off-site innovative construction methods and strategies *(4)*. The **Retrofitting Manager** includes a recommendation engine to select the most efficient combination of (i) off-site and on-site fabrication and (ii) workflow and task sequencing. As discussed in the previous section, users will be able to access the Training Manager component to support just-in-time on-the-job in-field training and support.

In Phase 3, the RINNO platform is continuously monitoring and analysing the building performance in real time. The system uses an extensible **Multi-Sensor Network *(5)*** installed at the building to gather data including energy consumption, indoor environmental conditions (e.g., temperature, humidity, etc.), environmental quality (e.g., CO_2, noise, etc.) and occupancy, amongst others. As discussed, data streams are collected from the beginning of the renovation process *(1)*; thus, the **Building Lifecycle Renovation Manager** is able to compare the designed (expected) and actual performance of the building *(6)*. These data can inform the behavioural profile of building users, which can then be used by the Building Lifecycle Renovation Manager to introduce personalised intelligence in the building control specific to the needs and requirements of the building users.

A key consideration in deep renovation is the design for deconstruction, recovery and reuse before and during refurbishment, across the operational phase and once the building or subsidiary elements come to the end-of-life (Phase 4). In addition including best practice content, data on materials and methods for end-of-life scenarios in the **Renovation Repository *(8)***, where feasible and appropriate, the RINNO Platform can integrate third-party solutions to support the end-of-life phase, e.g., electronic material passports [93], material and energy flow analyses [94] and BIM for demolition [95].

Finally, the **Renovation Workflow & Transactions Manager** supports the supervision, project management, and communication across the entire renovation project lifecycle and injects trust into the renovation process by providing mechanisms to introduce assurance and accountability through transparency and novel smart contract-based payment mechanisms *(7)*. This has the added benefit of accelerating payment to suppliers upon pre-agreed triggering events. Similarly, the **Renovation Workflow & Transactions Manager** could provide a similar service among funders and owners through the Finance Module, releasing funds as specific stages or activities are completed and certified.

6. Pilot Sites

The primary use case for the RINNO project is deep renovations of residential buildings. To evaluate its stepwise framework, components and modules, the RINNO platform will be used in the renovation of buildings at four pilot sites in Greece, Poland, France and Denmark. These buildings are all multi-unit social housing buildings situated in different climatic regions and with diverse local building codes and regulations. Each building features different construction materials and elements and is equipped with different HVAC

systems and other related building systems and features. In total, RINNO will evaluate 2514 m^2 of deep-renovated floor area. While not prejudicing the output of the RINNO framework, the technologies to be utilised in the different pilot sites are likely to be a diverse mix of pre-fabricated envelope components, insulation and harvesting and RES technologies coupled with novel software solutions.

While improved energy efficiency at the same or better thermal comfort is a goal of each pilot site, the means and outcomes will vary depending on the specific renovation plan for each pilot site. For example, the Greek pilot site will involve the renovation of a multi-family building to the Passive House Premium standard. In others, RINNO will showcase best practice deep renovation for social housing. As such, RINNO developed a comprehensive evaluation framework for the project as a whole and for each RINNO component including baseline and summative measurements. These include targets for reduced energy consumption, the adoption and use of RES, thermal performance, renovation time and effort and comparative cost, as well as stakeholder satisfaction measures. The high-level KPIs for the project are outlined in Table 2 below.

Table 2. RINNO high-level KPIs.

Metric	KPI
Energy savings	>30%
Payback period	<4 years
Improved energy performance	>65%
RES penetration	>30%
Total cost reduction in comparison with typical renovation	>30%
Total time reduction in comparison with typical renovation	>20%
Durability guarantee	>25 years
Reduction in embodied energy	>20%
Utilisation of bio-based materials	>45%
Stakeholder satisfaction	>90%

The RINNO project runs from 2020 until 2024. In 2021, RINNO will develop a comprehensive data collection and management framework to support the operation of the RINNO platform and the evaluation of the project as a whole. This includes mechanisms for collecting stakeholder, process, local environment, building- and household-level data for each pilot site (including maintenance and stakeholder surveys) at different intervals, as well as information systems (e.g., BACS, BEMS, BIM, etc.), Internet of Things (IoT) nodes, and second- and third-party data sources. Machine learning techniques will augment these data and generate insights on building performance, condition and use from different stakeholder perspectives.

7. Conclusions

This paper presented the RINNO vision for a cloud-based open renovation platform. The plan for the project is to deliver a set of processes that when working together give a system, repository, marketplace and enabling workflow process for managing deep renovation from inception to implementation, all imbued with state-of-the-art decision support based on advanced machine learning techniques. The goal of the project is to develop a software platform and provide stakeholders in deep renovation projects with access to the data and decision support systems to (i) optimise renovation design, (ii) reduce renovation time, effort and cost, (iii) increase energy efficiency through greater adoption and use of RES, improved thermal performance and reduced energy consumption, and (iv) increase stakeholder satisfaction. A literature review identified seven design principles for an open renovation software platform. Such platforms should be full-lifecycle, multi-stakeholder and modular. They should support open collaboration and interoperability,

adopt an algorithmic analytics approach and be scalable and secure. The paper presented a high-level conceptual overview of the main components of the proposed open renovation platform and illustrated how this can be used in a stepwise fashion across the full-lifecycle of a deep renovation project from planning and design to end-of-life.

This concept paper provides space for renewed interrogation, understanding and awareness of the potential of cloud-based integrated design and delivery systems for deep renovation. While (i) synthesising rationales for and barriers to deep renovation, (ii) proposing design principles and components for an open renovation platform and (iii) highlighting the need for interaction and interoperability among systems across the lifecycle of a deep renovation project, the inherent limitations of the concept paper format present potentially fruitful avenues of interdisciplinary, multi-stakeholder and applied research moving forward. While the next phase of the RINNO project is to develop a full-cycle open renovation platform, by definition, its openness invites future collaboration from other researchers and practitioners. However, future research should not be limited to the technical aspects. While understood in general terms, there is no widely accepted definition of deep renovation, and one could argue it is either too broad or, when performance thresholds are adopted, too specific. A contingency approach to defining deep renovation may prove to be academically interesting and of practical value. Similarly, further international and longitudinal empirical research is needed on the determinants of deep renovation adoption, use and satisfaction and associated barriers. This requires a contingency and multi-stakeholder perspective. This paper proposed seven design principles for an open renovation platform, each of which requires further research, particularly in light of changing attitudes toward climate change and the potential impact of COVID-19. The COVID-19 pandemic accelerated the adoption and use of digital technologies. Residential dwellings became mixed use spaces for living and working. The convergence of digital and physical behaviours and the integration of computational capabilities into the built environment are likely to continue; however, it is unclear whether the sophistication and robustness of the systems to support these new use cases are sufficiently open, scalable, secure and equitable. The RINNO vision seeks to accommodate new computational paradigms including fog computing, edge computing, the Internet of Things and the incorporation of intelligence into the management of the built environment itself. However, these are all at a relatively early stage of conceptualisation and have their own discrete socio-technical challenges, which are further complicated when combined. Consequently, there is a substantial stream of research required on the interdependency of these systems and the human, organisational and technological implications in a deep renovation context. IT-enabled deep renovation requires a substantial investment of time, effort and resources in both innovation and adaptation throughout the value chain. Accelerated investment in deep renovation means delivering on the promise of not only energy efficiency, but energy savings and increased productivity at scale, as well as communicating this to stakeholders in the most appropriate way. Additional longitudinal research is required to ensure that the deep renovation sector is creating, capturing and communicating value appropriately and that software systems are designed to support these activities in a timely fashion.

Meeting the EU targets for energy efficiency and decarbonisation requires collaboration including innovation in materials, architectural design, fabrication, construction, ICT and socio-economic domains. To meet this challenge, RINNO has brought together 15 partners from across the deep renovation value chain to collaborate and re-imagine how deep renovation projects are organised, managed and evaluated. The RINNO project runs until 2024 and will develop a new open renovation software platform in line with the design principles and conceptual overview presented herein. RINNO will implement the platform at four large-scale real-world pilot sites with varying construction, regulatory, market and climate contexts and evaluate the performance of the platform against specific KPIs for energy consumption, adoption and use of RES, thermal performance, renovation time and effort, comparative cost and stakeholder satisfaction measures. By achieving

these outcomes, RINNO will help accelerate the rate of deep renovation in the EU and achieve the 2030 and 2050 targets for energy efficiency.

Abbreviations

The following abbreviations are used in this manuscript:

4M	Mapping, modelling, making and monitoring
API	Application programming interface
AR	Augmented reality
AWS	Amazon Web Services
B2B	Business-to-business
B2B2C	Business-to-business-to-consumer
B2C	Business-to-consumer
BACS	Building automation and control system
BEMS	Building energy management system
BIM	Building information modelling
CIB	International Council for Research and Innovation in Building and Construction
CO_2	Carbon dioxide
CSP	Cloud service provider
EC	European Commission
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
HVAC	Heating, ventilation and air conditioning
IAAS	Infrastructure-as-a-service
ICT	Information and communications technology
IoT	Internet of Things
ISV	Independent software vendor
IDDS	Integrated design and delivery solution
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
KPI	Key performance indicator
kWh	Kilowatt hour
m^2	Metres squared
NZEB	Nearly zero energy building
OSS	One-stop-shop
PV	Photovoltaic
QoE	Quality of experience
QoS	Quality of service
RES	Renewable energy source
SDG	Sustainable Development Goal
VR	virtual reality

References

1. United Nations. Paris Agreement. 2015. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed on 12 April 2021).
2. United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://sdgs.un.org/2030agenda (accessed on 12 April 2021).
3. European Commission. Kickstarting the Journey towards a Climate-Neutral Europe by 2050-EU Climate Action Progress Report. November 2020. Available online: https://ec.europa.eu/clima/sites/clima/files/strategies/progress/docs/com_2020_777_en.pdf (accessed on 12 April 2021).
4. European Commission. 2030 Climate & Energy Framework. 2021. Available online: https://ec.europa.eu/clima/policies/strategies/2030_en (accessed on 12 April 2021).
5. European Commission. The New Energy Efficiency Measures. 2021. Available online: https://ec.europa.eu/energy/sites/default/files/documents/technical_memo_energyefficiency.pdf (accessed on 12 April 2021).
6. European Commission. Impact Assessment-Stepping up Europe's 2030 Climate Ambition: Investing in a Climate-Neutral Future for the Benefit of Our People. 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020SC0176&from=EN (accessed on 12 April 2021).
7. European Commission. Preliminary Analysis of the Long-Term Renovation Strategies of 13 Member States. 2021. Available online: https://ec.europa.eu/energy/sites/default/files/swd_commission_preliminary_analysis_of_member_state_ltrss.pdf (accessed on 12 April 2021).
8. European Commission. A Renovation Wave for Europe—Greening Our Buildings, Creating Jobs, Improving Lives. 2020. Available online: https://ec.europa.eu/energy/sites/ener/files/eu_renovation_wave_strategy.pdf (accessed on 12 April 2021).
9. Innovate UK. *Retrofit Revealed—The Retrofit for the Future Project Data Analysis Report*; Innovate UK: Swindon, UK, 2013.
10. D'Oca, S.; Ferrante, A.; Ferrer, C.; Pernetti, R.; Gralka, A.; Sebastian, R.; Op't Veld, P. Technical, financial, and social barriers and challenges in deep building renovation: Integration of lessons learned from the H2020 cluster projects. *Buildings* **2018**, *8*, 174. [CrossRef]
11. Vavallo, M.; Arnesano, M.; Revel, G.M.; Mediavilla, A.; Sistiaga, A.F.; Pracucci, A.; Magnani, S.; Casadei, O. Accelerating Energy Renovation Solution for Zero Energy Buildings and Neighbourhoods—The Experience of the RenoZEB Project. *Multidiscip. Digit. Publ. Inst. Proc.* **2019**, *20*, 1. [CrossRef]
12. Shnapp, S.; Sitha, R.; Laustsen, J. What Is Deep Renovation? 2013. Available online: https://www.gbpn.org/sites/default/files/08.DR_TechRep.low_.pdf (accessed on 12 April 2021).
13. Agliardi, E.; Cattani, E.; Ferrante, A. Deep energy renovation strategies: A real option approach for add-ons in a social housing case study. *Energy Build.* **2018**, *161*, 1–9. [CrossRef]
14. Mills, B.; Schleich, J. Residential energy-efficient technology adoption, energy conservation, knowledge, and attitudes: An analysis of European countries. *Energy Policy* **2012**, *49*, 616–628. [CrossRef]
15. Bruel, R.; Fong, P.; Lees, E. *A Guide to Developing Strategies for Building Energy Renovation*; Buildings Performance Institute Europe: Brussels, Belgium, 2013.
16. Baek, C.H.; Park, S.H. Changes in renovation policies in the era of sustainability. *Energy Build.* **2012**, *47*, 485–496. [CrossRef]
17. Ferreira, M.; Almeida, M. Benefits from energy related building renovation beyond costs, energy and emissions. *Energy Procedia* **2015**, *78*, 2397–2402. [CrossRef]
18. Haase, M.; Lolli, N.; Thunshelle, K. *Renovation Concepts for Residential Buildings. Research Status, Challenges and Opportunities*; ZEN Report; SINTEF akademisk forlag: Trondheim, Norway; Norwegian University of Science and Technology: Trondheim, Norway, 2020.
19. Jochem, E.; Madlener, R. The forgotten benefits of climate change mitigation: Innovation, technological leapfrogging, employment, and sustainable development. In *Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers*; OECD: Paris, France, 2003.
20. Guerra-Santin, O.; Boess, S.; Konstantinou, T.; Herrera, N.R.; Klein, T.; Silvester, S. Designing for residents: Building monitoring and co-creation in social housing renovation in the Netherlands. *Energy Res. Soc. Sci.* **2017**, *32*, 164–179. [CrossRef]
21. Klumbyte, E.; Bliudzius, R.; Fokaides, P. Development and application of municipal residential buildings facilities management model. *Sustain. Cities Soc.* **2020**, *52*, 101804. [CrossRef]
22. Curtis, F.; Simpson-Housley, P.; Drever, S. Household energy conservation. *Energy Policy (UK)* **1984**, *12*, 452–456. [CrossRef]
23. Abrahamse, W.; Steg, L.; Vlek, C.; Rothengatter, T. A review of intervention studies aimed at household energy conservation. *J. Environ. Psychol.* **2005**, *25*, 273–291. [CrossRef]
24. OECD. *Greening Household Behaviour: The Role of Public Policy*; OECD: Paris, France, 2011.
25. Van Raaij, W.F.; Verhallen, T.M. A behavioural model of residential energy use. *J. Econ. Psychol.* **1983**, *3*, 39–63. [CrossRef]
26. Scott, S. Household energy efficiency in Ireland: A replication study of ownership of energy saving items. *Energy Econ.* **1997**, *19*, 187–208. [CrossRef]
27. Huebner, G.M.; Cooper, J.; Jones, K. Domestic energy consumption—What role do comfort, habit, and knowledge about the heating system play? *Energy Build.* **2013**, *66*, 626–636. [CrossRef]
28. Giraudet, L.G. Energy efficiency as a credence good: A review of informational barriers to energy savings in the building sector. *Energy Econ.* **2020**, *87*, 104698. [CrossRef]

29. Prati, D.; Spiazzi, S.; Cerinšek, G.; Ferrante, A. A User-Oriented Ethnographic Approach to Energy Renovation Projects in Multiapartment Buildings. *Sustainability* **2020**, *12*, 8179. [CrossRef]

30. Attia, S.; Eleftheriou, P.; Xeni, F.; Morlot, R.; Ménézo, C.; Kostopoulos, V.; Betsi, M.; Kalaitzoglou, I.; Pagliano, L.; Cellura, M.; et al. Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. *Energy Build.* **2017**, *155*, 439–458. [CrossRef]

31. De Gaetani, C.I.; Mert, M.; Migliaccio, F. Interoperability analyses of BIM platforms for construction management. *Appl. Sci.* **2020**, *10*, 4437. [CrossRef]

32. Grilo, A.; Jardim-Goncalves, R. Value proposition on interoperability of BIM and collaborative working environments. *Autom. Constr.* **2010**, *19*, 522–530. [CrossRef]

33. Arayici, Y.; Fernando, T.; Munoz, V.; Bassanino, M. Interoperability specification development for integrated BIM use in performance based design. *Autom. Constr.* **2018**, *85*, 167–181. [CrossRef]

34. Shirowzhan, S.; Sepasgozar, S.M.; Edwards, D.J.; Li, H.; Wang, C. BIM compatibility and its differentiation with interoperability challenges as an innovation factor. *Autom. Constr.* **2020**, *112*, 103086. [CrossRef]

35. Curry, E.; O'Donnell, J.; Corry, E.; Hasan, S.; Keane, M.; O'Riain, S. Linking building data in the cloud: Integrating cross-domain building data using linked data. *Adv. Eng. Inform.* **2013**, *27*, 206–219. [CrossRef]

36. Eastman, C.; Jeong, Y.S.; Sacks, R.; Kaner, I. Exchange model and exchange object concepts for implementation of national BIM standards. *J. Comput. Civ. Eng.* **2010**, *24*, 25–34. [CrossRef]

37. Smith, D.K.; Tardif, M. *Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers*; John Wiley & Sons: Hoboken, NJ, USA, 2009.

38. El Asmi, E.; Robert, S.; Haas, B.; Zreik, K. A standardized approach to BIM and energy simulation connection. *Int. J. Des. Sci. Technol.* **2015**, *21*, 59–82.

39. International Organisation for Standardisation. *29481-1: 2016: Building Information Models—Information Delivery Manual—Part 1: Methodology and Format*; International Organisation for Standardisation: Geneva, Switzerland, 2016.

40. Almaatouk, Q.; Othman, M.S.B.; Al-khazraji, A. A review on the potential of cloud-based collaboration in construction industry. In Proceedings of the 2016 3rd MEC International Conference on Big Data and Smart City (ICBDSC), Muscat, Oman, 15–16 March 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 1–5.

41. Bello, S.A.; Oyedele, L.O.; Akinade, O.O.; Bilal, M.; Delgado, J.M.D.; Akanbi, L.A.; Ajayi, A.O.; Owolabi, H.A. Cloud computing in construction industry: Use cases, benefits and challenges. *Autom. Constr.* **2020**, *122*, 103441. [CrossRef]

42. Yusof, M.M.; Papazafeiropoulou, A.; Paul, R.J.; Stergioulas, L.K. Investigating evaluation frameworks for health information systems. *Int. J. Med. Inform.* **2008**, *77*, 377–385. [CrossRef] [PubMed]

43. EMBuild. Barriers That Hinder Deep Renovation in the Building Sector. 2017. Available online: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5b3a088c0&appId=PPGMS (accessed on 26 May 2021).

44. Cooremans, C.; Schönenberger, A. Energy management: A key driver of energy-efficiency investment? *J. Clean. Prod.* **2019**, *230*, 264–275. [CrossRef]

45. Bertoldi, P.; Economidou, M.; Palermo, V.; Boza-Kiss, B.; Todeschi, V. How to finance energy renovation of residential buildings: Review of current and emerging financing instruments in the EU. *Wiley Interdiscip. Rev. Energy Environ.* **2021**, *10*, e384.

46. Van Oorschot, J.; Halman, J.; Hofman, E. The continued adoption of housing systems in the Netherlands: A multiple case study. *J. Constr. Eng. Manag. Innov.* **2019**, *2*, 167–190. [CrossRef]

47. Bertone, E.; Sahin, O.; Stewart, R.A.; Zou, P.X.; Alam, M.; Hampson, K.; Blair, E. Role of financial mechanisms for accelerating the rate of water and energy efficiency retrofits in Australian public buildings: Hybrid Bayesian Network and System Dynamics modelling approach. *Appl. Energy* **2018**, *210*, 409–419. [CrossRef]

48. Vogel, J.A.; Lundqvist, P.; Arias, J. Categorizing barriers to energy efficiency in buildings. *Energy Procedia* **2015**, *75*, 2839–2845. [CrossRef]

49. Prins, M.; Owen, R. Integrated Design and Delivery Solutions. *Archit. Eng. Des. Manag.* **2010**, *6*, 227–231. [CrossRef]

50. Owen, R.B.; Amor, R.; Dickinson, J.; Prins, M.; Kiviniemi, A. *Research Roadmap Report-Integrated Design and Delivery Solutions (IDDS)*; International Council for Research and Innovation in Building and Construction: Rotterdam, The Netherlands, 2013.

51. BRESAER. BRESAER-Breakthrough Solutions for Adaptable Envelopers in Building Refurbishment. 2019. Available online: http://www.bresaer.eu/about/ (accessed on 12 April 2021).

52. EASEE. EASEE-Envelope Approach to Improve Sustainability and Energy Efficiency in Existing Multi-Storey Multi-Owner Residential Buildings. 2016. Available online: https://cordis.europa.eu/project/id/285540 (accessed on 12 April 2021).

53. MEEFS. MEEFS-Multifunctional Energy Efficient Façade System for Building Retrofitting. 2016. Available online: https://cordis.europa.eu/project/id/285411 (accessed on 12 April 2021).

54. Plug-N-Harvest. Plug-N-Harvest—Plug-N-Play Passive and Active Multi-Modal Energy Harvesting Systems, Circular Economy by Design, with High Replicability for Self-Sufficient Districts & Near-Zero Buildings. 2017. Available online: https://cordis.europa.eu/project/id/768735 (accessed on 23 April 2021).

55. BuildHeat. BuildHeat-Standardised Approaches and Products for the Systemic Retrofit of Residential Buildings, Focusing on HEATing and Cooling Consumptions Attenuation. 2020. Available online: https://cordis.europa.eu/project/id/680658 (accessed on 12 April 2021).

56. IMPRESS. IMPRESS: New Easy to Install and Manufacture PRE-Fabricated Modules Supported by a BIM Based Integrated Design ProceSS. 2019. Available online: https://cordis.europa.eu/article/id/413460-old-meets-new-sustainable-retrofit-of-buildings-through-prefabricated-panels (accessed on 12 April 2021).

57. REFURB. REFURB—REgional Process Innovations FOR Building Renovation Packages Opening Markets to Zero Energy Renovations. 2018. Available online: https://cordis.europa.eu/article/id/240740-accompanying-home-owners-on-their-renovation-journey (accessed on 12 April 2021).

58. Boza-Kiss, B.; Bertoldi, P. One-stop-shops for energy renovations of buildings. *Joint Res. Cent. Eur. Energy Effic. Platf. (E3P)* **2018** . Available online: https://e3p.jrc.ec.europa.eu/sites/default/files/documents/publications/jrc113301_jrc113301_reportononestopshop_2017_v12_pubsy_science_for_policy_.pdf (accessed on 12 April 2021).

59. McGinley, O.; Moran, P.; Goggins, J. *Key Considerations in the Design of a One-Stop-Shop Retrofit Model*; CERI 2020; Civil Engineering Research Association of Ireland: Cork, Ireland, 2020.

60. NEWTREND. NEWTREND: New Integrated Methodology and Tools for Retrofit Design towards a Next Generation of ENergy Efficient and Sustainable Buildings and Districts. 2018. Available online: https://cordis.europa.eu/project/id/680474 (accessed on 12 April 2021).

61. 4RinEU. 4RINEU Results. 2021. Available online: https://4rineu.eu/results/ (accessed on 12 April 2021).

62. P2ENDURE. Background. 2021. Available online: https://www.p2endure-project.eu/en/project/background (accessed on 12 April 2021).

63. MORE-CONNECT. MORE-CONNECT Final Publishable Report. 2019. Available online: https://www.more-connect.eu/wp-content/uploads/2019/09/MORE-CONNECT-WP1_D1.7-Final-publishable-report.pdf (accessed on 12 April 2021).

64. REZBUILD. REZBUILD: A Multi-Collaborative Refurbishment Ecosystem. 2021. Available online: https://rezbuildproject.eu/multi-collaborative-refurbishment-ecosystem/ (accessed on 12 April 2021).

65. Tiwana, A.; Konsynski, B.; Bush, A.A. Research commentary—Platform evolution: Coevolution of platform architecture, governance, and environmental dynamics. *Inf. Syst. Res.* **2010**, *21*, 675–687. [CrossRef]

66. Mainali, B.; Mahapatra, K.; Pardalis, G. Strategies for deep renovation market of detached houses. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110659. [CrossRef]

67. Marini, A.; Passoni, C.; Belleri, A. Life cycle perspective in RC building integrated renovation. *Procedia Struct. Integr.* **2018**, *11*, 28–35. [CrossRef]

68. Farahani, A.; Wallbaum, H.; Dalenbäck, J.O. The importance of life-cycle based planning in maintenance and energy renovation of multifamily buildings. *Sustain. Cities Soc.* **2019**, *44*, 715–725. [CrossRef]

69. Farahani, A.; Wallbaum, H.; Dalenbäck, J.O. Optimized maintenance and renovation scheduling in multifamily buildings—A systematic approach based on condition state and lifecycle cost of building components. *Constr. Manag. Econ.* **2019**, *37*, 139–155. [CrossRef]

70. Ballon, P.; Van Heesvelde, E. ICT platforms and regulatory concerns in Europe. *Telecommun. Policy* **2011**, *35*, 702–714. [CrossRef]

71. Rozanski, N.; Woods, E. *Software Systems Architecture: Working with Stakeholders Using Viewpoints and Perspectives*; Addison-Wesley: Boston, MA, USA, 2012.

72. Lynn, T. ; Rosati, P.; Haugen, K.; Brownlow, C.; Walsh, R. Deliverable 8.1: Report on RINNO Dissemination & Communication Plan. 2020. Available online: https://rinno-h2020.eu/publications/report-on-rinno-dissemination-communication-plan/ (accessed on 12 April 2021).

73. Liang, X.; Yu, T.; Guo, L. Understanding stakeholders' influence on project success with a new SNA method: A case study of the green retrofit in China. *Sustainability* **2017**, *9*, 1927. [CrossRef]

74. ISO/IEC/IEEE. ISO/IEC/IEEE Systems and software engineering—Architecture description. In *ISO/IEC/IEEE 42010:2011(E) (Revision of ISO/IEC 42010:2007 and IEEE Std 1471-2000)*; IEEE: Piscataway, NJ, USA, 2011; pp. 1–46. [CrossRef]

75. Baldwin, C.Y.; Clark, K.B. Managing in an age of modularity. *Manag. Modul. Age Archit. Netw. Organ.* **2003**, *149*, 84–93.

76. Pil, F.K.; Cohen, S.K. Modularity: Implications for imitation, innovation, and sustained advantage. *Acad. Manag. Rev.* **2006**, *31*, 995–1011. [CrossRef]

77. Kaklauskas, A.; Zavadskas, E.K.; Raslanas, S. Multivariant design and multiple criteria analysis of building refurbishments. *Energy Build.* **2005**, *37*, 361–372. [CrossRef]

78. Juan, Y.K.; Kim, J.H.; Roper, K.; Castro-Lacouture, D. GA-based decision support system for housing condition assessment and refurbishment strategies. *Autom. Constr.* **2009**, *18*, 394–401. [CrossRef]

79. Levine, S.S.; Prietula, M.J. Open collaboration for innovation: Principles and performance. *Organ. Sci.* **2014**, *25*, 1414–1433. [CrossRef]

80. Paulsson, V.; Emeakaroha, V.; Morrison, J.; Lynn, T. Cloud Service Brokerage: A systematic literature review using a software development lifecycle. In Proceedings of the Americas Conference on Information Systems (AMCIS) 2016, San Diego, CA, USA, 11–14 August 2016.

81. Paulsson, V.; Emeakaroha, V.C.; Morrison, J.; Lynn, T. Cloud service brokerage: Exploring characteristics and benefits of B2B cloud marketplaces. In *Measuring the Business Value of Cloud Computing*; Lynn, T., Mooney, J., Rosati, P., Fox, G., Eds.; Springer Nature Switzerland AG: Cham, Switzerland , 2020.

82. Qolomany, B.; Al-Fuqaha, A.; Gupta, A.; Benhaddou, D.; Alwajidi, S.; Qadir, J.; Fong, A.C. Leveraging machine learning and big data for smart buildings: A comprehensive survey. *IEEE Access* **2019**, *7*, 90316–90356. [CrossRef]

83. Cáceres, J.; Vaquero, L.M.; Rodero-Merino, L.; Polo, A.; Hierro, J.J. Service scalability over the cloud. In *Handbook of Cloud Computing*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 357–377.

84. Bondi, A.B. Characteristics of scalability and their impact on performance. In Proceedings of the 2nd international workshop on Software and performance, Ottawa, ON, Canada, 17–20 September 2000; pp. 195–203.

85. Armbrust, M.; Fox, A.; Griffith, R.; Joseph, A.D.; Katz, R.; Konwinski, A.; Lee, G.; Patterson, D.; Rabkin, A.; Stoica, I.; et al. A view of cloud computing. *Commun. ACM* **2010**, *53*, 50–58. [CrossRef]

86. Marston, S.; Li, Z.; Bandyopadhyay, S.; Zhang, J.; Ghalsasi, A. Cloud computing—The business perspective. *Decis. Support Syst.* **2011**, *51*, 176–189. [CrossRef]

87. Leimbach, T.; Hallinan, D.; Bachlechner, D.; Weber, A.; Jaglo, M.; Hennen, L.; Nielsen, R.; Nentwich, M.; Strauss, S.; Lynn, T.; et al. Potential and impacts of cloud computing services and social network websites. In *Publication of Science and Technology Options Assessment*; European Parliamentary Research Service: Brussels, Belgium, 2014.

88. Radu, L.D. Green cloud computing: A literature survey. *Symmetry* **2017**, *9*, 295. [CrossRef]

89. Parn, E.A.; Edwards, D. Cyber threats confronting the digital built environment. *Eng. Constr. Archit. Manag.* **2019**. [CrossRef]

90. Mantha, B.; de Soto, B.G.; Karri, R. Cyber security threat modeling in the AEC industry: An example for the commissioning of the built environment. *Sustain. Cities Soc.* **2021**, *66*, 102682. [CrossRef]

91. Ciholas, P.; Lennie, A.; Sadigova, P.; Such, J.M. The security of smart buildings: A systematic literature review. *arXiv* **2019**, arXiv:1901.05837

92. Mundt, T.; Wickboldt, P. Security in building automation systems-a first analysis. In Proceedings of the 2016 International Conference On Cyber Security And Protection Of Digital Services (Cyber Security), London, UK, 13–14 June 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 1–8.

93. BAMB. BAMB—Buildings as Material Banks: Integrating Materials Passports with Reversible Building Design to Optimise Circular Industrial Value Chains. 2019. Available online: https://cordis.europa.eu/project/id/642384 (accessed on 12 April 2021).

94. FISSAC. FISSAC—Fostering Industrial Symbiosis for a Sustainable Resource Intensive Industry Across the Extended Construction Value Chain. 2019. Available online: https://cordis.europa.eu/project/id/642154 (accessed on 12 April 2021).

95. HISER. HISER—Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste. 2019. Available online: https://cordis.europa.eu/project/id/642085 (accessed on 12 April 2021).