Boosting the Renovation Wave with Modular Industrialized Renovation Kits: mapping challenges, barriers and solution strategies

J. van Oorschot
M. S. Di Maggio
P. Op 't Veld
A. Tisov

A common positioning paper by six H2020 projects on deep renovation.

Boosting the Renovation Wave with Modular Industrialized Renovation Kits: mapping challenges, barriers and solution strategies

Abstract

Successfully applied in other industries, the application of modularity and construction 4.0 strategies are seen as key to step up the pace of building renovation to achieve European Union (EU) climate goals for 2050. This led to the development of Zero Energy Renovation Kits addressing the need for efficient, sustainable and customizable deep-renovation solutions. The European innovation program Horizon 2020 supports various projects in developing market ready Zero Energy Renovation Kits. This positioning paper reports on the results of a workshop at the Sustainable Places 2021 Conference by six Horizon 2020 projects, assessing the challenges and barriers to develop, adopt and/or implement Zero Energy Renovation Kits. As a result, 32 technological, market, financial, legal, and institutional challenges and barriers were identified. During this workshop strategies were also discussed that could allow overcoming the identified challenges and barriers. This paper presents a coherent framework, which maps the intervention strategies against the challenges and barriers. The position paper concludes by addressing the implications for innovation managers, decision makers and policy makers to sustain the market for Zero Energy Renovation Kits. Finally, further research opportunities are highlighted.

Date
July 27th, 2022

Autors
J. van Oorschot[1]
M.S. Di Maggio[2,3]
P. Op 't Veld[2]
A. Tisov[2]

[1]Zuyd University of Applied Sciences, Smart Urban Redesign Research Centre, Nieuw Eyckholt 300, 6419 DJ Heerlen, The Netherlands: john.vanoorschot@zuyd.nl

[2] Huygen Engineers & Consultants, Urmonderbaan 22 (Gate 2), Building 220, 6167 RD Sittard-Geleen, The Netherlands; p.optveld@huygen.net

[3]ABT, Arnhemsestraatweg 358, 6881 NK Velp, The Netherlands; m.d.maggio@abt.eu

Graphic Design
R. Veneklaas

Contents

With contributions of the coordinators of the H2020 projects

Project name	Contributors
INFINITE BUILDINGRENOVATION 958397	Stefano Avesani, Eurac Research, IT
PLURAL 958218	Maria Founti, NTUA, GR
DRIVE 841850	Ana Tisov, Huygen Engineers & Consultants, NL
StepUP 847053	Giulia Barbano, IES, UK Michele Scotton, UNISMART
ProGETonE 723747	Annarita Ferrante & Anastasia Fotopoulo, UNIBO, IT
ENSNARE 958445	Peru Elguezabal, Tecnalia, ES

1. Introduction

Left - Example of a modular and industrialized Building Envelope Kit from the DRIVE 0 project

Right - The INFINITE mock-up in EURAC

With an insufficient rate of existing building renovation, there is need to step up the pace of building renovation to achieve European Union (EU) climate goals for 2050. Industrialization and related technological innovations, especially Zero Energy Renovation Kits, are at the core of boosting the Renovation Wave.

Innovative Building Envelop Kits should therefore adhere to the following pre-conditions (D'Oca et al., 2018; Decorte et al., 2020; Op't Veld, 2015):

- Speeding up the renovation time, avoiding disturbance for occupants as much as possible, i.e. support user-centric deep-renovation approaches
- Make the renovation more cost-effective
- Providing a higher performance and resource efficiency, both in energy and material
- The potential of re-use of building materials and urban mining

Effective ways for quality insurance

Towards further energy efficiency and decarbonisation of the EU building stock, modularity and industrialisation of Zero Energy Renovation Kits (Construction 4.0) for the deep renovation market are key strategies to improve both production and resource efficiency in constructing and retrofitting housing. Modularity in itself is a concept that is observed as a major beneficiary in numerous industries, but relatively new to the deep-renovation market. Modularity is seen as a key strategy to improve both production and resource efficiency in constructing and retrofitting housing (Ellen MacArthur Foundation, 2015a, b). Modular product systems are developed with an one-to-one mapping between functions and physical technical subsystems with standardised interfaces (Salvador, 2007; Ulrich, 1995). The use of Construction 4.0 principles, such as point clouds, Building Information Models (BIMs) annex Digital Twins or material passports et cetera, could further advance modular and industrialized Zero Energy Renovation Kits (Newman et al., 2020).

As a typical characteristic, Zero Energy Renovation Kits innovated as modular product systems balance technology efficiency improvement, in terms of prefabrication and industrialization, with a growing demand for customization - in order to meet specific project needs and client demands. This results in a mutually beneficial setting where the client is able to obtain benefits in the form of a well customized product that perfectly adheres to the client's specific needs. In addition to this, the client is able to procure the product at a relatively lower cost benefitting from economies of scale. Modularity and Industrialization have not only benefited the ever-evolving high-tech industries, but also the traditional, vertically specialized construction industry (Cacciatori and Jacobides, 2005). Recently, a number of EU H2020 projects explore these new strategies for deep renovation as a contribution to the EU Renovation Wave, including DRIVE 0, STEP UP, ProGETonE, INFINITE, PLURAL, and ENSNARE. See Figure 1 for an example of a modular and industrialized Building Envelope Kit from the DRIVE 0 project.

However, the innovative Zero Energy Renovation Kits developed in these Horizon 2020 projects face specific technological, market, financial, legal, and institutional challenges and barriers which need to be overcome to meet its full potential. This leads to the essential research question of this paper: which technological, market, financial, legal, and institutional challenges and barriers hinder the market uptake of modular and industrial Zero Energy Renovation Kits, and which strategies could overcome these challenges and barriers? A workshop was organized during the Sustainable Places 2021 Conference to explore this research question in detail. Based on the Zero Energy Renovation Kits developed in the DRIVE 0, STEP UP, ProGETonE, INFINITE, PLURAL, and ENSNARE projects the specific challenges and barriers were identified and mapped and subsequently propositions and strategies were explored to overcome the identified challenges and barriers. This paper in particular contributes by developing a coherent framework of challenges, barriers and intervention strategies to guide further uptake of Zero Energy Renovation Kits.

This paper is structured as followed. Section 2 elaborates on the conceptual and theoretical background of Zero Energy Renovation Kits. Subsequently, Section 3 will discuss the methodology followed to address the research question. The findings of the workshop are discussed in section 4. The concluding section 5, presents the key lessons learned and recommendations from workshop results. Moreover, the implications for innovation managers, decision makers and policy makers will be addressed. The section also concludes with exploring the avenues for further research needs.

ProGETone demonstration project in Athene, seismic proof renovation

Modularity in itself is a concept that is observed as a major beneficiary in numerous industries, but relatively new to the deep-renovation market. Modularity is seen as a key strategy to improve both production and resource efficiency in constructing and retrofitting housing.

2. Zero Energy Renovation Kits: conceptual and theoretical background

Industrial Building (IB) practices in the construction sector aim at raising efficiency by rationalising the construction process through the adoption of production technologies and methods found in highly industrialized mass-production industries like automotive. The three underpinning characteristics portraying the essence of IB are standardisation; prefabrication, and; system building (Zhang et al., 2014). Standardization is considered a prerequisite for the application of industrial production processes, both on- and off-site (Gann, 1996; Lessing et al., 2005). The predominant application of industrialised production methods is usually off-site prefabrication (Gann, 1996; Gibb, 2001). However, industrialized house building could also include site-based methods while still applying industrialised design and production principles (Thuesen and Hvam, 2011). The term 'systems building' has been introduced to describe a set of building components which are linked together and that require a well-coordinated system of technical and organizational interfaces (Gann, 1996; Finnimore, 1989; Vogler, 2016). In line with the digital revolution 'Industry 4.0', system building has been introduced recently as a fourth cornerstone of IB in attempt to fully automate design and construction processes by integrating a complex array of digital tools, technologies and programming languages that act in unison (Newman et al., 2020).

A Zero Energy Renovation Kit is seen as modular when it has separable subsystems that can be combined in different ways to provide 'standardized variety'.

Based on these general characteristics various attempts have been made to develop and introduce Industrial Housing System (IHS) applying mass-production principles to construct housing within a controlled environment and delivered through a well-coordinated integrated system (Grimscheid and Scheublin, 2010; Blismas et al., 2010; Kamar et al., 2009; Hamid et al., 2008). A specific type of IHS are Zero Energy Renovation Kits, defined as integrated solutions, including the envelope, the technical building systems and elements, the appliances, the energy production systems which allow the delivery of a net zero energy consumption building (Saheb, 2016). Zero Energy Renovation Kits have been introduced to step up the pace of building renovation to achieve European Union (EU) climate change policies for 2050. In fact, industrial building and modularity and related technological innovations are at the core of boosting the Renovation Wave (Renz and Zafra Solas, 2016; Saheb, 2016).

Beyond efficiency gains, firms are looking for ways to improve the sustainability, circularity, and level of customization in a way that does not increase project risks, complexity and building costs of deep-renovation projects. Applying industrial construction and deep-renovation methods based on product modularity has gained growing attention (Barbosa et al., 2017; Bertram et al., 2019; Hofman et al., 2009) and is seen as a green innovation strategy to offer deep-renovation solutions that contribute to the development and well-being of human needs while respecting natural resources and regeneration capacities (Tello and Yoon, 2008). Following Salvador (2007), a Zero Energy Renovation Kit is seen as modular when it has separable subsystems that can be combined in different ways to provide 'standardized variety'. In addition to Saheb's (2016) definition, a modular Zero Energy Renovation Kits is typically characterized by a one-to-one mapping between functions and physical subsystems and have standardized, decoupled interfaces (Ulrich, 1995). Decoupling reflected by its disassembly potential, implies that changes in one subsystem do not require changes in other interfacing subsystems (Baldwin and Clark, 2000). Modular Zero Energy Renovation Kits has the potential to substantially improve product and process sustainability by facilitating access to individual modules and components of the product system, thereby facilitating refurbishing, re-use and recycling (Chung et al., 2014; Kimura et al., 2001; Ma and Kremer, 2016; Okudan Kremer et al., 2013). This is especially relevant for modules that age more rapidly than parts they interface with, or that improve faster, for example due to higher innovation clock speeds, than other parts leading to an opportunity for modular upgrades of the system.

See table 1 for examples of core technologies applied in modular Zero Energy Renovation Kits. Modularity in housebuilding has gained substantial attention in the past two decades. We refer to various scientific articles (da Rocha et al., 2015; Doran and Giannakis, 2011; Halman et al., 2008; Hofer and Halman, 2005; Hofman et al., 2009; Lennartsson and Björnfot, 2010; Pero et al., 2015; Viana et al., 2017; Voordijk et al., 2006) and doctoral dissertations (Hofman, 2010; Jensen, 2014; Sheffer, 2011; Wolters, 2002) for further reading and additional examples.

Industrial and modular housing systems, Including Zero Energy Renovation Kits, are hardly adopted beyond their demonstration status across a range of subsequent projects, i.e. ‘the history of IB is rich in examples of failures’ (Arif and Davidson, 2009; Lind, 2011). This discontinued adoption is problematic, since the deep renovation market, clients and industry alike, do not benefit from the potential of industrial and modular building practices (Goodier and Gibb, 2007; Grimscheid and Scheublin, 2010; Pan et al., 2007; Songip et al., 2013; Thillart, 2002). It may be considered as a missed opportunity, since industrial and modular building practices have been identified as an important condition for solving worsening developments in the housing sector such as labour and skills shortage (ECSO, 2017); significant housing shortage (ECSO, 2018b) and a detrimental environmental impact (ECSO, 2018a).

Many related innovations seem to fall into a chasm after they have been taken up by early adopters in the market (Egmond et al., 2006; Matinaro and Liu, 2015; Naney et al., 2012) (and subsequently fail to be adopted beyond demonstration projects (Brown and Hendry, 2009; Femenias, 2004; Femenias et al., 2009; van Hal, 2000).

It seems that context specific, empirical studies unravelling the challenges, barriers and interventions strategies innovators dealing with developing and introducing industrial and modular Zero Energy Renovation Kits are missing.

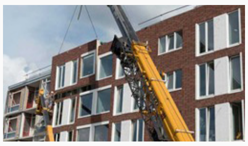
	Modular product system		
Company	**Technology**		**Services**
Aliva (Italy)	Cladding system		Consultancy & design; structural design and engineering; on-site, installation and project management
WEBO (Netherlands)	Facade system (timber frame modules)		Fully engineered as ‘Digital Twin’ (BIM); fully automated production; delivery to the construction site; on-site installation (without scaffolding)
Factory-0 (Netherlands)	Integrated indoor climate system		In-house product development department; in-house production facilities (system integrator); on-site installation and commissioning, monitoring; “remote” management annex monitoring; service & maintenance

Table 1

3. Methodology

3.1 Moderated focus group discussion

A workshop, involving six innovation projects on the development and application of modular and industrial Building Renovation Kits, was conducted to gain insight into technological, market, financial, legal and institutional challenges and barriers hinder the market uptake of modular and industrial Zero Energy Renovation Kits. As a second aim, strategies that could overcome the identified challenges and barriers were identified. The workshop session is best described as a moderated focus group discussion session and took place during the Sustainable Places event 2021 in Rome. This methodology was chosen because it allows one to retain a holistic and project overarching perspective to the main challenges and perspective sustaining the development of a deep-renovation market for modular and industrial Zero Energy Renovation Kits.

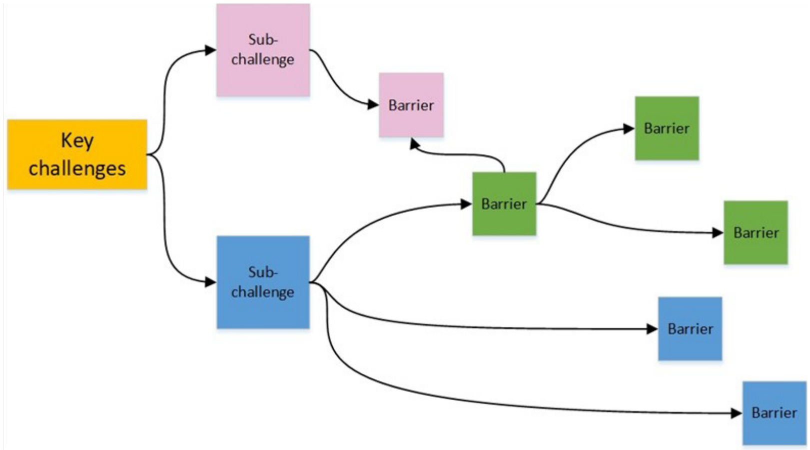
3.2 Selection of case projects

For a holistic perspective it was decided to select cases from cross-border

Table 2 - EU clustered Projects background

Project name	Timeframe	Description project objectives
INFINITE Industrialized durable building envelope retrofitting by all-in-one interconnected technology solutions	Start 2020 End 2025	The project aims at increasing the market penetration of industrialised all-in-one envelope systems for the nZEB building renovation from 1st to 2nd generation of systems. To demonstrate tools, techs, business models to boost the adoption in real market to show the "where and how" the Renovation4.0 can have success. >> https://infinitebuildingrenovation.eu/
PLURAL Plug-and-use renovation with adaptable lightweight systems	Start 2020 End 2024	The main contribution from PRURAL is to design, validate and demonstrate a palette of versatile, adaptable, scalable, off-site prefabricated "Plug-and-play" solutions that take into account user needs named "Plug-and-Use" (PnU) kits. Second, to select and incorporate renewable energy technologies in prefabricated façade components. And finally, to optimize the PnU performance for different building types, climates and socio-economic conditions. >> https://www.plural-renovation.eu/
DRIVE 0 Driving decarbonisation of the EU building stock by enhancing a consumer centred and locally based circular renovation process	Start 2019 End 2023	The aim of the project is develop market ready renovation products & concepts based on: local availability; Use of bio based materials and components; Emphasis on modular plug & play prefab solutions for building envelope elements and services, and; Automated BIM controlled production processes. Meanwhile, developing attractive consumer centred business models based on circular renovation concept. Providing occupants with attractive and understandable information on building performances in use. >> https://www.drive0.eu/
STEP UP Solutions and technologies for deep energy renovation process uptake	Start 2019 End 2023	StepUP develops a new process for deep renovation for decarbonisation, to minimise performance gap, reduce investment risk and maximise value. To achieve this, the project uses continuous feedback loops and promotes an iterative deep energy renovation approach, based on data insights, which positively impacts on energy costs, Indoor Environmental Quality (IEQ) and comfort. >> https://www.stepup-project.eu/
PROGETONE Proactive synergy of inteGrated Efficient Technologies on buildings' Envelopes	Start 2017 End 2022	The project idea is based on the innovative integration of technologies to achieve a multi-benefit approach by a closer integration between energy and non-energy related benefits. Thus, the project aims at combining in a same integrated system the highest performances (iii): Energy requirements, Safety and Social sustainability; to increase of the desirability of retrofit options and the real estate value of the buildings >> http://www.progetone.eu/
ENSNARE ENvelope meSh aNd digitAl framework for building Renovation	Start 2020 End 2024	The overall contribution of ENSNARE is to provide a systemic methodology combining products, systems and solutions. The main goal of ENSNARE is to boost the implementation of NZEB renovation packages in Europe. Two Key Structures are developed as supporting framework: Modular envelope mesh facilitating mechanical assembly & interconnection; A digital platform supporting all stages of the renovation process. >> https://www.ensnare.eu/

innovation projects, i.e. EU Horizon 2020 projects focusing on deep renovation and industrialization of envelope kits were selected. The starting points of this analysis are the experiences collected by six EU projects, which have been invited to join the workshop: DRIVE 0, STEP UP, ProGETonE, INFINITE, PLURAL, ENSNARE. Specifically, these innovation projects were selected because a) the key focus on the development of modular and industrial Building Renovation Kits and b) are currently running. The moderators ensured that the projects represent as many EU countries as possible. See Table 2 for a short description of each of the selected projects.



Scheme used for the mapping of the challenges, sub-challenges and barriers

3.3 Data collection

At the start of the workshop two short keynotes and Q&A were provided to ensure a general understanding about what is meant by modularity and industrialization in the field of deep-renovation. Next to this it has been asked to the project representatives to bring the two major challenges they encounter, or predict to encounter, within their projects. A presentation of each project and its specific challenges has been provided to set a clear context for discussion. Following the first informal mapping of challenges from each project representative, the interactive exercises started in a shared platform called ''Miro board'', an online whiteboard, where the input from each project has been gathered in a systematic way through the completion of four exercises.

Exercise 1

The first exercise focused on the collection of two key challenges per project, to be branched into smaller sub-challenges with their nature, key stakeholders involved and a qualitative risk rating assessment of the identified barriers (see figure 2 for an indication how this was mapped in the Miro board).

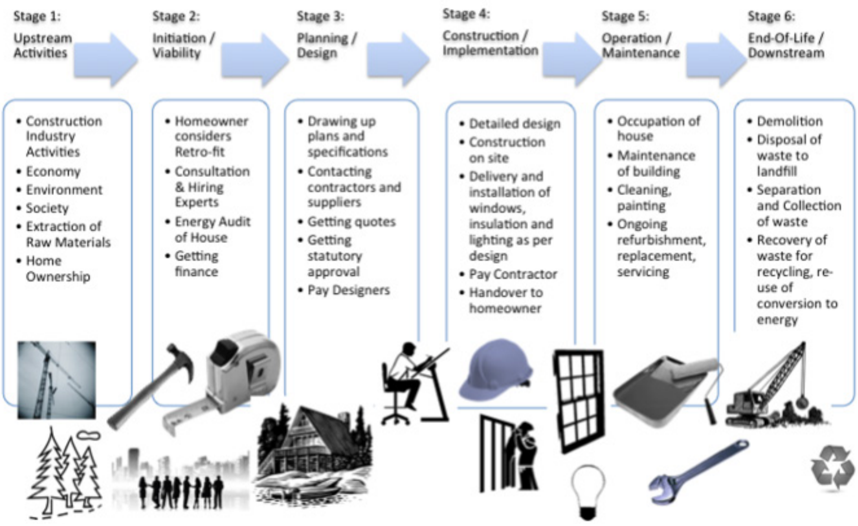
Then, participants were asked to identify the barriers the activities of a project design and construction timeline, in order to assess the likeliness of such barriers to occur at specific times of the deep-renovation process, see Figure 3. For more details we refer to the DRIVE 0 project which specifically took into account the implications on the deep-renovation process applying Zero Energy Renovation Kits (Van Oorschot et al., 2021a).

Exercise 2

The second exercise focused on the categorization of the barriers encountered within the following areas: building regulations, building typology, costs and time, training skills, responsibilities and liabilities, technology readiness level.

Exercise 3

The third exercise of the workshop focused on the identification of the solutions that could be deployed to overcome the challenges and barriers elaborated in exercise 1 and 2. The



Conventional project timeline of design and construction process and associated activities (adopted from Dunphy et al. (2013))

proposed intervention strategies embody the preliminary findings of ongoing research projects and reflect the preconditions which need to be met applying Zero Energy Renovation Kits in the deep-renovation market. These intervention strategies were grouped by category: legal, geometry, training, technology readiness level, costs/ time related.

Exercise 4

Exercise 4 was developed as a reality check for the suggested strategic interventions to overcome the key challenges and barriers to Zero Energy Renovation Kits: within the context of this fourth exercise it was asked to the project representatives to pinpoint the interventions strategies that could help addressing the key challenges and barriers within the context of their project. Finally, the overview of such comprehensive set of strategies was organized within a roadmap framework to boost actual development. By selecting the most urgent strategies to be accomplished within the next year, the mid-term strategies in 5 years' time and the long-term strategies in 20 years. During the second part it was discussed more in detail how the identified 'adoption and market barriers' need to be overcome to meet the identified preconditions to successfully introduce Zero Energy Renovation Kits in deep-renovation projects. In the following section, section 4, results from the workshop are reported and analyzed more in depth.

3.4 Data analysis

The analysis consisted of coding the content of the Miro Board. Coding consists of segmenting, separating and disassembling the data obtained during data collection into smaller units of information that are easier to handle, after which the data are reassembled and analysed. The first 'open coding' step took place during the workshop. This step consisted of a first order analysis of the key challenges and barriers as well as intervention strategies addressed by the workshop participants. In the next step, 'axial coding' was employed to reorganize and reassemble the codes identified in the previous phase. The output of this step consists of mapping single challenges, barriers and interventions strategies into categories and is considered an essential intermediary step towards mapping challenges, barriers and interventions into a coherent framework, also referred as theoretical coding. Identifying the first-order challenges, barriers and intervention strategies and, subsequently, building a coherent framework was supported by a data structure that consisted of various research notes and matrices as suggested by Miles and Huberman (1994), see the Miro board and the tables and figures included in this article.

Find the Miro board here: https://miro.com/app/board/o9J_lv2wiH8=/

4. Findings

The workshop was organized at the 2021 Sustainable Places Conference in Rome, Italy. The platform used to conduct the workshop was a Miro board, an online whiteboard, to allow data collection and feedback gathering from the case partners and general participants. The workshop was organized in a hybrid setting in which people joined both physically and online (due to the restrictions following the Covid-19 pandemic). Both groups of participants were able to access the Miro board using mobile devices, to participate in the workshop. The findings of the four exercises are presented in sections 4.1-4.4 subsequently.

4.1 Exercise 1 results: mapping key challenges of the 6 Horizon 2020 projects
Within the context of the first exercise conducted, it was asked to the workshop participants and representatives of the six Horizon 2020 projects to clarify the following items:

- Key challenges and sub-challenges of their project
- Nature of challenge
- Stakeholder involved
- Risk associated to it

The feedback and discussions around this topic have been reported in Table 3 below.

Table 3 - Exercise 1
Mapped challenges of the 6 EU projects on deep renovation

Project name	Key challenges	Sub-challange	Nature of challange	Key stakeholders	Risk rating
INFINITE BUILDING RENOVATION	Industrialised renovation cost attractiveness	1. Defining fair benchmark (traditional retrofit features): 2. Co-benefits evaluation; 3. Benefits for different stakeholders in the value chain; 4. When using industrialised retrofit? Performance and Quality requirements to take into account	Processes + Stakeholders	Investors VS Industrial technology providers	HIGH
	Multi-functionality: warranties, liability etc.	1. Warranties and liability to be provided to owners 2. value-chain still not established (it is new business)	Business of stakeholders	Stakeholders business models	MEDIUM
PLURAL	Lack of knowledge	1. No market demand;	Private and public entities	Decision makers, architects, contractors	LOW
	Technology compatibility	1. Development of IT design tools for flexible integration of façade with RES technologies	Process	Technology developers	MEDIUM - LOW
ENSNARE	Technologies need to match under a synergetic approach	1. Understand the optimum performance for each individual technology 2. Design the industrialised solution based on those principles 3. Develop specific design tools to support different stages of renovation process (decision making, design, manufacturing, installation...) 4. Establish clear responsibilities for gathering the information at each phase is necessary and a comprehensive building data checklists are required. 5. Having a comprehensive building data checklist	Product's performance	Industrials providing the technology Designers, Architects	MEDIUM
	Communication between the stakeholders.	1. Establish communication protocols 2. ICT to establish communication channels 3. Centralised BIM digital models to work collaboratively	Different disciplines, skills and working cultures	All stakeholders in the value chain	HIGH
DRIVE	Circularity	1. Taxation of labour rather than raw materials causing low competitiveness of recycled products compared to virgin raw materials 2. Difficult to obtain recycled materials for re-use in a building retrofit 3.Mistrust for the performance of the materials	Process, product's performance	Governments, product manufacturers, clients, designers	HIGH
	Modularity	1. Certification is costly, complex and lengthy 2. Integration within projects is complex (i.e. matching construction process and supply chain set up) 3. New value chain relationships	Product, process	Product manufacturers, investors	HIGH
StepUP	Adaptability of technologies to existing buildings	1. Shape of the building, existing systems, connections etc.	Process	Designers, manufacturers, contractors	MEDIUM
	Granting future evolution of the technology	1.Industrialised components should avoid on-site work as much as possible, so how to ensure the replacement / addition of a new technology is positive and non-destructive	Service	Product manufacturers	HIGH
ProGETonE	Legislative restrictions	1. New policies recommendations are necessary; 2. Engaged stakeholders are required	Process	Professionals, owners	HIGH
	High costs of new products and services	1.Lack of trust in such innovative & non-mainstream solutions and products 2. Lack of technical knowledge in product installation, functioning	Process	Professionals, owners, investors	MEDIUM

As shown in Table 3, workshop participants indicated several types of challenges. The results of the exercise show that most of the EU project cases challenges are ‘’process’’ related, with a minority of product and stakeholder engagement challenges. In terms of stakeholders, product manufacturers are those ones facing the most challenges across the project cases involved.

This exercise was complemented by the request to locate such challenges on a project timeframe, so that it could be possible to identify when specific barriers arise during a deep renovation project. The barriers encountered along the project timeline are mapped in Table 4.

There is homogeneity in the spreading of the barriers to deep renovation across the whole building design and construction process stages, with peaks at viability/planning stage and construction and implementation stage. By looking more closely at the barriers, these are quite diverse and span from the legal/political ones to the training related and lack in skilled capacity for the deep renovation. Interestingly, there are few challenges allocated to the operational phase of the project, which can be interpreted as trust in the functionalities of the technologies being deployed, as well as lack of vision/experience in this phase.

During the upstream activities the challenges involve a lack of business models for the building envelope kits technologies coupled with mistrust on the performance of the innovative components, which does not facilitate the market uptake of such products in the first instance. Within the stage of viability and planning, challenges related to the compatibility of the technological kits with “Plug & Play connections” with the existing building systems and components emerge, making it difficult for the industrialised solution kits to be implemented. This fact might as well negatively affect the decision to go for a deep renovation process, since no design tools are used in the planning and design phase to assess these options in comparison with other standard best practice solutions. During the construction and implementation phase a lack of skilled workers capacity to install the building envelope kits is faced. This can easily lead to rising prices for labour, due to the few potential contractors in the market that can undertake such works.

As per the operational phase and end of life scenarios, warranties and liabilities to be provided to owners of deep retrofitted buildings constitute still a grey area that limits the engagement of building owners with regard to the integration of such technologies in the building envelope.

4.2 Exercise 2 results: mapping the barriers to the deep renovation

The second exercise focused on the mapping of the barriers to deep renovation distinguishing in six types of barriers:

- Political/legal or institutional barriers;
- Project context or building typology and geometry related barriers;
- Costs/time optimization barriers;
- Training, knowledge and skills related barriers;
- Barriers related to inadequate allocation of liabilities/responsibilities;
- Technology readiness related barriers.

Table 4 - Exercise 1 pt. 2
Challenges versus project timeline steps

Stages of the project	Already experienced	Current challanges	Predicted challanges
Stage 1 Upstream activities	Taxation of labour rather than raw materials; Lack of certification as guarantee for decision makers	Need for new business models to enable new products to succeed (circular BM, product as a service BM.); Industrialised renovation cost, cost-attractiveness; material costs surge	
Stage 2 Initiation / Viability	Certification (fire) & permissions; trust and engagement of key actors; Difficult to obtain recycled materials for re-use	Early decision support tool; Lack of regulatory framework; Existing buildings are often not compatible with the connection systems of new plug & play circular components	National/local regulations do not allow in many cases to increase the volume or the thickness of the facade. Multi-property buildings make it difficult to agree on the implementations of such innovative approaches
Stage 3 Planning/ Design	Adapt design to local legislations/ consensus of tenants/ local experts to be involved/adaptation of existing technologies/reach the specific goals (energy, structure); new way of interacting to design the technical solutions	Design tools including innovative solutions; Tools that match technology capabilities; Interaction of different industrialized products in the same building; Tools for accurate installation of industrialized panels	
Stage 4 Construction/ Implementation	Adaptable control and monitoring systems; on-site preliminary work planning are key	High upfront costs/ adaptation to unexpected issues/integration of technologies; Lack of certification of products; Interaction of different industrialized products in the same building; Multi-ownership/engagement to monitor and communicate; As per the constructive aspects, Require reinforcement of the load-bearing structures to support the new loads	Installation according to provider guidelines; Lack of workforce adapted to such products
Stage 5 Operation/ Maintenance		Multi-functionalities: warranties, liability issues	
Stage 6 End of life scenario	Durability is still a big gap for integrated technological solutions	Warranties and liability to be provided to owners; Procedures for controlled deconstruction/ demolition process	Market exploitation/limited market & Lack of financial incentives & Investors

Barrier type	Identified barriers & challenges	Drive 0	INFINITE	Plural	Ensnare	StepUP	ProGETonE
Political/legal or institutional barriers	• Adapt design to local legislations/local experts to be involved for bureaucratic procedures			●	●	●	●
	• Taxation of labour rather than raw materials						
	• National/local regulations do not allow in many cases to increase the volume or the thickness of the facade.	●	●				●
	• Not established manufacturing and installation procures and certification	●		●	●		
	• Lack of certification	●					
Project context or building typology and geometry related barriers	• 3D laser scanning not yet mature enough to substitute conventional measuring for accuracy in installation			●			
	• Scan to BIM/integration of existing technologies						●
	• Require reinforcement of the load-bearing structures to support the new loads	●	●		●		
	• Adaptability of the preassembled solution to the existing façade	●		●	●	●	
	• Tools for accurate installation of industrialized panels				●		
	• Data acquisition tools to get a reliable picture about the building's status				●	●	
	• Existing buildings are often not compatible with the connection systems of new plug & play circular components						
	• Interaction of different industrialized products in the same building		●	●	●	●	●
	• Need for systems that can be adapted to the specific requirements of the facade/space to be renovated			●	●	●	●
	• Multi-property buildings makes it difficult to agree on the implementations of such innovative approaches	●	●			●	●
Costs/time optimization barriers	• Industrialised renovation cost-attractiveness	●	●	●			●
	• Lack of "one- stop shop" process						●
	• There cannot be a universal retrofit solution optimised in terms of time/cost. Each building has its own requirements; this prohibits cost-time optimization	●		●	●	●	●
	• All stages: Specific tools to support different stages of renovation process are missing (decision making, design, manufacturing, installation…)	●			●		
Training, knowledge and skills related barriers	• Need to train designers/architects in the use of new "integrated" tools; train workforce for more complex installations	●		●	●	●	●
	• Installation must be very precise - guidelines must be available			●			●
	• Lack of technical knowledge and communication from the technical companies and professionals						
	• Lack of workforce adapted to such products	●			●		●
	• Lack of design skills to integrate modular product systems in the overall design				●		
Barriers related to inadequate allocation of liabilities/responsibilities	• Warranties and liability to be provided to owners are not yet clear	●	●	●	●	●	
	• Multi-functionalities: warranties, liability are not certain		●		●		
	• Difficult to obtain recycled materials for re-use	●					
	• Mistrust for the performance of the materials	●					
	• Reverse logistics (from projects to supply chain) underdeveloped	●		●			●
Technology readiness related barriers	• Need for new business models to enable new products to succeed (circular BM, product as a service BM, et cetera)	●		●	●		●
	• Business models are necessary to facilitate the implementation of the deep renovation process	●				●	●
	• Reorganization of value chain with new business models	●		●	●		●

Table 5 - Exercise 2
Mapping the barriers to the deep renovation of the building stock

Within the political and legal context for the implementation of deep retrofit solutions, national and local regulations do not allow in many cases to increase the volume or thickness of the façade to a certain extent. This fact, coupled with the lack in structured procedures and certification of products can restrict the implementation of deep retrofit strategies already at planning/viability stage, with consequential detrimental effects on the de-carbonization of the existing building stocks.

Scan-to-BIM activities and 3D laser scanning are not yet mature to substitute conventional measuring tools for installation of building components in existing premises. In fact, realizing a reliable scanning of existing buildings geometry and features is a recognized as challenging, due to lack of accuracy and compatibility with existing best practice technologies. As emerged also from the previous exercise, there is a need to acquire reliable data on the building status through data acquisition tools, which is a significant step that can inform the selection of the most effective retrofit solutions per project case. This topic is also addressed in more detail in one of the project cases, namely the EU funded INFINITE project, and in the preceding project MORE-CONNECT.

Once the technologies are developed and ready to be implemented in projects, it requires skilled workforce to install such new innovative components in existing buildings. Especially because specific guidelines and procedures need to be followed that are directed towards ease of assembly/disassembly methods. However, construction companies undertaking refurbishment projects do not often have enough in-house knowledge adapted to such installation and maintenance procedures, which largely differ from current on-site construction practices. This fact is a relevant bottleneck for construction and facilities management industry players, which need to invest more time and costs to train their workers on the adoption, installation and maintenance of deep retrofit solutions. It is evident from the workshop exercise, that the technological barriers are not related to the readiness of the product development per se, rather the lack of trust in such new and pioneering solutions which is also exacerbated by the absence of business models that can support and frame the innovative technologies for the industrialization of the building sector.

The value chain of the deep renovation process shall also be revisited and simultaneously re-organized to introduce new business models, also the most disruptive ones like Façade as a service, Comfort as a service, et cetera.
Despite the fact that modular and industrialized renovation solutions offer many substantial advantages compared to traditional renovation solutions, there are still many barriers that hamper the speeding up the market uptake. The barriers for an accelerated market uptake are not that much on a product level or technology level but more on a process and institutional level.

In the table above the participants elaborated more on the barriers encountered in their EU projects with regard to the six categories identified.

4.3 Exercise 3 results: solutions to the deep renovation barriers

The participants to the workshop were then asked to address the following questions:
1. How can we overcome the barriers?
2. Who are the players that can introduce the solutions?

Solutions were discussed and proposed by

Table 6 - Exercise 3
Solutions to the barriers of the deep renovation

Barrier type	Envisioned intervention strategies	Drive 0	INFINITE	Plural	Ensnare	StepUP	ProGETonE
Political/legal or institutional barriers	• Creation of circular networks to push cross-sectoral collaboration	●				●	●
	• Platforms to link supply and demand (how do clients learn about - the existence of - deep-renovation solutions)						
	• Standardise norms, testing, .. to support performance verification and assure performances in time (warranties - liabilities)	●	●	●	●	●	
	• Standards & regulation for innovative solutions.				●	●	●
	• Creation of certification frameworks	●		●			
	• Political motivation for market uptake of innovative solutions via national EU incentives				●	●	●
	• Adaptation of regulations						●
	• Integration of technical, financial and benefits information for the end users			●	●	●	
	• Fiscal incentives to make recycled materials more competitive (subsidies, taxation)	●			●		●
	• Reducing labour taxes to make recycling more competitive	●					
	• Development of one-stop-shop concepts to leverage the implementation the modular and/or industrial produced deep-renovation technologies in projects	●		●	●		●
Project context or building typology and geometry related barriers	• Lighter solutions / Substitutions instead of additions	●	●	●	●		
	• Shared protocols for technology interoperability	●		●	●	●	
	• Creating pioneer examples to be promoted by the local authorities as attractive prototypes for the end users/clients	●		●	●	●	●
	• Implementation of Market platforms with clusters of providers for products, services and related activities to the deep renovation						●
Costs/time optimization barriers	• Co-benefits evaluation and co-design		●				
	• Intensively introduce "standardised" LCC (and LCA) as methods and KPIs	●	●	●			●
	• Foster the creation of new business roles in the deep industrialised renovation: the facilitator / one-stop-shop (e.g. Envelope4Service)		●	●	●	●	●
	• Demonstration activities quantifying the benefits of the whole operation LCA perspective	●		●	●		●
	• Reorganization of value chain with new business models	●		●			●
Training, knowledge and skills related barriers	• New training content and methodology	●			●	●	●
	• Standardization of Process						
	• ICT tools to establish communication channels oriented towards different stakeholders			●	●		
	• Foster co-design tools and BIM process			●		●	●
	• Informative platforms to facilitate the integration of new technologies/solutions/ strategies into the current building design & practice towards deep renovation and building re-shaping	●			●	●	●
	• New training & education towards circularity	●					●
Barriers related to inadequate allocation of liabilities/responsibilities	• None identified during the workshop						
Technology readiness related barriers	• Develop IT tools that couple design - manufacturing - assessment			●	●	●	
	• Quality assessment tools to assess the conditions/product specifications of technologies during its various life cycle stages (rest-value)	●		●			
	• Development of objective tools to assess the performance of deep-renovation technologies and communicate these performances beyond the scope of the project	●		●	●		●
	• Developing new PnP (Plug &Play) connectors				●	●	

the six EU project representatives covering a large part of the barriers encountered.
On the legal and political spectrum, the solutions proposed referred in large part to the creation of standards and frameworks for boosting the Zero Energy Renovation Kits implementation:

- Standards & regulation for innovative solutions
- Creation of certification frameworks
- Political motivation for market uptake of innovative solutions via national EU incentives
- Creation of circular networks to facilitate interdisciplinary collaboration

To overcome barriers related to geometry and country specific requirements, the implementation of pilot projects and prototypes is seen of value as well as the introduction of market platform with clustered products and process to undertake deep renovation retrofit programmes. This approach has already been initiated by EU funded projects such as re-MODULEES, which aims at the capitalization of retrofit solutions already available in the market.

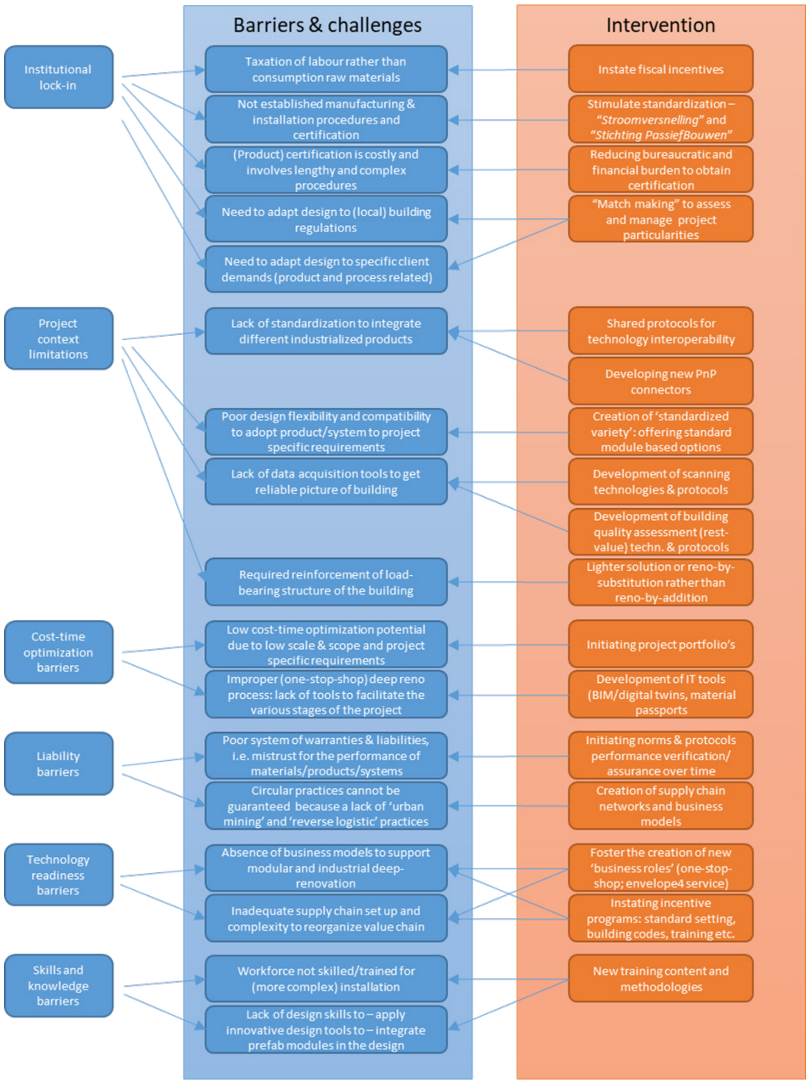
From a green innovation point of view, introducing LCA and LCC methods as standards in deep-renovation projects could stimulate the adoption of Zero Energy Renovation Kits. Especially because Zero Energy Renovation Kits tend to combine a higher purchasing price with reduced operating cost due to increased energy efficiency. LCA and LCC methods inform decision makers in deep-renovation projects about best value for money taking into account that within deep-renovation projects implementation decisions tend to be based on acquisition costs rather than total value offered. Additionally, upcoming business models such as one-stop-shops; "façade as a service", and; "comfort as service" requires expertise in for example service provision, warranties and liabilities. Thus, new business roles and specialisms in the deep renovation will emerge with the introduction of Zero Energy Renovation Kits.

Shared among all the project representatives is the urgency of developing training contents and educational services to form the deep renovation roles of the future. This is connected with the rising of new ICT tools, specific plug- in's, sophisticated digital twins and BIM processes intended at streamlining the industrialization of the building renovation and associated work pipelines, which are still fragmented and in large part unregulated. The deep renovation technologies are in fact not comparable in an objective way nor a database with the available TRL ready innovations can be accessed by consultants and experts in the field. The development of objective tools to assess the performance of deep-renovation technologies and the communication of these performances beyond the scope of the project could help decision makers in the design and construction industry with informed selection of the most effective kits per project. This selection can be helped and supported also by the use of tools that couple the design/manufacturing and monitoring stages of the Zero Energy Renovation Kits from start to assembly/ disassembly until the kits end of life stage. Moreover, the knowledge of smart connectors and "Plug & Play" solutions systems shall be propelled and wide spread across the technical design and construction sector, since this is recognised as a key element in the development of industrialised kits technologies and their effective installation on projects.

As result of this study and analysis of the data gathered from the workshop, the following framework has been built up to organize the barriers in relation to the corresponding solutions that can be deployed (Figure 4).

From a green innovation point of view, introducing LCA and LCC methods as standards in deep-renovation projects could stimulate the adoption of Zero Energy Renovation Kits.

Coherent framework of barriers and intervention strategies



4.4 Exercise 4 results: reality check

Following the mapping of the barriers to the deep renovation process and the associated potential solutions gathered from the previous three exercises, it was asked to the project representative to apply such brainstormed large array of solutions and technical strategies to their European projects, to start exploring practical directions to inform each project development and process. This exercise can be seen as a 'reality check' of the feasibility and possible deployment of the measures highlighted in connection with the real project cases from the 6 participating project teams. See table 7 below with the results of this exercise.

To conclude the workshop, participants were asked to draft a roadmap to foster deep renovation processes indicating the main actions to be taken to successfully overcome the several barriers and challenges mapped. More specifically, the attendees of the workshop were asked to answer the following questions:

1. Can you locate the strategies to overcome the barriers to the deep renovation in the timeline framework?
2. What is the most urgent action to address?
3. What actions are less urgent?

Table 7 - Exersie 4 pt. 1
Reality check of deep renovation solutions in relation to the six participating project cases.

Solutions type	Envisioned intervention strategies	Drive 0	INFINITE	Plural	Ensnare	StepUP	ProGETonE
Political/legal or institutional barriers	• Creation of circular networks to push cross-sectoral collaboration						
	• Platforms to link supply and demand (how do clients learn about - the existence of - deep-renovation solutions)						
	• Standardise norms, testing, .. to support performance verification and assure performances in time (warranties - liabilities)		●				
	• Standards & regulation for innovative solutions.						
	• Creation of certification frameworks			●	●		
	• Political motivation for market uptake of innovative solutions via national • EU incentives	●				●	●
	• Adaptation of regulations						
	• Integration of technical, financial and benefits information for the end users						
	• Fiscal incentives to make recycled materials more competitive (subsidies, taxation)						
	• Reducing labour taxes to make recycling more competitive						
	• Development of one-stop-shop concepts to leverage the implementation						
	• the modular and/or industrial produced deep-renovation technologies in projects						
Project context or building typology and geometry related barriers	• Lighter solutions / Substitutions instead of additions						
	• Shared protocols for technology interoperability						
	• Creating pioneer examples to be promoted by the local authorities as attractive prototypes for the end users/clients	●	●	●	●	●	●
	• Implementation of Market platforms with clusters of providers for products, services and related activities to the deep renovation		●				
Costs/time optimization barriers	• Co-benefits evaluation and co-design						
	• Intensively introduce "standardised" LCC (and LCA) • as methods and KPIs						
	• Foster the creation of new business roles in the deep industrialised renovation: the facilitator / one-stop-shop (e.g. Envelope4Service)	●	●				●
	• Demonstration activities quantifying the benefits of the whole operation LCA perspective	●	●	●			●
	• Reorganization of value chain with new business models			●			
Training, knowledge and skills related barriers	• New training content and methodology			●		●	
	• Standardization of Process						
	• ICT tools to establish communication channels oriented towards • different stakeholders						
	• Foster co-design tools and BIM process		●	●		●	●
	• Informative platforms to facilitate the integration of new technologies/ solutions/ strategies into the current building design & practice towards deep renovation and building re-shaping	●					
	• New training & education towards circularity		●				●
Barriers related to inadequate allocation of liabilities/responsibilities	• None identified during the workshop						
Technology readiness related barriers	• Develop IT tools that couple design - manufacturing - assessment		●	●	●	●	●
	• Quality assessment tools to assess the conditions/product specifications • of technologies during its various life cycle stages (rest-value)						
	• Development of objective tools to assess the performance of deep-renovation technologies and communicate these performances beyond the scope of the project						
	• Developing new PnP (plug &Pluy) connectors						

Table 8 - Exercise 4 pt. 2
Timeline to boost the deep renovation

Timeline to boost the deep renovation			
	Now & 2022	**In the next 5 years**	**In the next 10 to 20 years**
Strategies to boost the deep renovation	• Introduction of "standardised" LCC and LCA as methods and KPIs analysis • Financial/Economical incentives for the deep renovation • Creation of circular networks to push cross-sectoral collaboration • Education & trainings in order to increase legitimacy, awareness • Development of IT tools that couple design - manufacturing - assessment • Demonstration activities to quantify the benefits of the whole operation LCA perspective • Facilitation of lighter solutions for construction and Substitutions instead of additions • New training content and methodology	• Shared protocols for technology interoperability • Standardise norms, testing etc. to support performance verification and assure performances in time • Foster the creation of new business roles in the deep industrialised renovation: the facilitation of one-stop-shop (e.g. Envelope4Service) • Political motivation for market uptake of innovative solutions via; national EU incentives • New training & education towards circularity • Reducing labour taxes to make recycling more competitive • Creation of certification frameworks • Develop IT tools that couple design - manufacturing - assessment • Demonstration activities quantifying the benefits of the whole operation LCA perspective • Reorganization of value chain with new business models	• Political motivation for market uptake of innovative solutions via; national EU incentives • Reorganization of value chain with new business models

5. Conclusion, implications and directions for further research

5.1 Conclusions

Despite the fact that modular and industrialized renovation solutions, i.e. Zero Energy Renovation Kits, offer many substantial advantages compared to traditional renovation approaches, there are still many barriers that hamper speeding up market uptake. This paper identified 32 technological, market, financial, legal and institutional barriers hindering the market uptake of modular and industrial Zero Energy Renovation Kits.

Identified as the main overarching barrier, it seems that there is still no level playing field in the market for innovative modular and industrialized renovation technologies. For circular renovation technologies the situation is even more critical. This indicates that market uptake is not hindered by product or technology related barriers but predominately affected by process and institutional impediments. The current situation shows that the traditional renovation market is still dominated by traditional construction companies, both large and small companies. Also, the traditional way of renovation creates a workflow where there are many layers involved in the renovation process. For Zero Energy Renovation Kits some of these layers are redundant as tasks and responsibilities shift upstream the value stream towards the suppliers of the key modules of the Zero Energy Renovation Kits (building envelope modules; HVAC 'engines'; service platforms et cetera). Taking into account that many traditional construction companies have a total other 'earning model' than new innovative companies is one of the reasons that there is still no level playing field in the renovation market. This means that decision-making about deep-renovation is dominated by a lowest-acquisition-cost orientation rather than an evaluation of the Total Cost of Ownership (TCO). The evaluation of the TCO of an asset includes assessing the cost of acquiring an asset plus the operation cost throughout the product's lifecycle. Too often decision-making within deep-renovation projects is based on acquisition costs rather than total value (and total costs) offered. The modules constituting Zero Energy Renovation Kits products tend to combine a higher purchasing price with reduced operating cost due to increased energy efficiency and are therefore not selected. These findings are in line with research about introducing modularity in the housebuilding and as such the deep-renovation sector. Research has emphasized the need to balance modularity in product, process and supply chain designs when introducing a potentially successful modular products - such as Zero Energy Renovation Kits (Fine et al., 2005; van Oorschot et al., 2021b; Voordijk et al., 2006; Wolters, 2002). The suggested intervention strategies identified in this article also point in this direction.

During the workshop also the need for upskilling, training contents and educational services was mapped and discussed, in order to prepare both craftsman and specialists for working with new renovation technologies, designs and tools. This will also determine and form the deep renovation roles of the future. Nevertheless, these (re-)training efforts, specialization and continuing professional development (CPD), are a major setback for construction companies as they require high initial investments that is seen as a burden and in many countries not incentivised.

This cannot be seen separately from the introduction of new ICT applications and BIM adoption in general in deep renovation, such as sophisticated digital twins, specific plug-in's, advanced geomatics, point clouds to BIM, and applications intended at streamlining the industrialization of building renovation and associated workflows which are still fragmented and in large part unregulated. As ICT applications become available, particularly in the field of advanced geomatics, working with it requires radical revision of traditional deep-renovation design, engineering and production processes. The transition of the deep-renovation sector towards Construction 4.0 (Newman et al., 2020) has the potential to come to a disruptive price reduction without limiting quality delivered to client/building owners.

Although, as mentioned, on a product level in terms of product development there are no significant barriers mapped, there are still some issues to be solved. First, a key technology barrier for zero energy renovation kits concerns the complexity of standardization and certification, in combination with warranties and liabilities that need to be provided to clients/building owners. The absence of industry standards enhances the lack of trust of clients in innovative and non-mainstream solutions, products and concepts, and subsequently leads to risk-averse behavior hindering the uptake of zero energy renovation kits. Various studies highlight the importance of standard setting in het uptake of green innovation in the housebuilding industry (Mlecnik et al., 2016; van Oorschot et al., 2021b). Second, in the excessive pursuit of developing industrialized and modular innovations for the deep-renovation market, Zero Energy Renovation Kits tend to be inflexible, showcases a low level of customization and fail to address contextual differences among projects. For occupants, the relative advantage of Zero Energy Renovation Kits should encompass immediate benefits such as comfort improvement or the replacement of particular building components because of their poor physical condition (Achtnicht and Madlener, 2014; Baumhof et al., 2018; Roders and Straub, 2015). For the diffusion of Zero Energy Renovation Kits it is key to connect to specific local drivers to trigger and to motivate end-users for deep renovation. Bottom-up target group-oriented innovation strategies are required to pinpoint the specific needs of the customer and translate these needs into sufficient customizable Zero Energy Renovation Kits by offering a sufficient level of 'standardized variety' (van Oorschot et al., 2019). However, SMEs in the deep-renovation market are generally not used to group-oriented thinking. It is considered vital to recognise the values, needs, preferences and behavioural choices of the specific target group, rather than developing Zero Energy Renovation Kits based on statistical data about housing typology indicators (Mlecnik et al., 2019; Zenker, 2009).

To summarize, the principal contribution of this paper is to offer a new conceptual perspective on the barriers and intervention strategies which affect the uptake of Zero Energy Renovation Kits. This paper contributes to the innovation literature in three ways. First, 32 barriers were identified from six Horizon 2020 project, grouped into technological, market, financial, legal and/or institutional barriers. Second, intervention strategies were mapped to overcome the barriers identified. Last, a coherent framework was developed to provide a holistic overview of the barriers and intervention mechanisms affecting the development, adoption and implementation of Zero Energy Renovation Kits.

5.2 Implications for innovation managers, decision makers and policy makers

Considering the conclusions in 5.1 for innovation managers, decision makers and policy makers it is important to take the following considerations into account. Concerning the barriers on an institutional level it is necessary to set the definitions for a fair benchmarking, including a clear evaluation of the co-benefits and the benefits for the different stakeholders in the whole value chain to facilitate a level playing field in terms of:

- Fostering transparency in procurement. Clients and decision makers should ask for fully comparable (all in) offers, containing the same elements, addressing the same phases in the process (for example, if also operation & maintenance aspects should be addressed) and covering the same level of liability and warranties.
- Facilitating new organization structures for contracting industrialized renovation works (for example, direct contract between client and supplier of industrial solutions). Clients like housing companies, building owners, institutional investors could make internal legal checks and procedures to facilitate new organization structures, new conditions for liability and warranties.

Fostering transparency in procurement. Clients and decision makers should ask for fully comparable (all in) offers, containing the same elements, addressing the same phases in the process (for example, if also operation & maintenance aspects should be addressed) and covering the same level of liability and warranties.

Concerning legal barriers recommendations and actions are very much depending on national and even local legislation and building regulations. Legal barriers can occur when new innovative products cannot be assessed within the framework of existing standards and regulations. In principle, one is obliged to make an assessment of buildings in terms of energy performance, construction, safety, etc., and it is clear that one should be able to assess all kinds of building designs and of technologies. However, building regulations, present or under development, clearly cannot cover all possible technologies. One solution is the to apply the 'principle of equivalence', i.e., the right to prove that a new product or solutions has the same performances and compliance with existing building regulations. In some countries, like the Netherlands, this principle is embedded in the national building code. However, such a process can be costly and time consuming. In many European countries, preparing ground for innovative industrialized renovation solutions can be facilitated on a local level, for example by a pro-active approach and support of local building supervising authorities.

Legal barriers currently also occur for the combination of new industrialized solutions with new disruptive business models and services, for example, 'façade as a service' or 'comfort as a service'. For example, in the Netherlands comfort as a service (i.e. comfort by leasing building services) is legally possible (as only an installation site is mandatory, not the installation itself) where for facades as a service this is not possible as a façade is considered as a fixed and mandatory part of the building. Solutions for assembly & disassembly (smart mechanical connectors) can offer a solution for this. As this barrier seems to be more on a higher abstraction level, it should be considered rather by national policy makers in the context of national building regulations.

More in general, Public Authorities could have a significant role in affecting deep renovation of the existing buildings in their municipality. Although the significance of this role varies a lot in different countries, even a small additional guidance from authorities and the way how it is focused, can give significant support to renovation while the leverage effect is substantial. However, to increase the rate of industrialized modular renovations, public authorities need to have a clear road map, concepts and tools with different kinds of options. With these concepts and pre-set options of different kinds on energy renovations, authorities can help and steer the deep renovations and develop their own functions. To implement these actions, monitoring, collecting data and analyzing it and creating realistic renovation options with reasonable payback time is also required. Industrialized modular renovation options need to include both long term and short term options and all of them target to optimize the life cycle of the building. Modularity is a prerequisite to achieve both long term and short term options. In addition to enhancing the energy efficiency, another important support of public authorities is the contribution to maintain the overall performance level of the building.

Concerning circular renovation solutions a much more disruptive consideration is given, i.e., to come to a transition in shifting from taxation on labor to taxation on raw materials.

Concerning *circular* renovation solutions a much more disruptive consideration is given, i.e., to come to a transition in shifting from taxation on labor to taxation on raw materials. This transition has several advantages:

- It will enhance the competitiveness of recycled products compared to virgin raw materials.
- As such a taxation measure will promote reuse and upcycling of materials it will mitigate the effects of the current shortage in raw materials in combination with rising costs for (traditional) building products, which is a thread of accelerating deep renovation in Europe.

Nevertheless, for this transition, national policy makers will need the support and endorsement on a European level to create a strong support base for a circular economy.

Concerning the barriers for product certification, specifically for circular renovation products, it is important to share the outcomes of H2020 deep renovation projects both on a technical outcomes and on the engaged barriers and challenges with standardizations bodies, i.e. the work developed within CEN TC350 related to circular economy. More specifically, on product level with CEN TC350 WG3: Products Level; (Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products); on concept level with CEN TC350 WG8: Sustainable Refurbishment; (Sustainability of construction works — Evaluation of the potential for sustainable refurbishment of buildings).

Concerning the need for upskilling, new training contents and continuous professional development, it is clear that industrialized modular renovation requires a different set of skills. Therefore the following steps are necessary:

- A definition of the new required skills
- Mapping of the skills gap
- Identifying and/or developing training programs to fill these skills gaps
- Set op training programs both for blue collar and white collar workers.

It is recommended to make a link with the many H2020 construction skills projects and capitalize and utilize their wealth of outputs. (For example, a solid method for skills mapping has been developed in the H2020 PROF/TRAC project).

A second recommendation is that an exchange between the H2020 projects on innovative deep renovations, and their identified needs of training, with the H2020 Construction Skills projects and their outcomes, could be very beneficial. (There is already an exchange between Construction Skills projects in the framework of the BUS exchange actions, but not with the projects that could use and capitalize these results).

5.3 Implications for further research

This research has contributed by offering a useful foundation for expanding the investigation about the uptake Zero Energy Renovation Kits. This will broaden our knowledge about the possibilities to apply construction 4.0 and modularity strategies in the construction industry, especially the housebuilding and deep-renovation market. Although the findings are based on an extensive workshop involving six Horizon

2020 projects in the field of Zero Energy Renovation Kits, to generalize the findings, additional empirical data is needed. To this end future research may focus on testing in a large-scale study the identified barriers and intervention mechanisms that affect the development, adoption and implementation of Zero Energy Renovation Kits. Also, the findings of this study implies that an extensive set of barriers and interventions affect the uptake of Zero Energy Renovation Kits. Future research should therefore take into account the 'system dynamics' of interrelated adoption variables (Tan et al., 2017). Applying conceptual maps could advance research into boosting the Renovation Wave applying Zero Energy Renovation Kits.

Second, future research could provide new insights into group-oriented thinking and collaborative innovation strategies, such as research into the application of consumer centred business models as an intermediary market device between different actors, on how consortia should address and activate local markets at a neighbourhood scale (Mlecnik et al., 2019). Moreover, research into modularity could unravel how the application of modularity creates an opportunity for the deep-renovation market to more efficiently meet a much larger range of customer requirements, and at the same time improve sustainability and productivity (van Oorschot et al., 2021b).

Third, future research could address the absence of marketing or market uptake strategies able to capitalize the results of Zero Energy Renovation Kits and relevant technical and non-technical innovations. This step is critical to the large scale adoption to boost the Renovation Wave in the EU: retrofit rates have to increase to around 2.5–3% of the housing stock per year to achieve policy (Sandberg et al., 2016). Therefore, the absence of market uptake strategies is considered the missing link between innovation developments in Horizon funded projects and large-scale adoption.
Finally, as a very practical recommendation, the coherent framework indicates which barriers and intervention strategies are at play affect the uptake of Zero Energy Renovation Kits in deep renovation projects. Therefore we suggest that decision-makers in deep renovation projects and innovation managers of Zero Energy Renovation Kits attempt to test our conceptual framework in practice (Slater et al., 2014; Taylor et al., 2010). Practice-based testing may improve insights about the uptake potential of a Zero Energy Renovation Kit when introduced in the market. Having this information can help in guiding the development strategy of future versions.

Acknowledgement
The authors would like to thank the representatives of the Horizon 2020 projects DRIVE 0 (841850), StepUp (847053), ProGETonE (723747), INFINITE (958397), PLURAL (958218), ENSNARE (958445) for their valuable contribution to this paper. These projects have received funding from the European Union's H2020 framework programme for research and innovation which is gratefully acknowledged.

References

- Achtnicht, M., Madlener, R., 2014. Factors influencing German house owners' preferences on energy retrofits. Energy Policy 68, 254-263.
- Arif, M., Davidson, C.H., 2009. The challenge of organizational design for manufactured construction. Construction innovation 9, 42-57.
- Baldwin, C.Y., Clark, K.B., 2000. Design rules, Volume 1: The power of modularity. mIt Press.
- Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M.J., Sridhar, M., Parsons, M., Bertram, N., Brown, S., 2017. Reinventing construction: A route to high productivity, p. 20.
- Baumhof, R., Decker, T., Röder, H., Menrad, K., 2018. Which factors determine the extent of house owners' energy-related refurbishment projects? A Motivation-Opportunity-Ability Approach. Sustainable cities and society 36, 33-41.
- Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., Woetzel, J., 2019. Modular construction: From projects to products, p. 34.
- Brown, J., Hendry, C., 2009. Public demonstration projects and field trials: Accelerating commercialisation of sustainable technology in solar photovoltaics. Energy Policy 37, 2560-2573.
- Cacciatori, E., Jacobides, M.G., 2005. The dynamic limits of specialization: vertical integration reconsidered. Organization Studies 26, 1851-1883.
- Chung, W.-H., Kremer, G.E.O., Wysk, R.A., 2014. Life cycle implications of product modular architectures in closed-loop supply chains. The International Journal of Advanced Manufacturing Technology 70, 2013-2028.
- D'Oca, S., Ferrante, A., Ferrer, C., Pernetti, R., Gralka, A., Sebastian, R., Op't Veld, P., 2018. Technical, financial, and social barriers and challenges in deep building renovation: Integration of lessons learned from the H2020 cluster projects. Buildings 8, 174.
- da Rocha, C., Formoso, C., Tzortzopoulos, P., 2015. Adopting product modularity in house building to support mass customisation. Sustainability 7, 4919-4937.
- Decorte, Y., Steeman, M., Krämer, U., Struck, C., Lange, K., Zander, B., de Haan, A., 2020. Upscaling the housing renovation market through far-reaching industrialization, IOP Conference Series: Earth and Environmental Science. IOP Publishing, p. 032041.
- Doran, D., Giannakis, M., 2011. An examination of a modular supply chain: a construction sector perspective. Supply Chain Management: An International Journal 16, 260-270.
- Dunphy, N.P., Morrissey, J.E., MacSweeney, R.D., 2013. Building energy efficiency: a value approach for modelling retrofit materials supply chains. Materials and processes for energy: communicating current research and technological developments, 649-657.
- ECSO, 2017. Improving the human capital basis. European Commission, Brussels.
- ECSO, 2018a. Improving energy and resource efficiency. European Union, Brussels.
- ECSO, 2018b. Stimulating favourable investment conditions. European Commission, Brussels.
- Egmond, C., Jonkers, R., Kok, G., 2006. A strategy and protocol to increase diffusion of energy related innovations into the mainstream of housing associations. Energy Policy 34, 4042-4049.
- Ellen MacArthur Foundation, 2015a. Growth within: A cricular economy vision for a competitive Europe.
- Ellen MacArthur Foundation, 2015b. Towards a circular economy: Business rationale for an accelerated transition.
- Femenias, P., 2004. Demonstration projects for sustainable building: towards a strategy for sustainable development in the building sector based on Swedish and Dutch experience, Department of Built Environment & Sustainable Development, School of Architecture, Centre for Environment and Sustainability. Chalmers University of Technology, Göteborg, p. 288.
- Femenias, P., Kadefors, A., Edén, M., 2009. The demonstration project as a tool for client driven innovation: exploring the possibilities from a Swedish perspective, Proceeding from the international conference Changing Roles; New Roles, New Challenges. Noordwijk an Zee, The Netherlands, 5-9 October 2009, pp. 199-210.
- Fine, C.H., Golany, B., Naseraldin, H., 2005. Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach. Journal of Operations Management 23, 389-403.
- Goodier, Gibb, 2007. Future opportunities for offsite in the UK. Construction Management and Economics 25, 585-595.
- Grimscheid, G., Scheublin, F., 2010. New Perspectives in Industrialisation in Construction - A State-of-the-Art Report, in: CIB (Ed.).
- Halman, J.I.M., Voordijk, J.T., Reymen, I.M.M.J., 2008. Modular approaches in Dutch house building: an exploratory survey. Housing Studies 23, 781-799.
- Hofer, A., Halman, J., 2005. The potential of layout platforms for modular complex products and systems. Journal of Engineering Design 16, 237-255.
- Hofman, E., 2010. Modular and architectural innovation in loosely coupled networks : matching customer requirements, product architecture, and supplier networks, Faculty of Engineering Technology, Construction Management and Engineering. University of Twente, Enschede, p. 219.
- Hofman, E., Voordijk, H., Halman, J., 2009. Matching supply networks to a modular product architecture in the house-building industry. Building Research & Information 37, 31-42.
- Jensen, P., 2014. Configuration of platform architectures in construction, Department of Civil, Enviromental and Natural Resources Engineering. Luleå tekniska universitet, LULEÅ.
- Kimura, F., Kato, S., Hata, T., Masuda, T., 2001. Product modularization for parts reuse in inverse manufacturing. CIRP Annals 50, 89-92.
- Lennartsson, M., Björnfot, A., 2010. Step-By-Step Modularity: a roadmap for building service development. Lean Construction Journal 2010, 17-29.
- Lind, H., 2011. Industrialized House Building In Sweden: A Stress Test Approach For Understanding success And Failure, 6th Nordic Conference on Construction Economics and Organisation–Shaping the Construction/Society Nexus, p. 79.
- Ma, J., Kremer, G.E.O., 2016. A systematic literature review of modular product design (MPD) from the perspective of sustainability. The International Journal of Advanced Manufacturing Technology 86, 1509-1539.
- Matinaro, V., Liu, Y., 2015. Virtual design and construction: innovation process and diffusion in Finnish construction business. International Journal of Innovation and Learning 18, 133-150.
- Miles, M.B., Huberman, A.M., 1994. Qualitative data analysis: An expanded sourcebook. Sage Publications, Incorporated.
- Mlecnik, E., Kumaraswamy, M., Liyanage, C., 2016.

Activating the adoption of innovation: lessons from a passive house network. Built Environment Project and Asset Management.
- Mlecnik, E., Straub, A., Haavik, T., 2019. Collaborative business model development for home energy renovations. Energy Efficiency 12, 123-138.
- Naney, D., Goser, C., Azambuja, M., 2012. Accelerating the adoption of lean thinking in the construction industry. Proceedings for the 20th International Group for Lean Construction, 291-300.
- Newman, C., Edwards, D., Martek, I., Lai, J., Thwala, W.D., Rillie, I., 2020. Industry 4.0 deployment in the construction industry: a bibliometric literature review and UK-based case study. Smart and Sustainable Built Environment.
- Okudan Kremer, G.E., Ma, J., Chiu, M.-C., Lin, T.-K., 2013. Product modularity and implications for the reverse supply chain, Supply Chain Forum: An International Journal. Taylor & Francis, pp. 54-69.
- Op't Veld, P., 2015. MORE-CONNECT: Development and advanced prefabrication of innovative, multifunctional building envelope elements for modular retrofitting and smart connections. Energy Procedia 78, 1057-1062.
- Pan, W., Gibb, A.G., Dainty, A.R., 2007. Perspectives of UK housebuilders on the use of offsite modern methods of construction. Construction management and Economics 25, 183-194.
- Pero, M., Stößlein, M., Cigolini, R., 2015. Linking product modularity to supply chain integration in the construction and shipbuilding industries. International Journal of Production Economics 170, 602-615.
- Renz, A., Zafra Solas, M., 2016. Shaping the future of construction: A breakthrough in mindset and technology, in: Forum, W.E., Group, T.B.C. (Eds.), Geneva.
- Roders, M., Straub, A., 2015. Assessment of the likelihood of implementation strategies for climate change adaptation measures in Dutch social housing. Building and Environment 83, 168-176.
- Saheb, Y., 2016. Energy Transition of the EU Building Stock: Unleashing the 4th Industrial Revolution in Europe. OpenExp, Paris.
- Salvador, F., 2007. Toward a product system modularity construct: literature review and reconceptualization. Ieee Transactions on Engineering Management 54, 219-240.
- Sandberg, N.H., Sartori, I., Heidrich, O., Dawson, R., Dascalaki, E., Dimitriou, S., Vimm-r, T., Filippidou, F., Stegnar, G., Zavrl, M.Š., 2016. Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. Energy and Buildings 132, 26-38.
- Sheffer, D.A., 2011. Innovation in modular industries implementing energy-efficient innovations in US buildings, Department of Civil and Environmental Engineering. Stanford University, Stanford.
- Slater, S.F., Mohr, J.J., Sengupta, S., 2014. Radical product innovation capability: Literature review, synthesis, and illustrative research propositions. Journal of Product Innovation Management 31, 552-566.
- Songip, A.R., Lau, B., Jusoff, K., Ramli, H.N., 2013. A working integrated model for the diffusion of construction innovation. American Journal of Applied Sciences 10.
- Tan, D.T., Gong, Y., Siri, J.G., 2017. The Impact of Subsidies on the Prevalence of Climate-Sensitive Residential Buildings in Malaysia. Sustainability 9, 2300.
- Taylor, G.S., Templeton, G.F., Baker, L.T., 2010. Factors influencing the success of organizational learning implementation: A policy facet perspective. International Journal of Management Reviews 12, 353-364.
- Tello, S.F., Yoon, E., 2008. Examining drivers of sustainable innovation. International Journal of Business Strategy 8, 164-169.
- Thillart, C.C.A.M.v.d., 2002. Customised Industrialisation in the Residential Sector - Mass Customisation modelling as a tool for benchmarking, variation and selection, Department of Real Estate & Housing; Faculty of Architecture. Delft University of Technology, Delft.
- Ulrich, K., 1995. The role of product architecture in the manufacturing firm. Research policy 24, 419-440.
- van Hal, A., 2000. Beyond the demonstration project: the diffusion of environmental innovations in housing, Faculty of Architecture, Delft University of Technology. Uitgeverij Æneas BV, Delft.
- van Oorschot, J., Halman, J., Hofman, E., 2019. The continued adoption of housing systems in the Netherlands: A multiple case study. Journal of Construction Engineering, Management & Innovation 2, 167-190.
- Van Oorschot, J., Ritzen, M., Rohith, A., 2021a. Development of a morphological design approach and guidelines for circular renovation, in: DRIVE-0, H. (Ed.).
- van Oorschot, J.A., Halman, J.I., Hofman, E., 2021b. The adoption of green modular innovations in the Dutch housebuilding sector. Journal of Cleaner Production, 128524.
- Viana, D., Tommelein, I., Formoso, C., 2017. Using Modularity to Reduce Complexity of Industrialized Building Systems for Mass Customization. Energies 10, 1622.
- Voordijk, H., Meijboom, B., de Haan, J., 2006. Modularity in supply chains: a multiple case study in the construction industry. International Journal of Operations & Production Management 26, 600-618.
- Wolters, M.M., 2002. The business of modularity and the modularity of business, Erasmus Research Institute of Management (ERIM). Erasmus University Rotterdam, Rotterdam.
- Zenker, S., 2009. Who's your target? The creative class as a target group for place branding. Journal of Place Management and Development.