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Defining a sustainable supply chain for buildings Off-Site envelope thermal insulation solutions: proposal of a methodology to investigate opportunities based on a context analysis

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***Abstract*— External wall thermal insulation is one of the most effective solutions on the market to increase energy efficiency in the built environment. Off-Site Construction (OSC), through better control of the various parameters involved, can bring important advantages, such as the reduction of construction time, the improvement of product and process quality, etc. In the last years, the rapidly growing demand for thermal insulation systems, stimulated also by tax incentives, has generated a unique situation in Italy compared to the rest of Europe, also leading to a considerable fragmentation of the supply chain with several players involved (component and system manufacturers, distributors, and installers). The complexity of such context makes Italy an extremely challenging and insightful case study for a supply chain and sustainability study, also considering the fact that the energy efficiency of the Italian building stock represents a crucial challenge to achieve the country's energy saving goals since 40% of final energy consumption derives from buildings and 75% of the building stock presents a low energy performance (energy labels E, F and G). This article presents both an analysis of the Italian market of manufacturers of building envelope thermal insulation solutions, highlighting the different players in the supply chain in terms of number, type, and marketed products and solutions, and a focus on sustainable and recycled materials. The study also aims to define a methodology to investigate the state of play and opportunities for industrialisation of this market and its bottlenecks. In the article, a questionnaire is proposed to collect information and opinions on the spread of OSC and the perception of companies and professionals regarding the advantages and disadvantages of industrializing the sector. A first validation of the survey is presented in the form of industrial focus groups.**

***Index Terms*— supply chain sustainability, industrial energy efficiency, off-site construction, construction industrialisation, sustainable building materials, modular buildings**

I. INTRODUCTION

Off-Site Construction (OSC) is a new approach to creating and renovating the built environment by reducing the intensity of activities carried out in the construction site and locating them mostly in the factory, a controlled environment where higher standards of process efficiency, quality and safety can be achieved (Jiang, Mao, Hou, Wu & Tan, 2018). Although OSC is still at a relatively early stage of implementation in many countries, in recent years this emerging construction technique has constantly been attracting more attention from academics and practitioners, due to its potential in achieving better project performances (Lihtmaa and Kalamees, 2024). China is the most prominent country in research in modern methods of construction, with particular interest in OSC of prefabricated structures and inter-modular connections (Doan, Mai, GhaffarianHoseini, Ghaffarianhoseini & Naismith, 2024). Specifically, it has been observed that OSC allows reducing project duration and construction waste and facilitates the construction process also where specific organisational measures must be deployed such as in developing countries (Hong, Shen, Mao, Li, & Li, 2016). Several studies have compared the performance of OSC and conventional construction methods in terms of cost (Hong, Shen, Li, Zhang & Zhang, 2018), energy performance (Hong, Shen, Mao, Li, & Li, 2016) and the overall sustainability of the process (Kamali and Hewage, 2017; Lopez-Guerrero, Vera and Carpio, 2022), which is an increasingly crucial decisional factor (Malik et al., 2019): it appears evident that OSC can be a powerful tool to tackle the renovation challenge that Europe will face in the next few years. In fact, as stated in the recast of the "Energy Performance of Buildings Directive" (EPBD): "The necessary decarbonisation of the Union building stock requires energy renovation at a large scale: almost 75 % of that

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building stock is inefficient according to current building standards, and 85-95 % of the buildings that exist today will still be standing in 2050. However, the weighted annual energy renovation rate is persistently low at around 1 %. At the current pace, the decarbonisation of the building sector would require centuries. (…) Supporting renovations at district level, including through industrial or serial type renovations, offers benefits by stimulating the volume and depth of building renovations and will lead to a quicker and cheaper decarbonisation of the building stock" (European Parliament, 2023). Hence, building renovation is a key goal and triggering and supporting building renovation is fundamental to at least triple the current renovation rate (up to 2 % in 2030 and 2.6 % in 2050 in Italy) (Italian Ministry for Environment and Energy Security, 2023).

OSC is heavily based on the modularity of products, prefabricated, and then assembled on site, and its feasibility depends on a paradigm shift in the design, production, supply chain optimisation and life-cycle assessment (Sonego, Echeveste and Galvan Debarba, 2018); therefore, an integrated strategy for production planning and optimisation throughout the whole supply chain is necessary (Abeynayake, Perera and Hadiwattege, 2022; Goulding, Pour, Arif and Sharp, 2014; Choi, O'Connor and Kim, 2016; Isaac, Bock and Stoliar, 2016; Jin, Gao, Cheshmehzangi and Aboagye-Nimo, 2018).

The development of OSC techniques requires to strength the integration with Lean Manufacturing and simulation/BIM tools (Daniel & Oshodi, 2023). The Lean integration leads to significate savings in makespan, costs, and waiting times compared to conventional non-lean optimization methods (Zheng et al., 2024). Additionally, the development of OSC needs new digital tools both in the design phase for manufacturing and assembly, and in the supply chain management phase (Cheng, Tang, Liu & Lei, 2023), as well as new skills and up-skilling strategies (Ginigaddara, Gajendran & Beard, 2023). The OSC presents several advantages from the sustainability point of view with a reduction of waste up to the 78 % (Zhang, Pan, Teng & Chen, 2024) and strong interlinks with circular economy principles (Obi, Arif, Daniel, Oladinrin & Goulding, 2023).

The digitalization of OSC has shifted to transforming the business model, procurement and supply chain; putting the procurement phase as a main driver to enhance the OSC supply chains (Tennakoon, Chileshe, Rameezdeen, Ochoa & Samaraweera, 2024). However, there are still big problems in the OSC supply chains related to the lack of: (i) knowledge in the construction workforce; (ii) preparedness for the changes; (iii) proper procurement models for OSC; (iv) end-to-end visibility of the supply chain to identify uncertainties; and (v) lack of national or government standards (Tennakoon et al., 2023).

The barriers for the implementation of OSC technologies have been analyzed in developed and developing countries, showing similar trends related to technical, knowledge, attitudinal, financial and process difficulties. These barriers can be faced with the cooperation (crucially in design phase) between contractors, architects, engineers, builders and project managers, in integrated supply chain management (Martin, Garner, Manewa & Chadee, 2024; Ali, Kineber, Elyamany, Ibrahim and Daoud, 2023; Akinradewo, Aigbavboa, Aghimien, Oke & Ogunbayo, 2023).

Implementing OSC in the Italian context presents additional challenges. First, many Italians are homeowners, and the real estate is therefore highly fragmented, which entails an additional barrier to arrange renovations at district level. In addition, the construction and building renovation national supply chain presents a considerable fragmentation.

The research activities described hereinafter focus on analysing the context for the optimization of the Italian OSC supply chain, considering renovation rather than new construction projects, providing an analysis of the current market and supply and the potential for energy efficiency, as well as the tools to create a common language shared by the main stakeholders. The first phase of the project has been focused on External Thermal Insulation Composite Systems for buildings (known as 'cladding' or ETICS). These commercial solutions, with an excellent level of diffusion on the national market, are composed of a series of elements and are on the market with different levels of prefabrication and integration. ETICS can therefore be considered an efficient solution with hybrid characteristics between traditional building renovation and OSC, with which they also share a large part of the production chain. For this reason, the analysis of the ETICS market is an excellent starting point for assessing the current state of building renovation technologies, and the prospects for the diffusion of state-of-the-art OSC solutions. This market includes different types of players: manufacturers of components (insulation materials, structures, and accessories), system builders

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(who purchase and certify insulation systems), distributors and installers. The components are made of energy-intensive materials (synthesised expanded polystyrene insulation, rock wool or glass wool; fibreglass or metal structures; concrete, etc.) and, therefore, a reduction in energy and material consumption would lead to an improvement in the competitiveness of the entire supply chain. For these reasons, in this work a focus is conducted on sustainable and recycled materials, allowing to considering future products, trends, and more sustainable business models.

By taking the first steps of this work in the complex Italian context, the research activities aim also at creating a generally valid methodology that could be adapted and replicated in any context. Moving along these lines, a questionnaire has also been developed to investigate OSC perception, in terms of general understanding, benefits and barriers to implementation, as well as energy efficiency status and practices. As regards OSC perception, the questionnaire is based on the recent work illustrated in (Attouri, Lafhaj, Ducoulombier and Linéatte, 2022) where a similar investigation was conducted in France and led to a deeper understanding of the status quo and market needs and opportunities.

II. PROPOSED METHODOLOGY FOR THE INVESTIGATION ON THE CURRENT USE AND OPPORTUNITIES FOR INDUSTRIALISATION OF THE BUILDING CONSTRUCTION MARKET AND BOTTLENECKS

The methodology graphically described in Figure 1 represents the overall procedural approach of the OFFICIO[1] project ("Ottimizzazione Filiere oFf-site per la rIqualifiCazione dell'ambIente cOstruito", i.e., "Optimization of Off-Site supply chains for the renovation of the built environment").

The first step of the methodology is the creation of a map of existing OSC supply chains in Italy, including also partially developed supply chains (i.e., supply chains of partially prefabricated solutions). This activity is conducted mainly using national databases and leads to a better understanding of the current situation as well as of main stakeholders involved. Based on this activity, a business model analysis is conducted to assess current models and identify innovative ones that could lead to a faster and more effective OSC implementation.

The second step is an energy analysis of production processes, focusing on the most energy intensive ones within the supply chain. This activity strongly relies on data provided to ENEA by large and energy intensive companies that are subject to an energy audit according to the Italian Legislative Decree no. 102 of 4 July 2014 (that include the national transposition of Art.8 of European Energy Efficiency Directive, EED) (Republic of Italy, 2014) and allows having a clear picture of the current energy efficiency status as well as of the improvement potentials. Based on this activity, a software tool is developed to facilitate companies easily identifying their energy efficiency losses.

The third step is the identification of good practices and the creation of benchmarking tools. This activity leads to the creation of sectorial guidelines for OSC implementation and development and of knowledge transfer tools to facilitate good practices exchanges among companies from different OSC supply chains characterized by different maturity levels (e.g., wood and steel supply chains).

In addition to the three described steps, a focus is conducted on "innovative" or "unconventional" (defined as sustainable, bio-based and/or and recycled) materials, allowing considering future products, trends, and more sustainable business models.

Such activities rely not only to the previously indicated data sources but also on the creation of a network of experts and stakeholders providing information, case studies and feedback where needed.

[1] The OFFICIO project is carried on by ENEA, the Polytechnic University of Milan, the Polytechnic University of Marche, and the University of Bologna in the framework of a broader program led by ENEA and funded by the Italian Ministry for Environment and Energy Security.

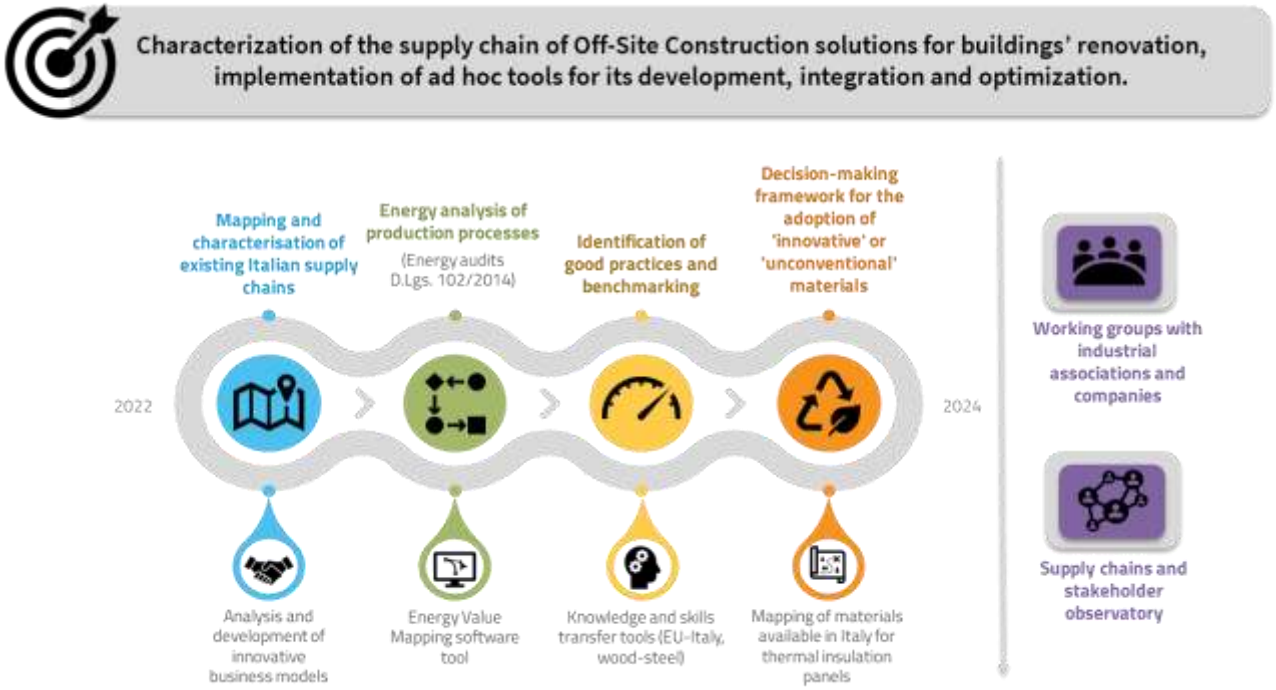

Figure 1: Graphical representation of the proposed methodological approach

This article mainly presents first results from steps one (i.e., the preliminary analysis of the Italian market of manufacturers of building envelope solutions) and four (i.e., the literature review on sustainable and recycled materials). In addition, the validation and diffusion of a questionnaire that will allow to expand the knowledge base for the first three steps is presented as a meaningful example of the stakeholder-oriented approach.

A. Preliminary analysis of the Italian market of manufacturers of building envelope solutions

The mapping of the Italian supply chain for the production and distribution of commercial solutions for the external insulation of buildings responds to the need to provide a structured analysis of a market currently undergoing an expansion phase in which solutions with different levels of integration coexist. The objective is therefore to identify and classify the players involved in the supply chain, the marketed solutions and their level of integration, existing certifications, best practices, and emerging technologies with a focus on pre-assembled solutions and their potential in the OSC market. The analysis was focused on companies that manufacture or market insulation materials, structures, and accessories for ETICS, thus excluding most of the raw material manufacturers as well as companies only involved in the installation of the solutions. The methodology used for the analysis is represented in Figure 2.

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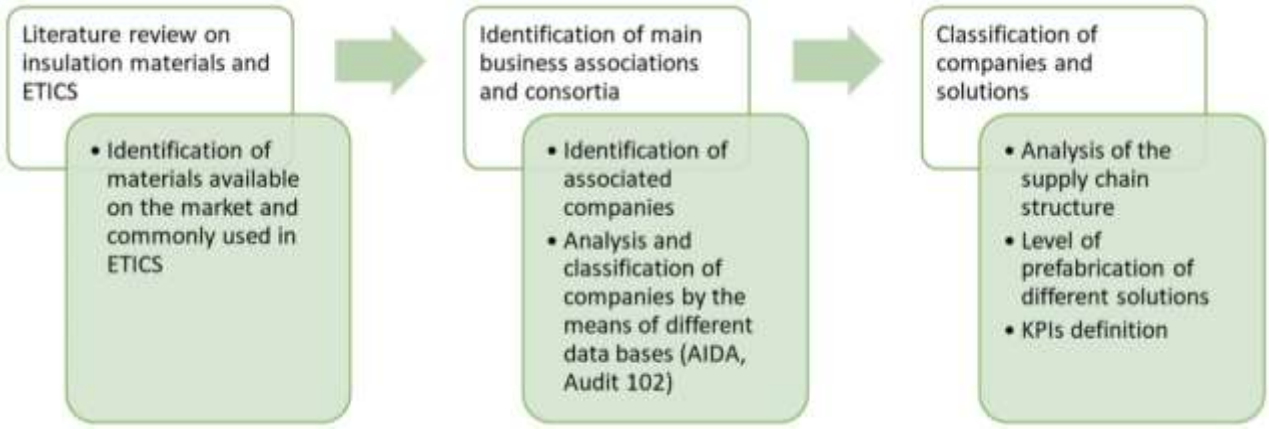

Figure 2: Representation of the methodology used for the preliminary market analysis

The enterprises have been individually analysed from the databases of the five main Italian business associations and consortia of manufacturers of insulation materials:

- ANIT - National Association for Thermal and Acoustic Insulation,
- AIPE - Italian Association of Expanded Polystyrene,
- ANPE - National Association of Rigid Polyurethane Foam,
- FIVRA - Associated Glass and Rock Insulating Factories,
- Cortexa - Consortium for Quality in External Thermal Insulation Composite Systems.

The mapping has been carried out at enterprise level, analysing four different aspects:

- Economic and management information,
- Insulation materials commercialized/manufactured,
- ETICS solutions: integration and certification,
- Energy information on the production process

The economic and management aspects analysed are mainly the size (micro, small, medium, and large), the management and ownership of the enterprise (from independent to multinational), and the NACE divisions (the two-digit numerical codes used to classify economic activities in the European Community). This information has been obtained from Aida, the main database of economic enterprises in Italy developed by Bureau van Dijk (AIDA, 2023).

The insulation material is the key element of ETICS. The physical, constructional, environmental, and economic characteristics of the envelope are strictly correlated to the properties of the insulation material, as also is the role of the different companies in the supply chain. Four insulation material categories have been considered in this phase:

- Plastic materials: the most used are the EPS (expanded polystyrene), the XPS (extruded polystyrene) and the PUR (rigid polyurethane). Two main kinds of enterprises are involved in the manufacturing of these materials: the raw material manufacturers, which are usually few large petrochemical companies that provide polystyrene and polyurethane in the form of semifinished products, and the transforming companies (several tens of SMEs in Italy) that elaborate those materials to obtain the commercial products that can be used in ETICS.
- Mineral wools: mainly glass and stone wools. In contrast to what previously discussed for plastic materials, both are manufactured by single companies that also manufacture the commercial products/complete solutions. The core process of melting and preparation of the fibres is done at very high temperatures. Hence, the process must be carried out in continuous by energy intensive companies (generally large multinational enterprises). Few of these companies manufacture mineral wools in Italy (but they produce other construction materials), while some enterprises present only project and distribution branches on the national territory.

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- Bio-based materials. This category includes natural insulation materials such as cork, wood fibres, or sheep wool. The companies that provide these materials are heterogeneous and with limited portfolios and productions.
- Alternative materials that include multiple non-bio-based materials such as hydrated calcium silicates, silicon oxides and other non-metallic and metallic materials in form of foam and solid gels.

The different ETICS have been categorized according to their degree of integration (where OSC systems represent the most integrated solution). More integrated products are characterized by a fully (or partially) pre-assembled envelope designed ad hoc. Intermediate solutions include ETICS kits (including anchoring, insulation panel/block and coating materials). ETICS kits can be sometimes certified according to EOTA (European Organisation for Technical Assessment) Technical Assessments regarding the PAC 04 family: External thermal insulation composite systems/kits. In the case of ETICS kits, the lower integration level in the supply chain is formed by the single components manufacturers.

Finally, ETICS and their manufacturers have been studied from the energy intensity point of view. Two main sources have been deeply analysed: (i) the EPD (Environmental Product Declarations), which are documents summarising information about the life-cycle environmental impact of products including some specific energy information related to the production stage, and (ii) the available energy audits, since, according to Italian legislation (i.e., the transposition of Art.8 of EED), and with specific Energy Intensive Industry programmes, ENEA collects and analyses the mandatory energy audits of large companies and energy intensive SMEs.

The activities related to the categorization and analysis of solutions and manufacturers have led to the definition of a first set of Key Performance Indicators (KPIs) that can be used for the characterization of the different players within the supply chain. This set of KPIs is still under development and will be updated through several interactions with project stakeholders over the next months. Such preliminary KPIs are described in Table 1.

Table 1: Definition of KPIs for the characterization of the different players within the supply chain

KPI	First possible value	Second possible value	Third possible value
Company size	Small-Micro	Medium	Large
Market positioning	--	B2B	B2C
Integration level of solutions	Component	ETICS (kit)	OSC / Semi-OSC
Solution certification	Component	ETA	CE
Available materials	Plastic materials	Mineral wools	Bio-based materials
Energy efficiency maturity level	Low	Medium	High

B. Literature review on sustainable and recycled materials

If on the one hand the thermal refurbishment of the building stock is vital, on the other hand the production of the most widely used thermal insulation materials is extremely energy intensive (Schiavoni, D'Alessandro, Bianchi and Asdrubali, 2016); therefore, although the building use phase has the highest environmental impacts (Lavagna et al., 2018), the use of carbon intense materials may shift the impacts from one phase (i.e., use phase) to another one (i.e., construction or refurbishment phase) limiting the environmental benefits. To overcome this issue, it is of utmost importance to select thermal insulating materials with a low environmental impact. Such materials are not widely used in the practice since research is still pioneering; nevertheless, in recent years the interest towards them is increasing and, consequently, also the number of scientific articles focused on this topic.

The authors conducted a systematic literature review to explore the state of the art about the materials with thermal insulation properties. Specifically, Scopus has been used to select the scientific literature published from 2017 until the end of 2022 responding to the keywords "thermal insulation material" and "building". To join the selected keywords the Boolean "AND" has been used. Figure 3 shows the procedure used to select literature including the exclusion criteria.

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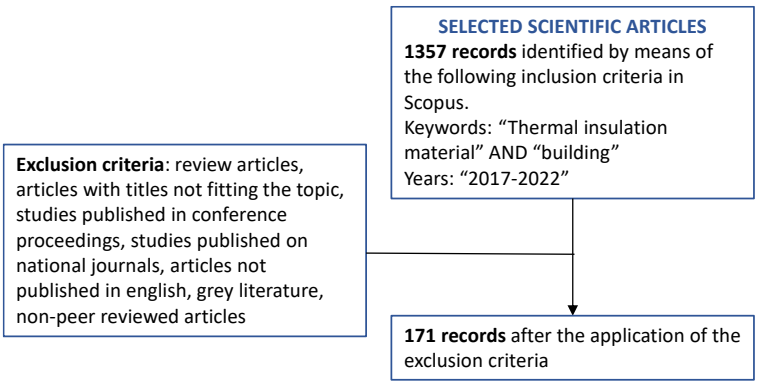

Figure 3: Flow diagram depicting the literature selection process

After a first screening, out of the 171 records, some of them reporting on multiple case studies, the authors selected 466 case studies fitting the topic. For each case study the authors retrieved identification data into an Excel spreadsheet.

C. Questionnaire

A questionnaire mainly aimed at collecting information related to the type of company and its role in the supply chain, the energy efficiency status as well as the perception of main barriers and benefits deriving from the implementation of OSC has been prepared; its diffusion among companies and OSC experts will provide useful insights to build on during phases one, two and three of the overall project methodology (Figure 1). The survey includes questions related to seven main areas of investigation: personal and professional information of the respondent, economic activity of the company, energy efficiency status and practices within the company; OSC general knowledge and perception; OSC perceived benefits; OSC perceived barriers to implementation and diffusion. Benefits and barriers have been listed according to six categories: time, costs, quality, productivity, safety and environment, customers. These categories and related issues have been defined by using (Attouri, Lafhaj, Ducoulombier and Linéatte, 2022) as a basis and adding, modifying, rephrasing according to feedback obtained by main stakeholders as well as literature. The main target audience of the questionnaire are companies operating across the entire supply chain, but the "benefits and barriers" part can be competed also by experts and other stakeholders. A first validation of the questionnaire aimed at assessing its clarity and usability for companies has been conducted within a restricted session of a focus group of experts, OSC companies and professional associations representatives, and a second validation will follow with a larger session before massive diffusion through the observatory network.

III. RESULTS

A. Preliminary analysis of the Italian market of manufacturers of building envelope solutions

The mapping of the supply chain of building envelope insulation solutions carried out as described in the previous section allowed identifying 112 companies operating in the Italian territory involved in the production and commercialization of ETICS. Out ff the 112 companies identified, 48% are associated with ANIT, 17% with AIPE, 4.5% with ANPE, 4.5% with FIVRA, and 24% of the companies are members of Cortexa. FIVRA, ANPE and AIPE are themselves members of ANIT and many of their members are also associated with ANIT as graphically shown in Figure 4.

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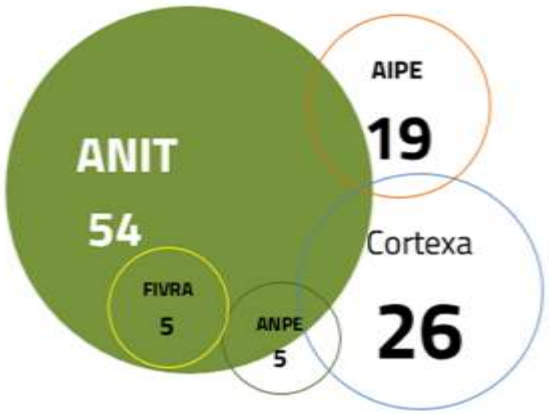

Figure 4: Italian ETICS supply chain: distribution of companies among main national associations (ANIT - National Association for Thermal and Acoustic Insulation, AIPE - Italian Association of Expanded Polystyrene, ANPE - National Association of Rigid Polyurethane Foam, FIVRA - Associated Glass Rock Insulating Factories, Cortexa Consortium for Quality in ETICS)

Regarding the main economic activity of companies in the ETICS production supply chain, 30% of them belong to NACE - *C22 Manufacture of rubber and plastic products,* 22% to C23 *Manufacture of other non-metallic mineral products*, and about 19% to C20 *Manufacture of chemicals and chemical products*. It can be noticed that the main economic activity of the enterprises is reflected in a different positioning within the ETICS supply chain. Specifically, about 58% of the firms belonging to NACE C22 (mainly associated with ANIT, ANPE and AIPE) deals with the production of insulation panels as part of their product portfolio (mainly in plastic materials but also assembling minerals) while about 23% expanded their activity on other ETICS, components or kits (four of them are in fact associated with Cortexa Consortium). The remaining companies in NACE C22 deal with anchoring components or prefabricated systems. As for the companies belonging to NACE C23 (associated with ANIT or FIVRA), only 18% of them deals exclusively with the production of panels while the remaining companies extended their activities to the production of ETICS including also different types of insulation materials (pre-assembled or kits). The companies within NACE C20 belong almost totally (except for one company) to NACE C20.3 - Manufacture of paints, varnishes and similar coatings, printing ink and mastics (85% of them are associated with Cortexa) and, thus, commercialize ETICS (kits or components) using plastic, mineral and natural insulating materials. 65% of these companies belong to foreign industrial groups. The overall distribution is shown in Figure 5.

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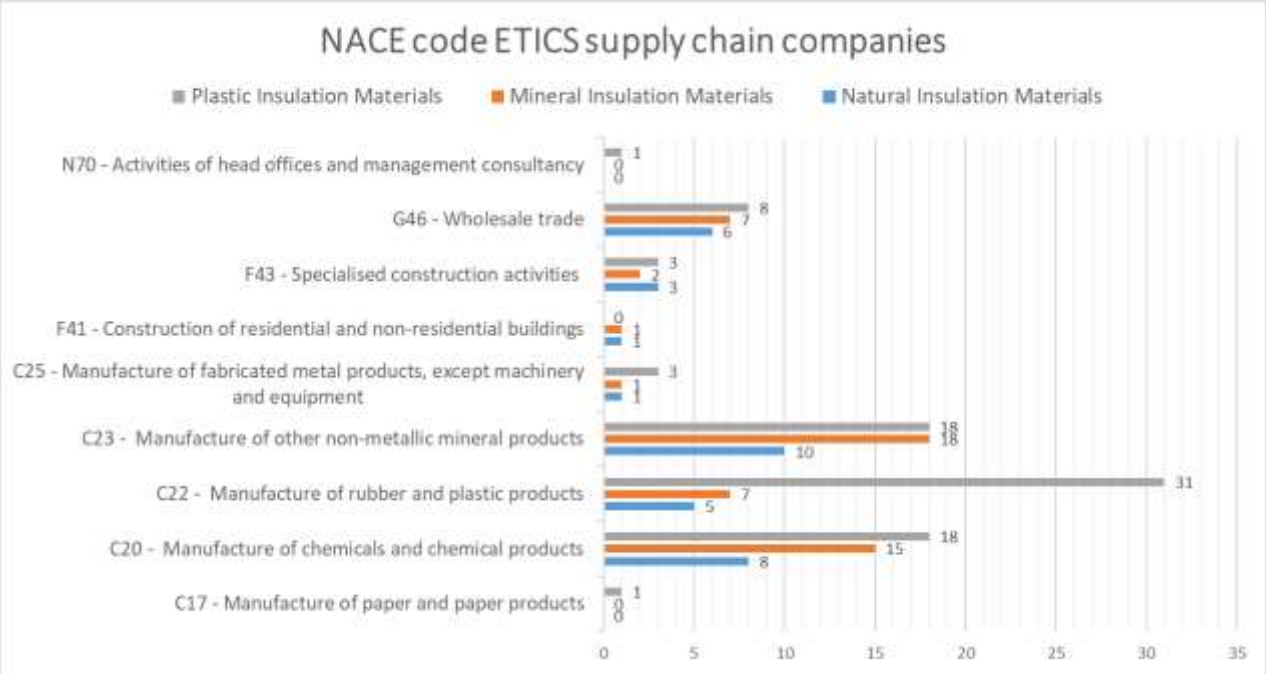

Figure 5: ETICS supply chain: distribution of firms among NACE codes

Figure 6 shows the percentage breakdown of companies according to the type of products commercialized. 56% of the companies supply ETICS, pre-assembled or as kits (ETA-certified or not), 35% deals with the commercialization (and in many cases production) of insulation panels, and 9% with the other components of ETICS (reinforcement, anchoring components, etc.).

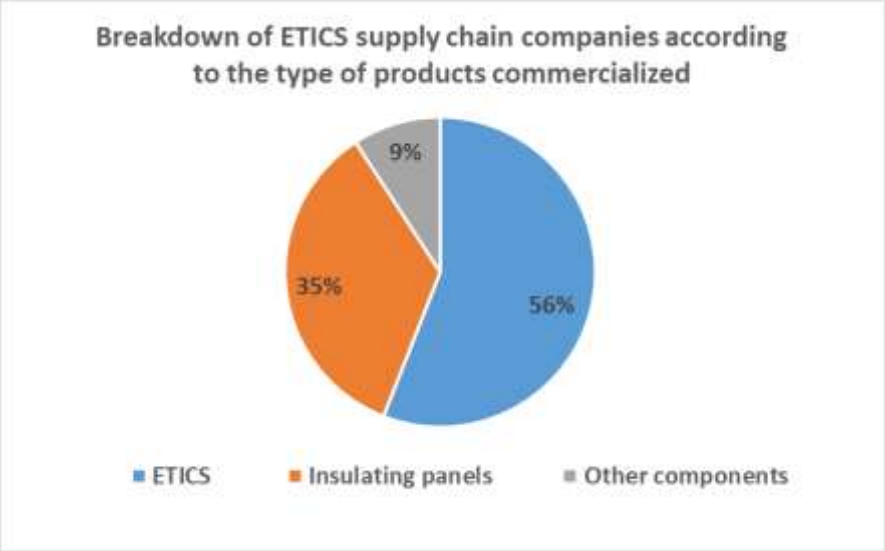

Figure 6: ETICS Italian supply chain: breakdown of companies according to the type of commercialized products

ETICS whose components have not been tested to work together but are purchased by the company or the installer from different manufacturers, cannot be certified as a system nor obtain CE system marking,

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thus they cannot guarantee specific performance such as thermo-hygrometric behaviour, durability, fire behaviour etc. To be considered a kit, ETICS must have obtained European Technical Approval - ETA according to ETAG 004 (EOTA, 2023) or EAD 040083-00-0404 and CE system marking for thermal insulation. In a certified kit, the individual products that make up the kit have been previously studied and tested to work together under specific installation rules.

Within the Italian ETICS supply chain, products marketed as "Exterior Insulation and Finishing System" (EIFS) have varying levels of integration, and about 53% of them are ETA-certified kits while 13% are non-ETA-certified kits (i.e., they are a set of components sold by the same company) and the remaining 34% are semi or fully industrially pre-assembled solutions. 34 % of OSC or semi-OSC solutions are represented by the solutions marketed by 17 companies in the supply chain.

The semi-OSC category includes industrially prefabricated panel solutions whose installation generally involves mechanical anchoring with reduced construction time compared to traditional solutions. Such solutions can generally be used for both retrofitting and new constructions and include, for example, expanded clay concrete elements coupled with expanded polystyrene insulation panels (Edil Leca, 2023) or EPS panels with joints and concealed dowels (ED System, 2023). Some marketed solutions (Ecosism, 2023) have the dual function of improving energy efficiency and seismic behaviour of buildings.

Fully OSC solutions, on the other hand, consist of custom-made prefabricated monoblocs characterized by short installation time in which all the components of the façade cell are already assembled in the factory. Thus, the elements that are transported to the construction site are complete façades with structures, cladding, insulation, and anchoring systems. Examples of these solutions include those described in (ED System, 2023) and (Manni Green Tech, 2023) (see Figure 7), while some others that can be found on the market are specifically designed for the thermal insulation of the window frame.

Figure 7: Installation of a fully OSC solution (Woodbeton, 2023)

Among the more than 100 companies involved in the Italian ETICS supply chain, a very small amount offers complete OSC solutions for building envelope insulation. Many companies produce prefabricated solutions that still require more or less complex and time-consuming site operations depending on how advanced the solution itself is. Some companies, although specialized in OSC solutions, are more focused on new constructions rather than on retrofitting of existing buildings. The materials used for prefabricated or OSC insulation solutions are mainly plastic or mineral.

According to the preliminarily defined KPIs, four different examples of recuring companies' typologies have been identified and illustrated in Figure 8. Also, these companies' typologies will be updated once the set of KPIs will be finalized.

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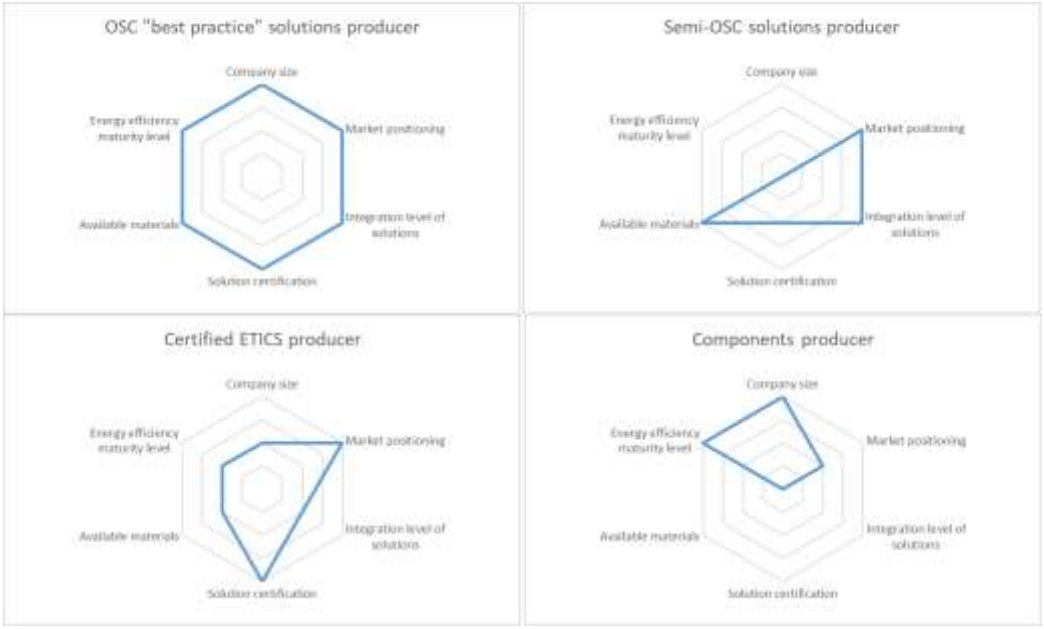

Figure 8. Examples of recuring companies' typologies identified through KPIs definition

B. Literature review on sustainable and recycled materials

Figure 9 shows the number of the articles about thermal insulation materials made by adding organic and inorganic wastes.

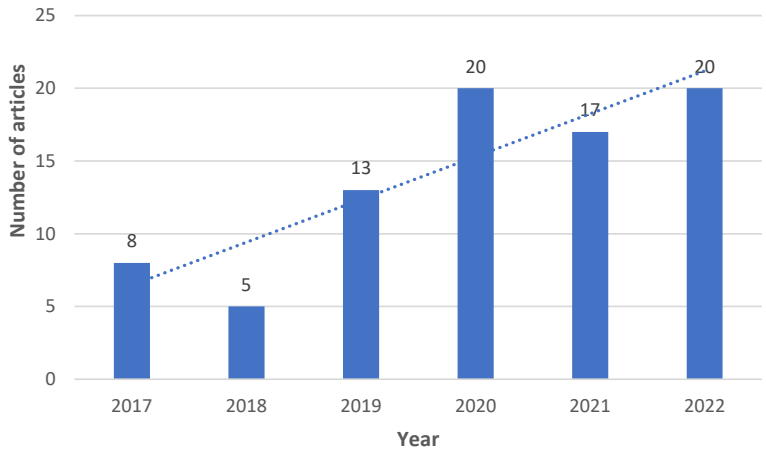

Figure 9: Number of articles retrieved about low impact thermal insulation materials published from 2017 to 2022

The authors reviewed 83 scientific international articles corresponding to 466 case studies. The literature review showcased that most of the sustainable thermal materials incorporate locally available wastes; specifically, both agricultural and forest wastes and animal wastes are used. For instance, some studies carried out in Morocco are focused on the use of wastes from hemp (Charai, Sghiouri, Mezrhab and Karkri, 2021), date palms (Oushabi, Sair, Abboud, Tanane and Bouari, 2017), peanut shells (Lamrani et al., 2017), and raw wool (EL Wazna et al., 2020). Furthermore, a study carried out in Algeria, an olive oil exporter, focused on the use of olive pomace (Belkharchouche and Chaker, 2017), and a study conducted in Spain,

focused on the use of mussel shells for bio-based insulation materials (Martìnez-Garcìa, Gonzàlez-Fonteboa, Carro-Lòpez and Pérez-Ordòñez, 2020). In Italy, some studies (i.e., (Ricciardi, Belloni, Merli and Buratti, 2021; Liuzzi, D'Alessandro, Martellotta, Rubino and Stefanizzi, 2022; Boquera et al., 2021)) were carried out about the use of agricultural wastes and cellulose in sustainable insulation materials. The reviewed case studies have been clustered into homogeneous categories: loose materials and foams, aerogel, blocks/bricks and structural materials, panels, and finishing materials (Figure 10).

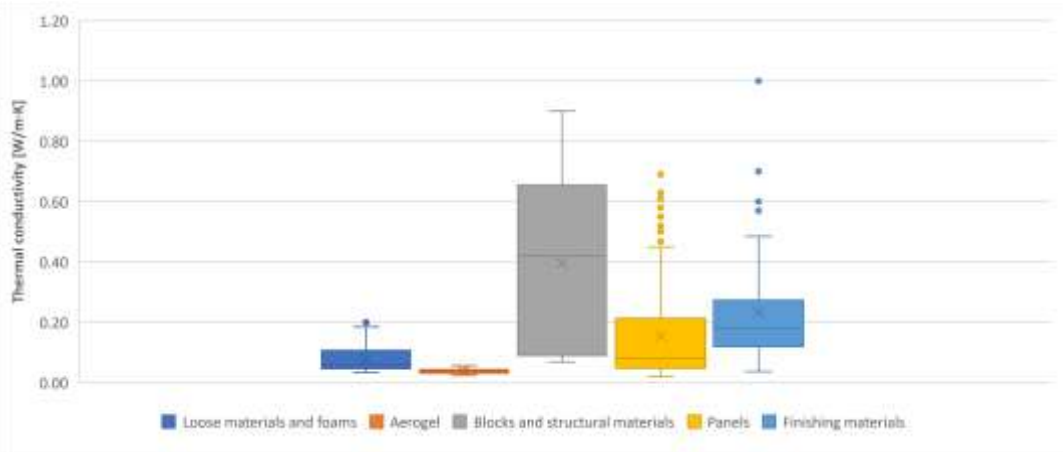

Figure 10: Thermal conductivity of the building thermal insulating materials

The literature review has shown that some sustainable thermal insulation materials have a good thermal performance (i.e., a low thermal conductivity value) comparable with that of the most common building insulation materials. For instance, (EL Wazna et al., 2020) found that raw wool used as loose material is characterized by thermal conductivity equal to 0.03 W/m•K which is similar to that of expanded polyurethane (Schiavoni, D'Alessandro, Bianchi and Asdrubali, 2016); nevertheless, the loose materials show a variation in the thermal conductivity which can be as high as 0.2 W/m•K. Contrariwise, aerogel from cellulose shows a very limited variability in thermal conductivity (i.e., from 0.02 to 0.06 W/m•K) as well as very good thermal performance; nevertheless, the wide deployment of aerogel in the building sector may be constrained by the high costs of this material (Schiavoni, D'Alessandro, Bianchi and Asdrubali, 2016). Blocks/bricks and structural materials show higher thermal conductivity values as well as the highest variability; however, regulations finalized to the energy saving do not impose specific thermal conductivity values to building structural parts. Moreover, Figure 10 displays that panels show a high variability in thermal conductivity; however, the lowest thermal conductivity value equals 0.03 W/m•K and corresponds to panels containing sheep wool, such a figure is similar to stone wool thermal conductivity. Lastly, the finishing materials containing organic and inorganic wastes can be characterized by the lowest thermal conductivity value equal to 0.04 W/m•K which is very similar to the thermal conductivity of expanded perlite and glass fibres (Schiavoni, D'Alessandro, Bianchi and Asdrubali, 2016).

C. Questionnaire

A complete representation of the preliminary structure of the questionnaire is given in Table 2 (See Supplementary Materials).

The first validation of such structure was conducted within a restricted session of a focus group composed by: four academic experts (from the three partner universities), five representatives of the main Italian

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business associations of manufacturers of insulation materials (ANIT, AIPE, ANPE and FIVRA) and three representatives of companies involved in the OSC supply chain (Knauf Insulation, Rockwool and Saint-Gobain). The focus group took place in Milan on the 19th of June 2023.

The participants to the focus group were asked to fill the questionnaire and also to provide feedback in relation to its clarity and usability, and the results were unanimously positive.

IV. DISCUSSION

The mapping of the Italian supply chain of building envelope insulation solutions has allowed to identify a small number of companies currently offering solutions that can be classified as fully OSC, but also a much larger number of companies offering ETICS (either kits or prefabricated panels) solutions that could potentially be interested in becoming part of the OSC supply chain. Over the last years, also thanks to the boost fromthe national government through the implementation of massive incentives schemes, the Italian ETICS market has rapidly developed, resulting in specular and chaotic development of the related supply chains. Companies from different NACE sectors have started to either produce or commercialise ETICS: at this stage of analysis, it appears that the integration level of the proposed solutions and the supply chain structure highly depends on the main insulation material used and therefore on the NACE sector of the insulation manufacturer. The impact of such differentiated supply chains on the development of a national OSC supply chain will need further investigation.

Certified kits are currently the most common form in which ETICS are commercialized, while fully OSC solutions are still very far from being largely diffused, although there seems to be interest towards their applications from both designers (and final customers) and producers, due to their potential benefits in terms of costs, quality and time. It is evident that the consistent effort put in place especially by consortia and manufacturers associations towards the definition and diffusion of certification schemes as well as of manuals and guides has revealed to be a best practice in terms of communication towards final customers and product placement.

Semi-OSC solutions, still requiring partial onsite assembly, are currently an attractive intermediate step between ETICS and OSC especially for renovation. In fact, they allow to achieve some OSC benefits while taking advantage of cost reductions due to serialization and mass production of ETICS components. In addition, they allow keeping logistic flexibility especially in areas where last-mile transportation of bulky materials might be difficult (e.g., historical towns and city centres).

As regards the literature review on sustainable and recycled materials, the increasing trend in the number of published articles about this topic will likely have an echo on the market that in the coming years will be more oriented towards more sustainable thermal insulation materials. All in all, the literature review has highlighted that both sustainable insulation materials with organic or inorganic wastes are spurring interest within the scientific community and that the newly developed materials have already reached thermal performances similar to those of the most widely used thermal insulation materials. Therefore, it is likely that in a near future the newly developed materials will substitute the more traditional and widespread ones providing high thermal insulation and less environmental impacts.

Finally, as regards the developed questionnaire, feedback from the focus group has highlighted its viability as a mean to gather insight on stakeholders' perspectives on OSC potential development. It will be further used in the following project's phases.

V. CONCLUSIONS

OSC has the potential to improve construction process efficiency and is, therefore, a promising technology to rapidly increase production capacity where needed to meet buildings' renovation requirements. Its implementation and diffusion are nonetheless yet to be completed, as it requires a deep shift in production management and practices. In addition, to allow developing effective and efficient OSC supply chains, it is

fundamental to gain knowledge and keep control over energy efficiency and sustainability practices along the different steps of the supply chain. To this end, a stakeholders-oriented methodology has been developed within the project OFFICIO that will allow mapping and characterizing existing supply chains in Italy, to study and innovate business models, to perform energy analyses of the most energy intensive production processes, and to create guidelines and tools to support companies in gaining and sharing knowledge and competences on this topic.

An analysis of the Italian ETICS market has allowed identifying, characterising, and categorizing companies already or potentially part of OSC supply chains according to economic and management information, insulation materials commercialized/manufactured, integration and certification of marketed solutions. At this stage of analysis, it appears that the integration level of the proposed solutions and the supply chain structure highly depends on the main insulation material used and therefore on the NACE sector of the insulation manufacturer. Certified kits are currently the most common form in which ETICS are commercialized, while fully OSC solutions are still very far from being largely diffused, although there seem to be interest towards their applications from both designers (and final customers) and producers. The main limitation of this study is that it has been carried out mainly on the basis of data gathered from databases and websites and is therefore missing, especially in its conclusions, the considerations and point of view of main stakeholders. This will be partially overcome through the questionnaire results once it will be widespread within the OFFICIO stakeholders' network, and specific interviews will also be conducted to this end with particularly active members of the observatory. Another obvious limitation of the study is geographical, considering its focus on the Italian market; nevertheless, the developed methodology can be applied to different context in future studies.

As concerns sustainable insulation materials with organic or inorganic wastes, they are spurring interest within the scientific community and have already proved to be able to offer thermal performances like those of the most widely used thermal insulation materials. Therefore, it is likely that in a near future the interest in the application of such materials will increase to reduce the environmental impact of constructions. Once again, the main limitation of this analysis is related to the lack of the stakeholders' consideration and perspective on the topic; it is in fact very difficult to analyse, on the basis of literature data, whether the identified materials could be actually used for OSC production (e.g. in terms of durability, potential to be used in the shape of panels, etc.). An additional data gathering activity will be performed on this matter through the OFFICIO stakeholders' network. In addition, future research on this topic will allow defining a decision support tool to facilitate companies to consider and evaluate the adoption of these materials within their products.

Finally, the structure of a questionnaire aimed at investigating OSC perception, in terms of general understanding, benefits and barriers to implementation, as well as energy efficiency status and practices, has been developed and its validation has been carried out. The validation, i.e., the discussion of the questionnaire within a restricted session of a focus group, has confirmed the proposed questionnaire to be viable for massive diffusion in a following phase of the project.

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SUPPLEMENTARY MATERIALS

Table 2: Structure of the questionnaire

Area of investigation	Topic of the question	Type of question

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Personal information	Name and surname	Open-ended question
	Company	Open-ended question
	E-mail	Open-ended question
	Consent to be included in the project mailing list	Closed-ended question (yes/no)
	Availability for further interactions with the project team	Closed-ended question (yes/no)
Professional information	Type of company	Closed-ended question (multiple choice with one possible answer: freelance; micro, small, medium, or big company, part of a larger group, public/research institution, professional association, other)
	Type of management	Closed-ended question (multiple choice with one possible answer: board of directors, family business, family business guided by a nominated CEO, multinational, other)
	Function within the company	Closed-ended question (multiple choice with one possible answer: owner, employee, general manager, energy manager, consultant, production manager, product manager, sales manager, R&D, other)
	Years of experience in the construction sector	Closed-ended question (multiple choice with one possible answer: less than 5, between 5 and 10, between 10 and 30, over 30)
	Experience with industrialized construction projects	Closed-ended questions (multiple choice with one possible answer: not applicable, less than 5 projects, from 5 to 10 projects, from 10 to 30 projects, over 30 projects)
Economic activity	NACE sector classification	Closed-ended question (multiple choice with one possible answer: two digits NACE sectors)
	Role within the construction sector	Closed-ended question (multiple choice with more than one possible answer: contractor, installer, designer, component manufacturer, systems/solutions provider) followed by an open-ended question to better describe the role
	Focus of the construction activity	Closed-ended question (multiple choice with more than one possible answer: new buildings, deep renovation of existing buildings)
	Type of customers	Closed-ended question (multiple choice with more than one possible answer: B2B, B2C)
	Certified management systems in place	Closed-ended question (multiple choice with more than one possible answer: ISO 9001, ISO 14001, ISO 50001, OHSAS 18001, none, other)
	Impact of existing incentives on business	Closed-ended question (yes/no)
Energy efficiency status and practices	Presence of an energy manager	Closed-ended question (yes/no)
	Presence of an energy management system	Closed-ended question (yes/no)
	Energy audit carried out within the last 4 years	Closed-ended question (yes/no)
	Energy efficiency measures implemented within the last 4 years	Closed-ended question (yes/no)
	Energy efficiency incentives used within the last 4 years	Closed-ended question (yes/no)
	Presence of an energy consumption monitoring system	Closed-ended question (multiple choice with one possible answer: no, yes with manual meters, yes with automated meters)
	Weight of energy costs on overall business costs	Closed-ended question (multiple choice with one possible answer: low, average, high)
	Weight of energy costs on overall operations costs	Closed-ended question (multiple choice with one possible answer: less than 5%, from 5 to

		10%, from 10 to 20 %, from 20 to 30%, over 30%)
	Main energy vectors	Closed-ended question (multiple choice with more than one possible answer: electricity, natural gas, automotive fuels, other)
	Presence of on-site energy production facilities (renewables)	Closed-ended question (yes/no)
	Presence of on-site energy production facilities (cogeneration/trigeneration)	Closed-ended question (yes/no)
Off-Site construction general knowledge (Off-Site Construction, OSC, refers to the production, planning, design, manufacture and assembly of building elements at a location other than that of the final installation, thus moving activities from the construction site to the factory)	Keywords used to describe off-site construction	Put the following keyword in order of relevance: modular construction, prefabrication, digitalization, industrialized construction, automation, drywall systems
	Basing on the given definition of OSC, current involvement of the company in the OSC sector	Closed-ended question (yes/no)
	Role of the company within the OSC sector	Closed-ended question (multiple choice with more than one possible answer: new buildings, energy renovations, other)
	Main activity of the company within the OSC sector	Closed-ended question (multiple choice with more than one possible answer: component manufacturer, insulation solutions assembly, distributor, supplier of structural prefabricated building solutions, supplied of thermal insulation prefabricated solutions)
OSC benefits	Time – Reduced construction time	Rate on the following scale: not relevant, quite relevant, relevant, highly relevant
	Time – Reduced overall project time	
	Costs – Improved control of project costs	
	Costs – Reduced materials costs	
	Costs – Reduced overall project costs	
	Costs – Reduced labour costs	
	Quality – Improved product and process quality	
	Productivity – Higher process efficiency	
	Productivity – Higher level of automation and digitalization	
	Productivity – Additional competencies acquired and more skilled workforce	
	Productivity – Market expansion and additional revenues	
	Productivity – Simplification and reduction of maintenance activities	
	Productivity – Avoid congestion on the construction site	
	Productivity – Reduced damage during installation and reduced waste	
	Safety and environment - Reduction of health and safety risks on the construction site	
	Safety and environment - Reduction of environmental impacts of renovation projects	
	Other benefits	Open-ended question
Barriers to OSC adoption and diffusion	Time – Additional logistics issues	Rate on the following scale: not relevant, quite relevant, relevant, highly relevant
	Time – Additional uncertainties	
	Costs – Higher initial costs	
	Costs – Higher design/panning costs	
	Costs – Limited choice of suppliers and need for “turnkey” solutions	

Quality – Additional coordination effort required among designers and suppliers	
Quality – Lower customization	
Productivity – Low availability and/or higher costs of specialized workforce	
Productivity - Organisational issues between design and implementation	
Productivity - Limited production capacity of suppliers	
Productivity – Smaller range of usable technical solutions due to prefabrication	
Productivity – Limited divisibility of project phases entailing limited possibility of project progress intermediate checks	
Productivity – Need for new professional figures	
Productivity – Limited possibility to transfer lessons learned and competencies from one project to another (higher projects specificity)	
Productivity – Less know-how available within companies	
Productivity – Less jobs created/available in the construction site	
Safety and environment – Additional coordination issues within the construction site	
Safety and environment – Need for new procedures	
Safety and environment – Lack of specific protocols and/or legislation	
Customers – Perception of a low-quality product	
Other barriers	Open-ended question

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Opredelitev trajnostne oskrbovalne verige za stavbe - rešitve toplotne izolacije zunanjega ovoja: predlog metodologije za preučevanje priložnosti na podlagi analize vsebin

Povzetek – Toplotna izolacija zunanjih sten je ena najučinkovitejših rešitev na trgu za povečanje energetske učinkovitosti v grajenem okolju. Gradnja izven gradbišča lahko z boljšim nadzorom različnih vključenih parametrov prinese pomembne prednosti, kot so skrajšanje časa gradnje ter izboljšanje kakovosti izdelkov in procesov. V zadnjih letih je hitro naraščajoče povpraševanje po toplotnoizolacijskih sistemih, ki so ga spodbujale tudi davčne spodbude, v Italiji ustvarilo edinstven položaj, v primerjavi s preostalo Evropo. To je povzročilo tudi precejšnjo razdrobljenost oskrbovalne verige z več udeleženci (proizvajalci komponent in sistemov, distributerji in inštalaterji). Zaradi kompleksnosti takšnega sistema, je Italija izjemno zahtevna in zanimiva študija primera za preučevanje oskrbovalne verige in trajnosti, tudi ob upoštevanju dejstva, da energetska učinkovitost italijanskega stavbnega fonda predstavlja ključni izziv za doseganje ciljev države

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glede varčevanja z energijo. 40 % končne porabe energije izvira iz stavb, 75 % stavbnega fonda pa ima nizko energijsko učinkovitost (energijske oznake E, F in G). V tem članku je predstavljena analiza italijanskega trga proizvajalcev rešitev za toplotno izolacijo ovoja stavbe, ki izpostavlja različne akterje v oskrbovalni verigi, glede na število, vrsto ter tržene izdelke in rešitve. Poudarek je na trajnostnih in recikliranih materialih. Namen študije je tudi opredeliti metodologijo za raziskovanje trenutnega stanja in priložnosti za industrializacijo trga ter njegovih ozkih grl. V članku je predlagan vprašalnik za zbiranje informacij in mnenj o razširjenosti gradnje izven gradbišč ter dojemanju podjetij in strokovnjakov glede prednosti in slabosti industrializacije tega sektorja. Validacija rezultatov je predstavljena v obliki industrijskih fokusnih skupin.

Ključne besede – trajnost oskrbovalne verige, industrijska energetska učinkovitost, gradnja izven gradbišča, industrializacija gradbeništva, trajnostni gradbeni materiali, modularne stavbe