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Delivering Sustainability in the Italian N-E Built Environment and Construction Sector: A Conceptual Research Framework

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Abstract: The main objective of this research is to describe a multidisciplinary investigation part of an ongoing research project. The contribution focuses on the identification and selection of innovative technologies and operative methodologies capable of fostering the sustainable innovation and resilience of the Italian N-E territory by addressing four challenges: energy transition, environmental challenges, adaptation to climate change, and digitalisation. The investigation devised an original conceptual research framework aiming to identify possible solutions and drawing a connection between them and the challenges, by considering the actions, the technological and methodological support, and, indirectly, the European and global policy objectives they help to reach. The research results are: (i) a definition of the four challenges in light of the built environment and construction sector; (ii) the conceptual research framework schema as a replicable instrument; (iii) its contextualization to the research scope; (iv) a preliminary list of technologies and methodologies supporting the sustainable innovation in the given territorial context; and (v) a ranking of the most promising solutions according to their effectiveness and application potential. The results highlight how, in the Italian N-E context, the solutions most effective in delivering sustainability and resilience are the ones operating in the built environment by preserving the built resources, mainly by addressing the building envelope and structure.

Keywords: innovative technologies; operative methodologies; energy transition; environmental challenges; climate change; digitalisation; sustainable built environment

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Citation: Zatta, E.; Condotta, M.; Revellini, R.; Tatano, V. Delivering Sustainability in the Italian N-E Built Environment and Construction Sector: A Conceptual Research Framework. *Buildings* **2023**, *13*, 2920. https://doi.org/10.3390/buildings13122920

Academic Editor: Adrian Pitts

Received: 29 September 2023
Revised: 17 November 2023
Accepted: 20 November 2023
Published: 23 November 2023

1. Introduction

This investigation was carried out in the "Interconnected Nord-Est Innovation Ecosystem" (iNEST) context, a research project funded by NextGenEU through the Italian National Recovery and Resilience Facility (NRRF). The overall project, spanning three years (2023–2026), is structured in nine main areas called "Spokes", each one of them focusing on a specific topic and involving a different multidisciplinary research group.

The contribution illustrates part of the first-year investigations conducted within Spoke 04, "City, Architecture and Sustainable Design". The general aim of the Spoke is to outline a strategic plan for the development of the construction and sustainable design sectors in the North-East of Italy, a fragile and unique territory in which the ethical commitment of design necessarily deals with the care and maintenance of an articulated landscape and a widespread historical architectural heritage within a territory characterised by significant environmental risks. As the three-year Spoke 04 activities are organised in 15 different Research Topics (RTs), the illustrated investigation—developed within one of them—is to be understood as a piece of a complex framework, not exhaustive per se, but rather an ongoing path interdependent with the other ones, both in terms of focus and scope.

The paper depicts the work carried out in 2023 within RT 1—task 3 (RT 1.3) by a research group involving three institutions. The objective of RT 1.3, as specified in the iNEST research programme, is to identify innovative technologies and operating methodologies capable of fostering the sustainable evolution of the built environment and the construction sector in the North-East of Italy. The overall task requires that the most promising solutions—preliminarily selected based on simplicity of replication, effectiveness in increasing sustainability, and efficiency in large-scale applications—have then to be examined, outlining supply chains and future patterns of reproducibility. It is to be noted that the latter activity is not included nor discussed in this contribution, which illustrates the research work up to the identification and assessment processes and results.

The technologies and methodologies (T/M) to be identified, besides aiming to deliver the expected transition by merging sustainability and innovation, should specifically act within four key thematic areas recognised as strategic by the Spoke 04 research programme:

- Energy transition (ET);
- Environmental challenges (EC);
- Adaptation to climate change (CCA);
- Digitalisation (D).

During the investigation, the four thematic areas were defined as “challenges” for two reasons: on the one hand, due to their current and future relevance in the built environment and construction contexts, and, on the other hand, because of their impacts on the whole of society, as they play a complex and interrelated role in delivering a comprehensive sustainability. Hence, the RT 1.3 research aims at supporting the transformation of the built environment and building sector by identifying solutions—namely, the technologies and methodologies—which should confront the pressures generated by buildings and infrastructures during their whole life cycle, while increasing the sustainability and resilience of the territory. In particular, the investigation focused on possible solutions to be implemented at the architectural scale and in the management of urban spaces, as the territorial scale was examined in depth by a different RT.

The Italian North-East region, the context of the research, presents a diffused and mixed building stock spanning from remarkable historical heritage examples to abandoned industrial buildings and underused dwellings—such as areas facing shrinkage processes. This variety also distinguishes the geographic distribution of the many settlements and their different urban fabrics, encompassing compact medieval towns, renaissance cities, post-WWII suburbs, scattered rural villages, mountain outposts, and an ubiquitous network of SME (small-to-medium-sized enterprise) facilities. Although the depicted heterogeneous background would suggest a quite dynamic building sector, both construction and practice in the territorial context reveal a slow innovation trend [1]. Despite the recent increase in refurbishment and renovation activities encouraged by post-pandemic incentives—soon to be over once the economic bonus runs out—the sector is still struggling to regain the undoubted relevance that distinguished it until the 2000s. Moreover, excluding market niches, construction still relies on a diffused consolidated technical know-how that appears to integrate sustainable and ecologic patterns too slowly to encourage an effective transition. On the contrary, the essential adaptation to climate change requires a deep transformation of the North-East built environment, especially considering the structural vulnerabilities of the territory [1]—hydrogeologic instability, seismic risk, soil impoverishment, and sea-level and salt wedge rise.

Current research trajectories addressing the built environment sustainability and resilience are mainly based on a reference background including a set of indicators and categories, either belonging to established assessment frameworks [2–4] or institutional ones [4–6]. Most of them share their reference’s scope and aim, providing possible improvements and new interpretations, while others build upon those grounds to provide operative suggestions [7]. The topic is usually approached at the urban scale [2,3,5,7], while investigations at the building scale [6,8] or involving multiple scales [4,9] are less frequent. Often, a number of principles [3,8] or focus areas [7] are identified, from the analysis of which specific categories or parameters, meaningful for the sustainable transition of the built environment, are drawn [2,3,10]. In addition, given the extent of the topic, several research products precisely delimit a perimeter by providing literature-based definitions clarifying their specific scope [2,3,5,8,9,11]. These contributions strongly enrich the upstream theoretical framework on which the sustainability and resilience principles for the built environment are rooted.

However, rarely are the built environment and construction sector sustainable transitions jointly examined. Moreover, as [7] highlights, frameworks supporting sustainable design by identifying methods and solutions to be implemented are lacking, and there is the need of instruments capable of interrelating the specific elements and components of complex contexts [12] such as the built environment itself. Within this scenario, the many benefits induced by the adoption of a transdisciplinary approach are acknowledged, especially in the architecture and urban planning fields [11] and in overcoming the compartmentalization of scientific knowledge. This is particularly crucial when confronting contemporary environmental questions such as climate change, land use, and the appropriate management of resources [13,14]. A transdisciplinary approach requires full and continuous collaboration during all phases of the investigation [11], as it strongly relies on co-creation of knowledge to tackle complex and interconnected themes [5,15] such as the ones pertaining to the sustainability [16] and resilience [17] domains.

The illustrated background demonstrates the need to adopt a cross-cutting perspective, and an approach consistent with such a complex field of application for the solutions to identify. Given the need to balance the innovation and preservation objectives within the investigation, it was clear how the technologies and methodologies should address not only future construction strategies, techniques, materials, and devices, but the recovery, preservation, and enhancement of existing buildings and settlements as well. This also requires paying attention to architectural and landscape aspects, by taking care of the built environment considering its natural and environmental context. The solutions to be identified should hence be consistent with a heterogeneous stock in terms of buildings and urban fabrics of past and future constructions [18]. In this sense, their innovative character could not only concern the technologies and methodologies themselves—such as techniques and approaches conceived specifically for new constructions—but also in an original implementation of the conventional ones or in an unconventional target. In line with this context, the investigation was undertaken by a multidisciplinary research group, which involved a total of 23 researchers—coordinated by the authors—experts in several fields (architectural design, architectural technology, building physics, heritage conservation, mechanics of structures, drawing and representation).

Considering both the peculiarities of the field of application and the adopted cross-curricular approach, the research presents two different degrees of replicability. In fact, in light of the territorial context and the scope of the investigation, the identified solutions can be relevant in other Central European contexts (i), while the developed multidisciplinary methodology can be relevant on a global scale and for different disciplines as well (ii).

The contribution is structured as follows. Section 2 illustrates the materials and methods of the investigation, detailing the three phases in which it was organised; Section 3 describes the results, clarifying their relevance both in terms of developed methodology and territorial contextualisation; Section 4 discusses the research outputs; and Section 5 draws the conclusions.

2. Materials and Methods

For carrying out the investigation, it was necessary to clearly define a scope and a structured framework to set the research within. It was assumed that, to reach the research objective, intermediate outputs were necessary, which could be considered as results in and of themselves. For this reason, the task was structured in three main phases (Figure 1):

- A first phase, clarifying the scope of the investigation by setting a perimeter defining the highlighted thematic areas (energy transition, environmental challenges, adaptation to climate change, digitalisation—thus, the four challenges) within the given field of application (built environment and construction sector). This output is considered also a result as it defines an architectural perspective that could support further research on the topic.

- A second phase, devising a conceptual research framework allowing the drawing of a clear connection between the objective (identification of innovative technologies and operative methodologies increasing the sustainability and resilience of the territory) and the scope of the investigation. This output represents a result as well, as the developed conceptual framework structure can be used in other fields of study.
- A third phase, carrying out the investigation based on the results of phases one and two, which was organized in three steps itself: (i) identification of the technologies and methodologies, (ii) screening of the preliminary results, and adjustments and fine tuning of the conceptual framework, and (iii) assessment and ranking of the technologies and methodologies.

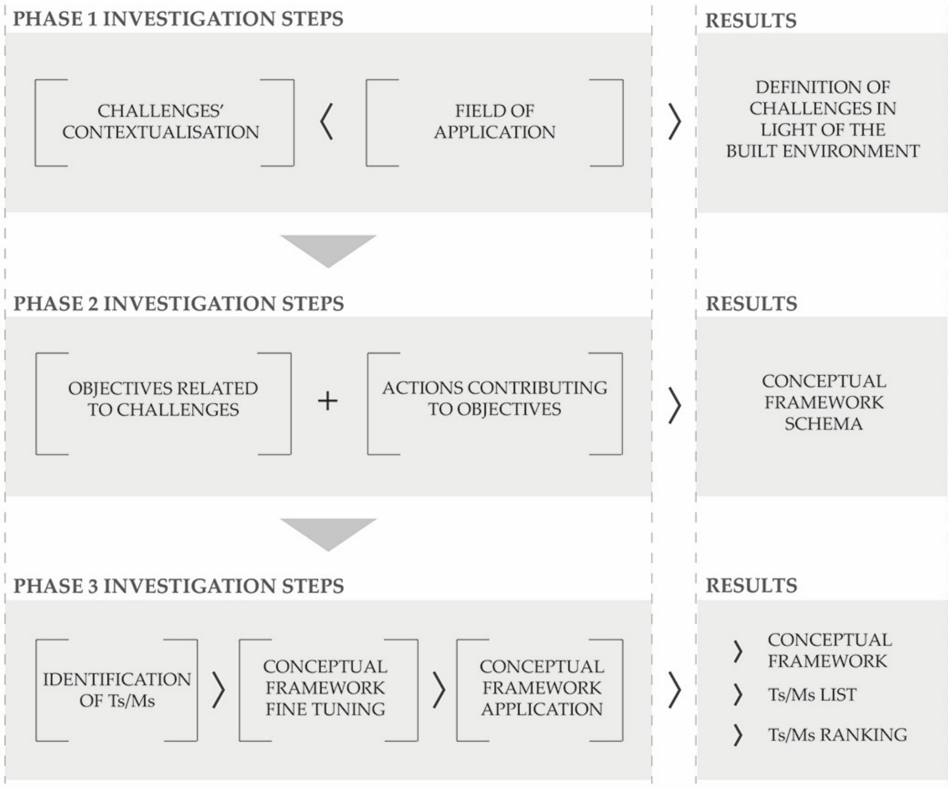

Figure 1. Structure of the investigation.

The materials and methods of the three phases are described as follows.

The first phase aimed at setting up a perimeter contextualising the four challenges within the specific field of application. For this purpose, a shared definition for each of the thematic areas was proposed, drawing from global and European policies and regulations and scientific reports. This allowed the clarification of the four challenges in terms of the boundaries of the research, the contribution in delivering sustainability, and the main policy objectives and processes to be enacted in this emerging framework—ultimately understanding the meaning and goals of each challenge within the built environment and building sector contexts. This phase acknowledged from the beginning the underlying relationship between the challenges, as, within the scope, digitalisation is not to be considered as a challenge per se, but rather a cross-cutting enabler, which could enhance the effectiveness in delivering energy transition, response to the environmental challenges, and adaptation to climate change. Therefore, and in line with the perspective illustrated in the introduction, it was agreed that innovation can be promoted without necessarily requiring the use of digital technologies as well, since the technologies and/or methodologies could be innovative because of their unconventional targets, novel implementation approaches or different fields of application than the one for which they were originally developed. In this sense, no bias influenced their identification. Table 1 lists the references used to create the definitions of the four challenges.

Table 1. References used to build the definition of the four challenges, listed according to their appearance in the definitions' themselves.

Challenge	References
Energy Transition	EC, 2019a [19]; EP, 2022 [20]; UNEP, 2023 [21]; EC, 2019b [22]; EC, 2020a [23]; EC, 2020b [24]; EC, 2019c [25]; EP, 2021 [26]
Environmental challenges	IPCC, 2022 [27]; EEA, 2019 [28]; UNEP, 2022 [29]; UNEP, 2023 [21]; EC, 2019a [19]; EC, 2020c [30]; EC, 2020d [31]; EP, 2022 [20]
CC adaptation	IPCC, 2014 [32]; UNFCCC [33]; UN, 1992 [34]; IPCC, 2022 [27]; EP, 2022 [20]; EC, 2019b [22]; EC 2021 [35]; EC, 2023a [36]
Digitalisation	BOD, 2023 [37]; COD, 2023 [38]; OOD, 2023 [39]; CECE, 2019 [40]; CEU, 2021 [41]; ECSO, 2021 [42]; EC, 2023b [43]; EURACTIV, 2019 [44]; EC, 2019d [45]; EC, 2023c [46]

The second phase entailed devising the research conceptual framework, a process with two different objectives. On the one hand, it intended to establish a clear and univocal link between the technologies and methodologies to be identified and the four thematic areas, to guarantee the results to be consistent with the scope of the investigation. On the other, it aimed at defining a tool to be utilised in phase three, to assess the contribution that a single technology or methodology may offer to each challenge, also by possibly making use of digital processes. For these reasons, the conceptual research framework was intended to take into account the cross-cutting nature of the digitalisation challenge.

Firstly, identifying a number of objectives directly related to the challenges (digitalisation excluded) was necessary. To deliver this step, several global, European, and Italian policies, strategies, and reports, both institutional and developed by public bodies, were examined through the lens of the sustainable transition of the built environment and construction sector. It was chosen to use different sources than the ones on which the four definitions were based, as the latter were mainly focused on the European level and linked to a normative approach, while the objectives should reveal a more comprehensive and strategic framework, also considering the Italian context. Table 2 lists the objectives identified and the related policies or strategies.

Table 2. Policies and strategies examined to identify the objectives pertaining to each challenge.

Source	Energy Transition	Environmental Challenges	Adaptation to CC
UNEP priorities [21]	-	• chemical pollution • nature	• climate change
8th EU EAP [20]	• decarbonisation	• non-toxic, circular, and regenerative economy • zero pollution • protection, sustainable use, restoration of ecosystems	• reducing vulnerability and strengthening resilience and adaptation to CC
EU strategy adaptation to CC [35]	-	-	• mitigation of CC effects • disaster risk reduction • improving resilience • ensuring delivery of ecosystem services

Table 2. *Cont.*

Source	Energy Transition	Environmental Challenges	Adaptation to CC
Italian National Recovery and Resilience Facility (NRRF), with reference to the "tasks" ("missione", M) and related specific "components" ("componente", C) [47]	• increasing PV energy production • energy communities and prosumers (M2C1) • increasing buildings' energy efficiency and seismic safety (M2C3) • sustainable mobility (M2C2) • hydrogen production, use and distribution (M2C2) • developing district heating systems (M2C3) • smart, resilient, and flexible renewables-based grids (M2C2) • digitalised, inclusive and energy-efficient cultural heritage and infrastructures (M1C3)	• efficient and circular waste management (also through traceability) (M2C1) • safe sourcing and sustainable use of water resources (M2C4) • safeguarding biodiversity and air quality (M2C4) • increasing green areas in urban contexts (M2C4) • address hydrogeological vulnerabilities of the territory (M2C4) • restoration of historic parks and gardens (M1C3) • strengthening seismic safety of religious heritage (M1C3) • Protection and valorisation of rural architecture and landscapes (M1C3)	• increasing resilience of energy distribution grids and infrastructures (M2C2) • supporting monitoring and provisional systems (M2C4)
2030 Agenda SDGs' goals, with reference to the specific targets [48]	• affordable, reliable, modern energy services (7.1)	• inclusive and sustainable urbanization and capacity for participatory, integrated, sustainable human settlement planning and management (11.3)	
	• increase share of renewable energy (7.2)	• strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries (13.1)	
	• improving energy efficiency 7.3)	• manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration (14.2)	
	• Develop quality, reliable, sustainable and resilient infrastructure [. . .] to support economic development and human well-being, with a focus on affordable and equitable access for all (9.1)		
		• sustainable infrastructure and industries: resource-use efficiency, clean technologies and process (9.4)	• Address impacts of disasters on people and economy, including water-related disasters, with a focus on people in vulnerable situations (11.5)
		• protect/restore water-related ecosystems (6.6)	
		• water quality, reduce [water] pollution, increase [water] recycling and reuse (6.3)	
		• protect/safeguard the world's cultural and natural heritage (11.4)	

Table 2. *Cont.*

Source	Energy Transition	Environmental Challenges	Adaptation to CC
2030 Agenda SDGs' goals, with reference to the specific targets [48]		• reduce the impact of cities: air quality, waste management (11.6)	
		• sustainable management, efficient use of natural resources (12.2)	
		• management of chemicals and wastes, reducing release to air, water and soil (12.4)	
		• reduce waste: prevention, reduction, recycling, reuse (12.5)	
		• prevent and significantly reduce marine pollution of all kinds (14.1)	
		• conservation, restoration, sustainable use of freshwater ecosystems (15.1)	
		• sustainable management of forests (15.2)	

Secondly, different actions obtainable through technical solutions and contributing to reach the objectives were proposed and discussed by the research group. The identification of potential actions was based on the literature and on the researchers' know-how. It is to be noted that an action could contribute to reaching more objectives. These two steps laid the groundwork for the identification of the technologies and methodologies to be carried out by examining the extent to which they could support the actions—ultimately setting up an indirect connection between the solutions and the four challenges (Figure 2). As already mentioned, the fact that the technologies and methodologies could make use of digital processes and solutions or be digital per se was considered as well (Figure 3).

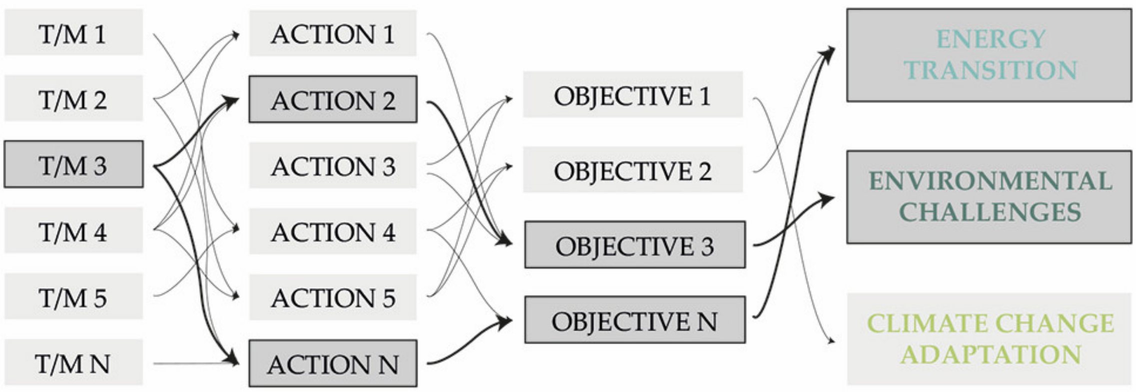

Figure 2. Graphical representation of the logical connections between the technologies and methodologies to the challenges, by defining the actions and objectives. For example, the figure highlights the connections between T/M 3 and the challenges through actions and objectives.

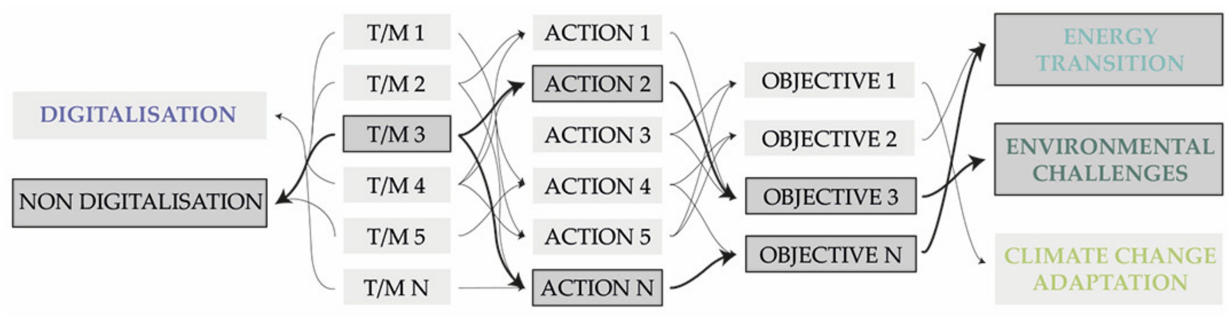

Figure 3. Graphical representation of the links between technologies and methodologies and the digital challenge.

To picture a more defined relationship between the identified solutions and the scope, a range of targets was considered to describe their potential applications to the built environment: urban space, indoor space, building structure, and building envelope. Figure 4 illustrates the roles of the four targets that the technologies and methodologies can be applied to within the conceptual matrix.

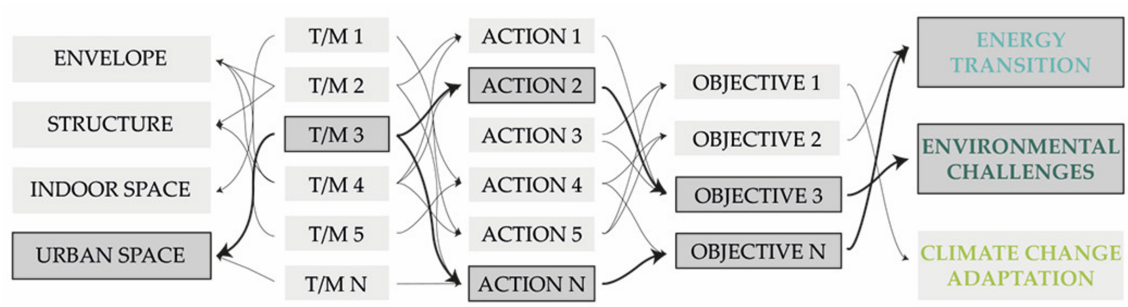

Figure 4. Graphical representation of the links between technologies and methodologies and the four targets.

The conceptual framework was then transposed in an online spreadsheet, shared with the research group, meant to collect the technologies and methodologies as entries, and organised to collect the following data for each of them: target(s) they can be applied to; action supported by the technology; objective(s) to be reached (one or more) by the specific action; connection to the confronted challenges (energy transition, environmental challenges, CC adaptation); connection to digitalisation (if the state-of-the-art solution already makes use of digital processes/devices); and a short description, references, and notes. The spreadsheet structure and functioning are exemplified in Table 3.

Table 3. Conceptual framework schema. Example of the collection of data pertaining to two entries (technologies or methodologies), carried out by filling in the shared spreadsheet.

Solution	Target [(a)]				Actions	Objectives	Challenges			Digital Challenge	Description	References	Notes
	E	S	I	U			ET	EC	CCA				
T/M 1 [(b)]	x			x	action (a)	obj. 1			x	x	...	...	...
					action (b)	obj. 2		x			...	...	...
					action (c)			x			...	...	...
T/M 2		x	x	x	action (d)	obj. 1	x				...	...	...
					action (b)	obj. 3		x			...	...	...

[(a)] E = envelope; S = structure; I = indoor space; U = urban space. [(b)] Solution 1: applies to urban space and envelope; through action (a) supports objective 1, helping to confront Climate Change Adaptation, and though actions (b) and (c) supports objective 2, helping to confront the Environmental Challenge; can make use of digital technologies or solutions.

Although being an instrument devised to effectively transpose the conceptual framework in a consistent and organised set of data, as an original methodology, the spreadsheet structure also represents a first result of the investigation that is detailed in Section 3.2.

The third phase saw the research team carrying out the investigation, a task involving three subsequent steps: (i) identifying innovative technologies and operative methodologies able to increase the sustainability of the built environment and construction sector in the Italian N-E territory based on their replicability, sustainable effectiveness, and efficiency in large-scale application; (ii) screening of the preliminary results and adjustments of the contents; and (iii) assessment and ranking of the solutions according to their potential contribution in confronting the three challenges.

During step (i), the members of the research team, individually or divided in groups, started the research, based on the literature and on the specific expertise of each researcher, to fill in the spreadsheet. Although every contribution fully or mainly derived from one of the disciplines involved, by contextualising it within the actions-objectives-challenges course, it was possible to highlight its cross-cutting character, both in contributing to one or more challenges and in its application to one or more targets.

Step (ii) involved a first screening of the preliminary results, which highlighted the need of some adjustments to the spreadsheet structure and contents, namely:

- Deriving from different policies or strategies, several objectives were similar, redundant, or could be included one into the domain of another.
- Although expressed by different words, some actions were equivalent in terms of effects.
- Being integrated by different research teams, each of them with a specific background and approach, some “action-objective-challenge” connections were not precise.

A simplification and a rearrangement of the contents were hence carried out:

- The original 30 objectives (9 pertaining to energy transition, 21 concerning the environmental challenges, and 4 concerning adaptation to climate change) were reorganised through merging them into 10 macro-objectives (respectively, 3, 5, and 2). The output of this activity is displayed in Table 4.
- the redundant actions were merged, and a univocal correspondence was drawn between each of them and the specific objectives (and macro-objectives) supported.
- the “action-objective-challenge” connections were verified and fine-tuned for each technology or methodology proposed.

Table 4. Rearrangement of the objectives in macro-objectives to optimise the conceptual framework structure.

Challenge	Macro-Objectives	(Sub-) Objectives	References
Energy transition [ET]	Decarbonisation	Reducing GHG emissions of production and consumption processes	7th EAP
		Reducing GHG emissions in products’ lifecycle	
	Improving energy efficiency	Improving energy efficiency of production, distribution, consumption processes	SDG 7.3 PNRR M2C3 PNRR M1C3
		Improving energy efficiency of buildings (existing and new constructions)	
		Improving energy efficiency of cultural heritage and infrastructures also through digitalisation	
	Increasing the share of renewable energy	Increasing renewable energy production, distribution, and final use	SDG 7.2 PNRR M2C1 PNRR M2C2
		Increasing PV efficiency and/or use	
		Supporting energy communities and prosumers	
		Smart, resilient, and flexible renewables-based grids	

Table 4. *Cont.*

Challenge	Macro-Objectives	(Sub-) Objectives	References
Environmental challenges [EC]	Protection, sustainable management and restoration of ecosystems and natural resources	Conservation, sustainable management and restoration of natural environment and landscapes	SDG 6.3 SDG 6.6 SDG 14.1 SDG 15.1 SDG 15.2 SDG 14.2 PNRR M2C4
		Conservation, sustainable use, and restoration of freshwater, marine, and all water-related ecosystems	
		Conservation, sustainable use, and management of forests	
		Safeguarding biodiversity and air quality	
	Quality, reliable, sustainable, and resilient human settlements	Supporting inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning and management	SDG 6.3 SDG 9.1 SDG 11.3 PNRR M2C4
		Increasing green areas in urban contexts	
		Increasing water quality, safe sourcing, and sustainable use, also through storage, recycling, and reuse	
		Addressing seismic and hydrogeological vulnerabilities of buildings and territories	
		Developing quality, reliable, sustainable, and resilient infrastructure	
		Supporting human well-being by promoting economic development and employment	
	Material resource sustainable management in a non-toxic, circular, and regenerative economy	Improving sustainable innovation and resource efficiency in infrastructures, productive systems, and supply chains, also promoting SME growth	SDG 6.3 SDG 9.4 SDG 11.6 SDG 12.4 SDG 12.5 PNRR M1C2 PNRR M2C1
		Reducing all waste through prevention, reduction, recycling, and reuse	
		Reducing the impact of cities through a sustainable and efficient material resource management	
	Zero pollution	Efficient management of chemicals, reducing their release to air, water, and soil	SDG 9.4 SDG 11.6 SDG 14.1 PNRR M2C4
		Preventing and significantly reducing air, water, and soil pollution of all kinds	
		Reducing impacts of human settlements on air quality and energy demand	
		Improving clean technologies and processes in infrastructure and industries	
	Protection and safeguarding of world's cultural and natural heritage	Protection and valorisation of rural architecture and landscapes	SDG 11.4 PNRR M1C3 PNRR M2C4
		Digitalised, inclusive, and energy efficient cultural heritage and infrastructures	
		Strengthening seismic safety through efficient monitoring	
		Restoration of historic parks and gardens	

Table 4. *Cont.*

Challenge	Macro-Objectives	(Sub-) Objectives	References
Adaptation to Climate Change [CCA]	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters	Strengthening adaptation and reducing vulnerability to CC	EU CC SDG 13.1 SDG 14.2 PNRR M2C2
		Management and protection of marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience and taking action for their restoration	
		Increasing resilience of energy distribution grids and infrastructures	
	Supporting provisional systems for human well-being and territories' safeguard	Efficient management of hydrogeological hazards, floods, and storms impacting on buildings and territories	PNRR M2C2 PNRR M2C4

The overall results of the simplification and rearrangement process are detailed in Section 3.2.

Step (iii), concerning the evaluation of the technologies and methodologies, entailed defining the parameters to base the choice on. In fact, simplicity in replication, effectiveness in increasing sustainability, and efficiency in large-scale implementation, despite being considered for the identification, are features difficult to be quantified by univocal criteria also due to the different modes, scales, and contexts of application. To support this process, a data visualisation tool was used to graphically represent the results: two alluvial diagrams were developed, and later interpreted, in light of the conceptual framework. This kind of graphic representation was selected since it allowed the qualitative description of the relationships between targets, technologies/methodologies, actions, objectives, and challenges, while quantitatively highlighting different elements or features just by slight arrangements in the setting of the source dataset. The diagrams were built starting from the conceptual framework spreadsheet structure. The datasets were organised to produce two different outputs, respectively aimed to identify:

- The technologies and methodologies contributing the most in addressing the challenges, depending on the actions supported, and presenting a potential extensive application, depending on the targets involved. This meant rearranging the spreadsheet relying on two different operations. On the one hand, the extent to which the solutions influenced the challenges was expressed by multiplying the dataset lines pertaining to each technology or methodology depending on the number of related actions. On the other, to highlight the multiple applications of the solutions, every action was multiplied based on the number of targets it acts on, paying attention to the action's actual pertinence and outcomes. Table 5 and Figure 5 exemplify the structure of the first dataset and the related alluvial diagram.
- The relationship between the identified solutions and the challenges, paying attention to cross-cutting digitalisation. The former dataset (Table 5) was complemented by a column which provided the data concerning, at the current state of the art, the use or non-use of digitalisation for each technology. Table 6 and Figure 6 exemplify the structure of the second dataset and the related alluvial diagram.

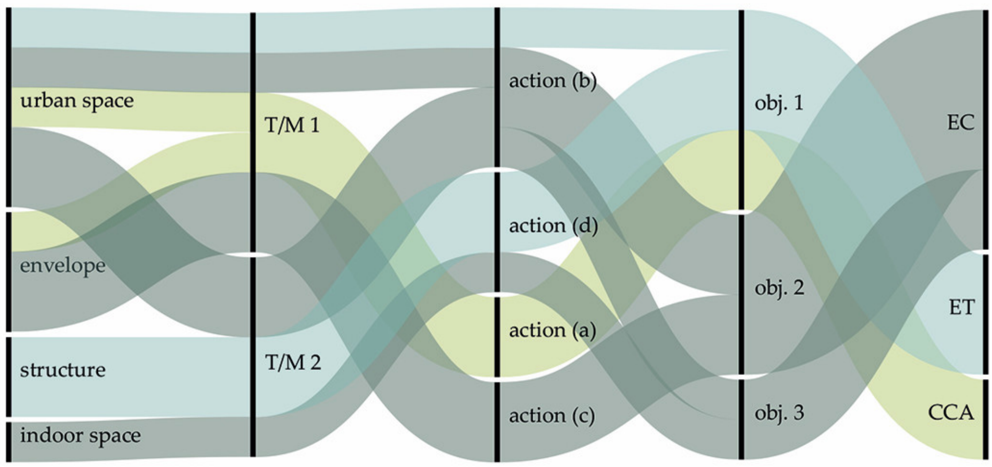

Figure 5. Alluvial diagram derived from the example dataset of Table 5.

Table 5. Example of the first dataset considering two entries (technologies or methodologies), based on the data sample used in Table 3.

Solution	Target	Actions	Objectives	Challenges
T/M 1 [a]	envelope	action (a)	obj. 1	CCA
T/M 1	envelope	action (b)	obj. 2	EC
T/M 1	envelope	action (c)	obj. 2	EC
T/M 1	urban space	action (a)	obj. 1	CCA
T/M 1	urban space	action (b)	obj. 2	EC
T/M 1	urban space	action (c)	obj. 2	EC
T/M 2 [b]	structure	action (d)	obj. 1	ET
T/M 2	structure	action (b)	obj. 3	EC
T/M 2	indoor space	action (d)	obj. 1	ET
T/M 2	urban space	action (d)	obj. 1	ET
T/M 2	urban space	action (b)	obj. 3	EC

[a] the line pertaining to solution 1 is repeated 6 times, since it supports 3 actions and each action acts on 2 targets. [b] the line pertaining to solution 2 is repeated 5 times, since it supports 2 actions and action (d) acts on 3 targets, while action (b) acts on 2 targets.

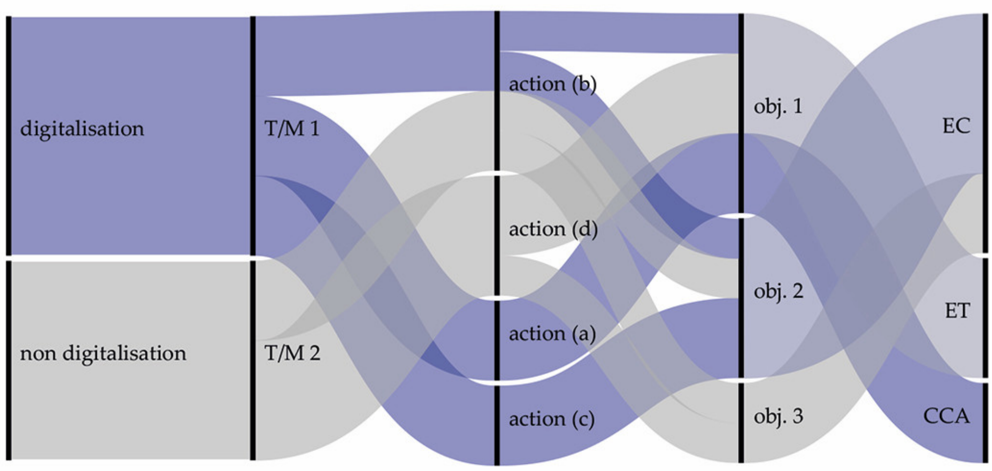

Figure 6. Alluvial diagram derived from the example dataset of Table 6.

Table 6. Example of the second dataset considering two entries (technologies or methodologies), based on the data sample used in Table 3.

Solution	Target [(b)]	Actions	Objectives	Challenges	Digital Challenge
T/M 1 [(a)]	envelope	action (a)	obj. 1	CCA	digit.
T/M 1	envelope	action (b)	obj. 2	EC	digit.
T/M 1	envelope	action (c)	obj. 2	EC	digit.
T/M 1	urban space	action (a)	obj. 1	CCA	digit.
T/M 1	urban space	action (b)	obj. 2	EC	digit.
T/M 1	urban space	action (c)	obj. 2	EC	digit.
T/M 2	structure	action (d)	obj. 1	ET	non digit.
T/M 2	structure	action (b)	obj. 3	EC	non digit.
T/M 2	indoor space	action (d)	obj. 1	ET	non digit.
T/M 2	urban space	action (d)	obj. 1	ET	non digit.
T/M 2	urban space	action (b)	obj. 3	EC	non digit.

[(a)] the lines follow the same principle of the ones in Table 5 both for T/M 1 and T/M 2. [(b)] the target column, although not visualised in the graphic (Figure 6), is still present in the table because the produced diagram builds upon the previous one, keeping the arrangement of Ts/Ms, actions and objectives.

Raw Graphs (www.rawgraphs.io, accessed on 22 May 2023) was the open-source software used for developing the diagrams, based on the duly edited spreadsheet saved in a .cvs format.

3. Results

The following subsections detail the results of the investigation. Section 3.1 illustrates the perimeter set to define the scope of the research, considering the challenges and their field of application, providing the definition of the four challenges. Section 3.2 describes the steps undertaken in phase 2 for the conceptual framework devising, also detailing the objectives rearrangement as well as the univocal correspondence set between actions and objectives elaborated during the third phase. Sections 3.3 and 3.4 finally present the several technologies and methodologies identified and depict the outputs of the decision-making process that led to the rating of the technologies and methodologies by interpreting the alluvial diagrams.

As outlined in the introduction, the contents illustrated in Sections 3.2–3.4 represent two different levels of results. In fact, the first ones (Section 3.2) derive from the structuring of an original and interdisciplinary methodology, which can be transposed in other fields of study, while the second ones (Sections 3.3 and 3.4) originate from the method application to a specific territory and can be relevant to similar European contexts.

3.1. Defining the Scope of the Research: Definitions of the Four Challenges in Light of the Built Environment and Construction Sector

3.1.1. Energy Transition

Defining the "energy transition" implies the need to identify: (i) the expected results of the transition itself, (ii) the broader context it is part of, and the envisaged (iii) instruments and (iv) features.

Concerning the (i) expected results, the transition specifically steers towards clean energy, and can be viewed as "the gradual transition away from fossil fuels towards a carbon-neutral economy" addressing "all levels of the economy—from energy generation all the way to people's homes" while "striving for a more secure, competitive and sustainable energy system which will address the existential challenge of our time—climate change" [19]. Decarbonisation through reducing emissions and boosting energy efficiency is an overall aim shared by the 8th EAP [20] and UNEP [21] as well.

In relation to (ii) the context, it is strictly related to the EU Green Deal implementation, that is "a new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050" [22]. The clean energy transition is hence fundamental, due to the "need to rethink policies for clean energy supply across the economy, industry, production and consumption, large-scale infrastructure, transport, food and agriculture, construction, taxation and social benefits" [22].

The (iii) main instruments playing an essential role are renewable energy sources [22] and their smart integration with energy efficiency and other sustainable solutions, among which are decarbonised gases [22]; renewable hydrogen, produced using mainly wind and solar energy [23]; innovative technologies and infrastructure (smart grids, hydrogen networks, carbon capture, storage and utilisation, energy storage) [22]; and a relevant share of geographically distributed renewable energies [24]. However, although not directly connected to clean energy production systems, namely renewables sources, or to more efficient plants and installations, other cross-cutting actions can support the carbon-neutral economy objective. In particular, all processes implying a reduction in carbon emissions compared to a BAU scenario indirectly act towards this aim, among them [22]: mobilising industry towards a circular economy in resource and energy-intensive value chains as constructions; building and renovating in an energy- and resource-efficient way adopting a life-cycle approach; and strategies preserving and restoring our natural capital through re-forestation and bio-circular economy.

Other (iv) features beyond the environmental perspective are fundamental: the clean energy transition must be fair and just [25] and increase our quality of life as citizens [19]. It is, in this sense, "a transition to a safe, sustainable, affordable and secure energy system relying on the deployment of renewables, a well-functioning internal energy market and the improvement of energy efficiency, while reducing energy poverty" [26].

3.1.2. Environmental Challenges

This research adopts a perspective in which the environmental challenges involve topics pertaining not only to the natural context, but also to the built one, and within a life cycle approach. This choice is not only grounded on the buildings' and infrastructures' operational and embodied carbon, which, together with their material resource consumption, represent a challenge to be undertaken indeed: it rather relies on the concept of taking care of the built environment at all scales and all aspects, from the territory to the architecture, without forgetting the role culture plays in it. Two more premises are fundamental to clearly define the perimeter of the "environmental challenges" adopted in this investigation. On the one hand, they encompass not only human-induced ecologic criticalities, but natural disaster risks inherent to the specific North-East territory of Italy as well, such as the seismic one. On the other hand, addressing the objectives identified for the human-induced environmental challenges means targeting the climate change causes over time, hence adopting an "ex-ante" approach to tackle CC. In this sense, IPCC [27] defines "human intervention to reduce emissions or enhance the sinks of greenhouse gases" as mitigation strategies. On the contrary, the objectives addressing specifically the climate change consequences from an "ex-post" perspective (the ones dealing with concepts such as vulnerability, adaptation, and resilience) are not considered part of the "environmental challenges", nor inherent to the territory's disaster risks, and are examined in the Climate Change Adaptation challenge.

Current human-induced environmental challenges are "rooted in global developments stretching back over decades", in which "the Great Acceleration of social and economic activity has transformed humanity's relationship with the environment" [28]. Such pressures on the environment are now contributing to climate change and, both directly and indirectly, inflicting harm on human health and well-being [28]. Their main drivers can be identified as: changes in land and sea use, unsustainable consumption and production patterns, climate change, and pollution of water, air, and soil [29]. Hence, mankind's environmental challenges can be translated into a set of objectives that, if reached, will significantly reduce the actual anthropic pressure on nature, if we "sustainably use, restore and protect the ecosystem services that it provides" [29]. Such objectives span through different areas and fields of the economic and social systems, the interlinkages among which [28,29] have to be acknowledged prior to defining the actions to undertake and the related instruments.

On a global scale, UNEP [21] identifies two priority areas to act in this context: (i) nature and (ii) chemical pollution. The related challenges are: (i) sustainable use, management, restoration, and protection of ecosystems, biodiversity, and habitats; and (ii) cleaner air, soil, and water, also by sustainable consumption and production patterns, addressing toxic chemical, plastic, and waste reduction. Among the potential means to adopt, resource efficiency strategies, circular economy processes, ecosystem-based approaches, and nature-based solutions are highlighted.

At the European level, the policy framework relies on the EU Green Deal [19], and the challenges it identifies to meet the target of decarbonisation by 2050. Those environmental issues can be organised into three specific policy objectives [30] which, considering how "zero pollution" addresses both emissions and waste, slightly differ from the global scale priority areas: (i) zero pollution, (ii) biodiversity, and (iii) circular economy—the latter examined in depth by the 2nd CEAP [31]. The main fields in which sustainability is to be delivered are food, energy, mobility, and buildings, and the DNH principle must be respected [30]. The recent 8th EAP [20], also building on the 2020 SOER (State of the Environment Report) [28], identifies among its priority objectives—hence, challenges: (a) a healthy, non-toxic circular economy; (b) zero pollution for a toxic-free environment, including air, water, and soil, as well as light and noise pollution; (c) protecting, preserving, and restoring biodiversity; (d) reducing environmental pressures in the areas of energy, industry, buildings and infrastructure, mobility, tourism, international trade, and the food system.

All the actions to undertake to address the environmental challenges have to be carefully evaluated in relation to the potential fragilities that distinguish the different areas of the North-East territory in the perspective of disaster risk prevention and reduction, as safety represents a necessary condition for a community's well-being [22].

3.1.3. Adaptation to Climate Change

In the climate change context, adaptation is defined as "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects" [32]. According to Article 1 of the United Nations Framework Convention on Climate Change [33], the latter is about "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" [34]. Consequently, climate change adaptation refers to the "changes in processes, practices and structures to moderate potential damages or to benefit from opportunities associated with climate change" [33].

The concept of "adaptation" encompasses actions undertaken for both strengthening resilience and reducing vulnerability to CC consequences. The former ones aim at enhancing "the capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity", while the latter approach "the propensity or predisposition to be adversely affected" by such events [27].

In the European context, several policies address the objectives to reach in order to cope with climate change effects.

The 8th EAP highlights the importance of "strengthening resilience and reducing vulnerability" [20] to foster adaptation.

The European Green Deal acknowledges the importance of tackling climate change effects through stronger "efforts on climate-proofing, resilience building, prevention and preparedness" and working on adaptation also by developing instruments integrating climate change into other risk management practices [22].

Since "climate change is happening today", the New EU Strategy on Adaptation to Climate Change was adopted "to build a more resilient tomorrow" [35], highlighting the importance to undertake long-term actions since "halting all greenhouse gas emissions would still not prevent the climate impacts that are already occurring"—that is, the "ex-ante" approach outlined in the environmental challenges definition. Such actions, and in particular nature-based solutions, will foster gains in adaptation, mitigation, disaster risk reduction, and biodiversity, while a better understanding of the interdependencies between climate change, ecosystems, and the services they deliver will allow minimising risks, improving resilience (especially local one), and ensuring the continued delivery of vital ecosystem services and features. The Strategy also defines the overall benefits of adaptation: (i) avoiding future human, natural and material losses; (ii) generating economic benefits by reducing risks, increasing productivity, and stimulating innovation; and (iii) the social, environmental, and cultural benefits.

Several actions tackling the climate vulnerabilities apply to the built environment, bearing in mind the cross-cutting relevance of buildings within the European climate policies [36]: they can be vulnerable to climate change but, at the same time, also assets through which large-scale adaptation strategies can be implemented. Nevertheless, policy decisions at the building scale need to be coordinated with wider strategies (such as urban planning ones) and underpinned with certain climate data, taking in mind that a one-size-fits-to-all-solution cannot exist [33].

In this sense, it is possible to talk about "buildings' adaptation to climate change", which considers how different buildings can adapt to climate change and the following impacts on the health, well-being, and productivity of the community.

3.1.4. Digitalisation

In its wider acceptation, the action of "digitalising" or "digitising" refers to the possibility of changing something physical to a digital form [37,38]. When applied to processes, supply chains, or business models, it involves "the adoption or increase in the use of digital technologies by an organisation, an industry or a country" [39], to "change a business model and provide new revenue and value-producing opportunities" (Gartner Online Dictionary, in [40], p. 11). Among the possible improvements and benefits digitalisation allows, the Italian Recovery and Resilience Facility observes how the digitalisation and innovation efforts do not only represent an objective per se, but a "cross-cutting necessity, as it concerns the continuous and necessary technological update in the productive systems" [41].

However, it is very difficult to provide a unique and exhaustive definition of digitalisation and its potential implementation patterns, especially when it is related to the building sector and to the built environment. In fact, this perspective requires examining both the novelties granted in innovating the construction processes, market, and supply chain through digital systems or technologies, and their outcomes in material shape, such as buildings and infrastructure, urban areas or private spaces, ultimately affecting our everyday lives at all scales.

Concerning the construction sector, which is a key driver in the EU economy, digital technologies and their interactions are necessary to improve its functioning in terms of competitiveness, resources, energy efficiency, and productivity [42]. Moreover, digitalisation can be considered fundamental in accelerating its sustainable transformation as well, addressing climate and environment protection challenges and lowering the European carbon footprint [43]. Nevertheless, to date, the building industry is one of the least digitalised in the EU economy [44]; hence, digitalisation constitutes both an opportunity and a challenge [45] due to the complexity and sector-based structure of the field. Within the urban built environment, the digitalisation impacts are widespread at all scales, in both private and public spaces. Nevertheless, many improvements can still be made to enhance the fruition, liveability, usability, and accessibility of buildings and open areas, most of all in terms of spatial justice and social inclusion and, of course, environmental sustainability.

Being part of the “twin transitions”, which significantly affect the construction field development, digitalisation in the building field will support all the actions towards decarbonisation, boosting energy efficiency, and avoiding GHGs emissions. This means improving the building process’s efficiency in several phases: supply of materials, surveys and data acquisition, design and building optimisation, construction site management (including material and energy flows), and buildings’ end-of-life effective management. Digitalisation’s sustainable benefits will affect the operational phase as well, through real-time data collection, allowing the monitoring and optimising of performance, functioning, maintenance, and safety.

ECSO [42] divides the most relevant digital technologies for the construction sector into three categories: (i) data acquisition (e.g., sensors; Internet of Things; 3D scanning); (ii) automating processes (e.g., robotics; 3D printing; drones); and (iii) digital information and analysis (e.g., Building Information Modelling—BIM; Virtual/Augmented Reality—VR/AR; Artificial Intelligence—AI; Digital twins). Although these technologies display different levels of development, with a wider diffusion and use of BIM, sensors, and drones, the sector efficiency and competitiveness could be significantly improved by “data acquisition, automating processes and other digital information and analysis related technologies” [42] (p. 12).

Dealing with a fragmented and heterogeneous supply chain and sector, mainly composed of SMEs, involving all the actors is crucial. As “digitalisation is both inevitable and pivotal for the competitiveness and sustainability of the European construction sector” [42] (p. 9), it has to become a driver, especially among SMEs, which are often unaware and/or not convinced of the benefits of digitalisation. The European Commission specific Handbook [46] is dedicated to spreading know-how on “technologies earmarked as relevant for construction SMEs” based on former studies, i.e., (i) Building Information Modelling (BIM); (ii) 3D printing, (iii) automated robots (incl. exoskeletons), (iv) drones, (v) 3D scanning, (vi) sensors, and (vii) Internet of Things (IoT) and mobile devices. Nevertheless, apart from qualified jobs, it has to be considered that reskilling and upskilling of the workforce involved in construction will be required.

3.2. Results of the Conceptual Framework Devising: Challenges, Objectives, Actions

The second phase of the research led to defining the conceptual framework contents to be gathered from the research groups. In this perspective, the structure of the spreadsheet used to collect the data (Table 3) represents a method employed, but also a preliminary result in and of itself.

Following the data gathering performed in phase 3, the simplification and rearrangement of the contents were carried out, according to the correspondence between the original 30 objectives and the 10 macro-objectives already depicted in Table 4. This reorganisation and the verification of the “challenge-objective-action” paths allowed the drawing of a univocal link between each action and the macro-objective(s) it supports, as illustrated in Table 7.

Table 7. Univocal correspondences identified between the collected actions and the macro-objectives supported.

Action	Macro-Objective	(Sub-) Objectives
Guaranteeing human independence, safety, and well-being	Quality, reliable, sustainable, and resilient human settlements [EC]	Supporting inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning and management Supporting human well-being by promoting economic development and employment
	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	all sub-objectives
	Supporting provisional systems for human well-being and territories' safeguard [CCA]	all sub-objectives
Improving ambient air quality and/or pollutants absorption	Zero pollution [EC]	Preventing and significantly reducing air, water, and soil pollution of all kinds Reducing impacts of human settlements on air quality and energy demand
	Protection, sustainable management, and restoration of ecosystems and natural resources [EC]	Safeguarding biodiversity and air quality
Improving biodiversity	Protection, sustainable management, and restoration of ecosystems and natural resources [EC]	Safeguarding biodiversity and air quality
	Quality, reliable, sustainable, and resilient human settlements [EC]	Increasing green areas in urban contexts
Improving coastal protection	Protection, sustainable management, and restoration of ecosystems and natural resources [EC]	Conservation, sustainable usem and restoration of freshwater, marine and all water-related ecosystems
	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	Management and protection of marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience and taking action for their restoration
Improving indoor air quality	Zero pollution [EC]	Preventing and significantly reducing air, water, and soil pollution of all kinds Reducing impacts of human settlements on air quality and energy demand
Improving resource-use efficiency in construction	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	all sub-objectives
Improving the circular management of material resources	Decarbonisation [ET]	Reducing GHGs emissions in products' lifecycle
	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	Reducing all waste through prevention, reduction, recycling, and reuse Reducing the impact of cities through a sustainable and efficient material resources management

Table 7. *Cont.*

Action	Macro-Objective	(Sub-) Objectives
Improving water purification and quality	Protection, sustainable management, and restoration of ecosystems and natural resources [EC]	Conservation, sustainable use, and restoration of freshwater, marine and all water-related ecosystems
	Zero pollution [EC]	Preventing and significantly reducing air, water, and soil pollution of all kinds
Improving water recycling and reuse	Quality, reliable, sustainable, and resilient human settlements [EC]	Increasing water quality, safe sourcing, and sustainable use, also through storage, recycling and reuse
Increasing efficiency of installations	Decarbonisation [ET]	Reducing GHGs emissions of production and consumption processes
	Improving energy efficiency [ET]	Improving energy efficiency of production, distribution, and consumption processes Improving energy efficiency of buildings (existing and new constructions)
Increasing soil permeability	Quality, reliable, sustainable, and resilient human settlements [EC]	Increasing green areas in urban contexts
	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	Strengthening adaptation and reduce vulnerability to CC
	Supporting provisional systems for human well-being and territories' safeguard [CCA]	Efficient management of hydrogeological hazards, floods, and storms impacting on buildings and territories
Increasing the performance of buildings envelope	Decarbonisation [ET]	Reducing GHG emissions of production and consumption processes Improving energy efficiency of buildings (existing and new constructions)
	Zero pollution [EC]	Reducing impacts of human settlements on air quality and energy demand
Increasing use of renewables	Decarbonisation [ET]	Reducing GHG emissions of production and consumption processes
	Increasing the share of renewable energy [ET]	Increasing renewable energy production, distribution, and final use
Increasing water retention (run-off regulation)	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	Strengthening adaptation and reduce vulnerability to CC
Local sourcing of building materials and elements	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	Reducing the impact of cities through a sustainable and efficient material resources management
Mitigating the overheating effects	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	Strengthening adaptation and reduce vulnerability to CC
Monitoring the vulnerabilities of the natural and built environment	Quality, reliable, sustainable, and resilient human settlements [EC]	Addressing seismic and hydrogeological vulnerabilities of buildings and territories
	Protection and safeguarding of world's cultural and natural heritage [EC]	Strengthening seismic safety also through an efficient monitoring
	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	Management and protection of marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience and taking action for their restoration

Table 7. *Cont.*

Action	Macro-Objective	(Sub-) Objectives
Monitoring the vulnerabilities of the natural and built environment	Supporting provisional systems for human well-being and territories' safeguard [CCA]	Efficient management of hydrogeological hazards, floods and storms impacting on buildings and territories
Optimising construction and demolition waste management	Decarbonisation [ET]	Reducing GHG emissions of production and consumption processes
	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	all sub-objectives
Optimising the building site management	Decarbonisation [ET]	Reducing GHG emissions of production and consumption processes
	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	Improving sustainable innovation and resource-efficiency in infrastructures, productive systems and supply chains, also promoting SMEs growth
Promoting re-forestation/afforestation and arboreal species in urban contexts	Protection, sustainable management, and restoration of ecosystems and natural resources [EC]	Conservation, sustainable management, and restoration of natural environment and landscapes
	Quality, reliable, sustainable, and resilient human settlements [EC]	Increasing green areas in urban contexts
Protecting heritage and other built resources	Protection and safeguarding of world's cultural and natural heritage [EC]	all sub-objectives
	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	Strengthening adaptation and reduce vulnerability to CC
Reducing exploitation of natural capital	Protection, sustainable management, and restoration of ecosystems and natural resources [EC]	all sub-objectives
	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	Reducing the impact of cities through a sustainable and efficient material resources management
Reducing heat island effect	Decarbonisation [ET]	Reducing GHG emissions of production and consumption processes
	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	Strengthening adaptation and reduce vulnerability to CC
Reducing seismic vulnerability of existing buildings	Quality, reliable, sustainable, and resilient human settlements [EC]	Addressing seismic and hydrogeological vulnerabilities of buildings and territories
	Protection and safeguarding of world's cultural and natural heritage [EC]	Strengthening seismic safety also through an efficient monitoring
	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	Strengthening adaptation and reduce vulnerability to CC
Reducing use of chemicals in construction materials	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	Reducing the impact of cities through a sustainable and efficient material resources management
	Zero pollution [EC]	Efficient management of chemicals, reducing their release to air, water, and soil

Table 7. *Cont.*

Action	Macro-Objective	(Sub-) Objectives
Setting micro- and small-scale distribution grids for renewables	Increasing the share of renewable energy [ET]	Smart, resilient, and flexible renewables-based grids
	Quality, reliable, sustainable, and resilient human settlements [EC]	Supporting inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning and management
	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters [CCA]	Increasing resilience of energy distribution grids and infrastructures
Using bio-based materials and substances	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	Reducing the impact of cities through a sustainable and efficient material resources management
	Zero pollution [EC]	Reducing impacts of human settlements on air quality and energy demand
Using carbon-storage materials	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	Reducing the impact of cities through a sustainable and efficient material resources management
	Zero pollution [EC]	Reducing impacts of human settlements on air quality and energy demand
Using non-energy intensive materials	Decarbonisation [ET]	Reducing GHGs emissions in products' lifecycle
	Material resource sustainable management in a non-toxic, circular, and regenerative economy [EC]	Reducing the impact of cities through a sustainable and efficient material resources management

3.3. Identification of the Collected Data: Innovative Technologies and Operative Methodologies for the Italian North-East Built Environment and Building Sector

The overall conceptual framework reorganised layout led to the final structure of the spreadsheet, the contents of which are fully displayed in the Supplementary Materials (Table S1). As anticipated in Section 2, Table S1 represents a result of the methodology application to the Italian North-East context and, at the same time, a method used for the following interpretation of the results themselves.

During the third phase of the investigation, a total of 38 innovative technologies and operative methodologies were collected; none of them was excluded or altered due to the rearrangements carried out as the preliminary results were gathered. The solutions were organised into seven groups or "strategies", based on their similar approach and/or aim—an organisation only meant to provide a further qualitative interpretation of the outputs, and which did not limit nor influence the data input in any way. The strategies are named as follows:

- Nature-based strategies (9 solutions).
- Renewable materials (3 solutions).
- Extending the lifespan of buildings and buildings' components and materials (7 solutions).
- Passive solutions for buildings (5 solutions).
- Digital information and analysis (4 solutions).
- Data acquisition and output (5 solutions).
- Renewable energy sources and installation (5 solutions).

Each strategy includes technologies and methodologies pertaining to different scales, contexts of application and disciplines or fields of study, as detailed in Table 8.

Table 8. List of the technologies (T) and methodologies (M) identified for each strategy.

Strategy		Solutions
Nature-based strategies	T.	Green roofs, Green facades, Rain gardens, Mobile flowerbeds, Bio-restoration and green chemistry products, Innovative TRC with nature-based fibres
	M.	De-paving or de-sealing solutions; Greening at urban scale, Above-ground farming
Renewable materials	T.	High-strength engineered wood structures, External and internal insulation of existing and new buildings with bio-based materials, Natural fibre building plugging
	M.	-
Extending the lifespan of buildings and buildings' components and materials	T.	Structural and non-structural concrete with high percentages of recycled aggregate from construction and demolition waste, Thermoplastic polymer panels and plates with high percentages of recycled material for transparent or semi-transparent building envelopes, Panels and plates with high percentages of recycled and recyclable material for buildings envelope, External steel braced frames equipped with advanced devices for seismic protection
	M.	Design for disassembly and reuse, Selective demolition or deconstruction for the reuse of components, Design for Adaptability/Flexibility/Change
Passive solutions for buildings	T.	Motorised brise-soleil with integrated PV cells, Phase Change Materials (PCMs) integration into the building envelope components, Breathe bricks for building envelope, Photocatalytic painting for external walls
	M.	Parametric-designed facades for new building or renovation-recladding
Digital information and analysis	T.	Building Information Modelling to facilitate existing buildings and heritage management, Virtual reality to manage the building site
	M.	Digital twins, Tracking of building materials and elements
Data acquisition and output	T.	Internet of Things for buildings' management, Internet of Things for a more inclusive space, Innovative techniques for monitoring of environmental, material, structural parameters, Drones for managing construction sites, existing buildings and territories
	M.	Transdisciplinary innovative methodology for vulnerability assessment
Renewable energy sources and installation	T.	Renewable energy sources integration in smart grids, Fault detection and maintenance forecast (HVAC systems), Solar films for windows or facades glass, Photovoltaic and smart glass for windows or facades, Organic photovoltaic
	M.	-

The Nature-based strategies include six technologies (Green roofs, Green facades, Rain gardens, Mobile flowerbeds, Bio-restoration and green chemistry products, Innovative Textile Reinforced Concrete (TRC) with nature-based fibres) and three methodologies (De-paving or de-sealing solutions; Greening at urban scale, Above-ground farming).

Among the renewable materials, three technologies were identified (High-strength engineered wood structures, External and internal insulation of existing and new buildings with bio-based materials, Natural fibre building plugging).

The strategy "Extending the lifespan of buildings and buildings' components and materials" includes four technologies (Structural and non-structural concrete with high percentages of recycled aggregate from construction and demolition waste (concrete and bricks), Thermoplastic polymer (PC, PMMA) panels and plates with high percentages of recycled material for transparent or semi-transparent building envelopes, Panels and plates with high percentages of recycled and recyclable material for buildings envelope, External steel braced frames equipped with advanced devices for seismic protection) and three methodologies (Design for disassembly and reuse, Selective demolition or deconstruction for the reuse of components, Design for Adaptability/Flexibility/Change).

The identified passive solutions for buildings include four technologies (Motorised brise-soleil with integrated PV cells, Phase Change Materials (PCMs) integration into the building envelope components, Breathe bricks for building envelope, Photocatalytic painting for external walls) and one methodology (Parametric-designed facades for new building or renovation-recladding).

The Digital information and analysis category includes two technologies (Building Information Modelling to facilitate existing buildings and heritage management, Virtual reality to manage the building site) and two methodologies (Digital twins, Tracking of building materials and elements).

The Data acquisition and output results include four technologies (Internet of Things for buildings' management, Internet of Things for a more inclusive space, Innovative techniques for monitoring of environmental, material, structural parameters, Drones for managing construction sites, existing buildings and territories) and one methodology (Transdisciplinary innovative methodology for vulnerability assessment).

The Renewable energy sources and installation category includes five technologies (Renewable energy sources integration in smart grids, Fault detection and maintenance forecast (HVAC systems), Solar films for windows or facades glass, Photovoltaic and smart glass for windows or facades, Organic photovoltaic).

The overall number of technologies (28) exceeds the number of methodologies (10). The difference between these two kinds of solutions lays in their names themselves. In fact, the technologies identify applications to be practically implemented in the built environment. On the contrary, the methodologies refer to operative processes supporting the design, management, or maintenance of the constructions and/or urban spaces, possibly concerning several phases of the building lifecycle. In this sense, a technology can be one of the instruments by means of which a methodology is implemented.

3.4. Rating of the Most Promising Solutions by Interpreting the Alluvial Diagrams

The assessment process of the third phase of the research was supported by the two alluvial diagrams developed to describe the relationships between technologies/methodologies, actions, objectives, and challenges. The two diagrams, despite being conceived to describe these links by a qualitative approach, aimed at highlighting in a quantitative way two different aspects.

Figure 7 shows the first alluvial diagram, in which the five examined categories are organised through the "descending" option: concerning the investigation objectives, the items located on the top part of the graph contribute better to support the challenges than the ones in the lower portion. The related database (Table S2) and a high-quality version of Figure 7 (Figure S1) are included in the Supplementary Materials.

The actions displayed on the top part of the figure are the ones implemented the most by the technologies and methodologies identified; the objectives are listed according to the number of actions supporting them; hence, the figure displays on the top the ones more addressed by the actions.

Table 9 lists the technologies and methodologies according to descending order, expressing the overall related number of actions. The latter is influenced by the targets addressed, paying attention to the action's actual pertinence and outcomes as exemplified in Section 2 (Table 5). The following Table 10 makes clear each of the solutions acting on the four targets, as well as the overall number of them.

Table 9. List of the technologies and methodologies and their related number of actions according to the descending order.

Rank	Technology or Methodology	No. of Actions
1	Tracking of building materials and elements	21
2	Selective demolition or deconstruction for the reuse of components	18
3	Transdisciplinary innovative methodology for vulnerability assessment	15
4	Innovative techniques for monitoring of environmental, material, structural parameters	14
	Drones for managing construction sites, existing buildings, and territories	14

Table 9. *Cont.*

Rank	Technology or Methodology	No. of Actions
5	Design for disassembly and reuse	12
	Organic photovoltaic	12
6	Digital twins	11
7	Rain gardens	10
	Renovation though Design for Adaptability/Flexibility/Change	10
	Virtual reality to manage the building site	10
	IoT for buildings management	10
8	Green roofs	9
	Green facades	9
	Innovative Textile Reinforced Concrete (TRC) made with nature-based materials	9
9	Depaving or de-sealing solutions	8
	External and internal insulation of existing and new buildings with bio-based materials	8
	Structural and non-structural concrete with high percentages of recycled aggregate from construction and demolition waste	8
	IoT for a more inclusive space	8
10	Portable garden and flower beds	7
	Greening at urban scale	7
	High strength engineered wood structures	7
11	Biorestoration and green chemistry products	6
	Natural-fibre building plugging	6
	External steel braced frames equipped with advanced devices for seismic protection	6
	Building Information Modelling to facilitate existing buildings and heritage management	6
12	Renewable energy sources integration in smart grids	5
	Photovoltaic and smart glass for windows or facades	5
13	Above-ground farming	4
	Thermoplastic polymer (PC, PMMA) panels and plates with high percentages of recycled material for transparent or semi-transparent building envelopes	4
	Panels and plates with high percentages of recycled and recyclable material for buildings envelope	4
	Motorised brise-soleil with built-in PV cells	4
	Photocatalytic painting for external walls	4
14	Parametric-designed facades for new building or renovation (recladding)	3
	Phase Change Materials (PCMs) integration in the building envelope components	3
	Breathe bricks for building envelope	3
	Fault detection and maintenance forecast (HVAC systems)	3
	Solar films for windows or facades glass	3

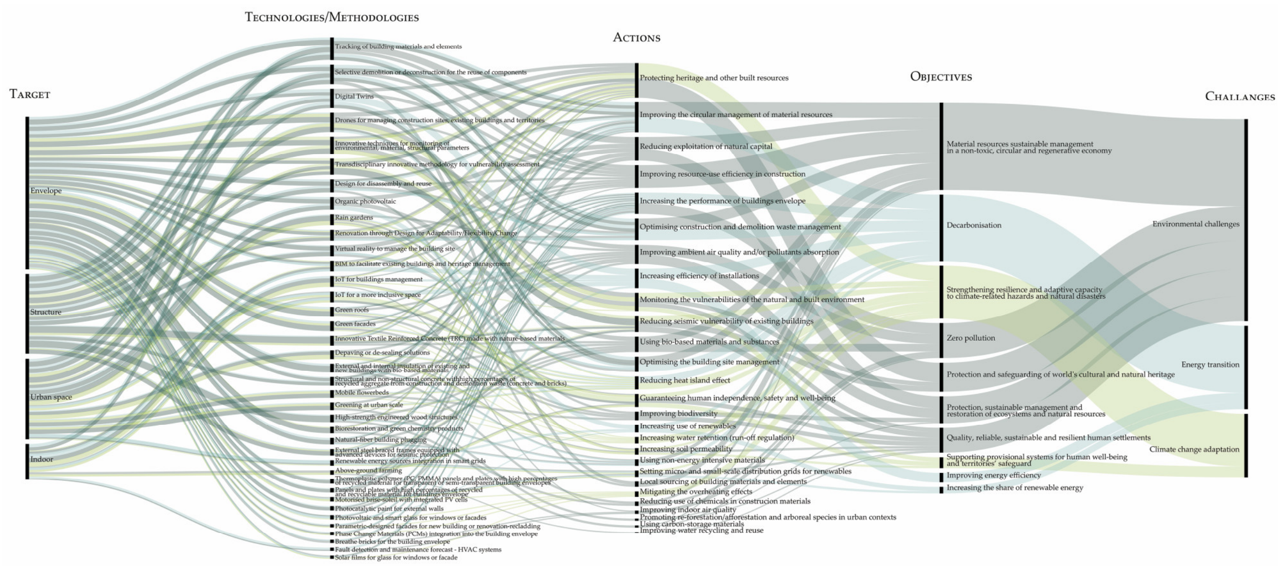

Figure 7. First alluvial diagram depicting the relationship between targets, solutions, actions, objectives, and challenges, ranking them according to the number of actions supported and targets addressed. The visualisation, following the "descending" option, ranks the T/M according to the degree by which they support the challenges and address the targets.

Table 10. List of the technologies and methodologies organised per target addressed.

Target	Technology or Methodology	No. of Ts/Ms
E	Green roofs; Green facades; Biorestoration and green chemistry products; External and internal insulation of existing and new buildings with bio-based materials; Natural-fiber building plugging; Structural and non-structural concrete with high percentages of recycled aggregate from construction and demolition waste (concrete and bricks); Thermoplastic polymer (PC, PMMA) panels and plates with high percentages of recycled material for transparent or semi-transparent building envelopes; Panels and plates with high percentages of recycled and recyclable material for buildings envelope; Design for disassembly and reuse; Selective demolition or deconstruction for the reuse of components; Renovation through Design for Adaptability/Flexibility/Change; Motorised brise-soleil with integrated PV cells; Parametric-designed facades for new building or renovation-recladding; Phase Change Materials (PCMs) integration into the building envelope; Breathe bricks for the building envelope; Photocatalytic paint for external walls; Virtual reality to manage the building site; BIM to facilitate existing buildings and heritage management; Digital twins; Tracking of building materials and elements; Innovative techniques for monitoring of environmental, material, structural parameters; Drones for managing construction sites, existing buildings and territories; Transdisciplinary innovative methodology for vulnerability assessment; Solar films for windows or façades glass; Photovoltaic and smart glass for windows or facades; Organic photovoltaic	26
S	Innovative Textile Reinforced Concrete (TRC) made with nature-based materials; High-strength engineered wood structures; Design for disassembly and reuse; Selective demolition or deconstruction for the reuse of components; Renovation through Design for Adaptability/Flexibility/Change; Structural and non-structural concrete with high percentages of recycled aggregate from construction and demolition waste (concrete and bricks); External steel braced frames equipped with advanced devices for seismic protection; Virtual reality to manage the building site; digital twins; Tracking of building materials and elements; Innovative techniques for monitoring of environmental, material, structural parameters; Transdisciplinary innovative methodology for vulnerability assessment	12
U	Rain gardens; Depaving or de-sealing solutions; Mobile flowerbeds; Greening at urban scale; Selective demolition or deconstruction for the reuse of components; Tracking of building materials and elements; IoT for a more inclusive space; Drones for managing construction sites, existing buildings and territories; Transdisciplinary innovative methodology for vulnerability assessment; Renewable energy sources integration in smart grids; Organic photovoltaic	11

Table 10. *Cont.*

Target	Technology or Methodology	No. of Ts/Ms
I	Above-ground farming; BIM to facilitate existing buildings and heritage management; digital twins; IoT for buildings management; IoT for a more inclusive space; Fault detection and maintenance forecast—HVAC systems	6

Figure 8 displays the second alluvial diagram, showing the technologies and methodologies that, at the current state of the art, make use of digital processes or devices and dividing them from the ones that do not show such feature. The related database (Table S3) and a high-quality version of Figure 8 (Figure S2) are included in the Supplementary Materials. The current organisation in two different groups does not exclude that, following future technical improvements or unprecedent applications, the solutions currently not linked to the digitalisation challenge could fall under the other category.

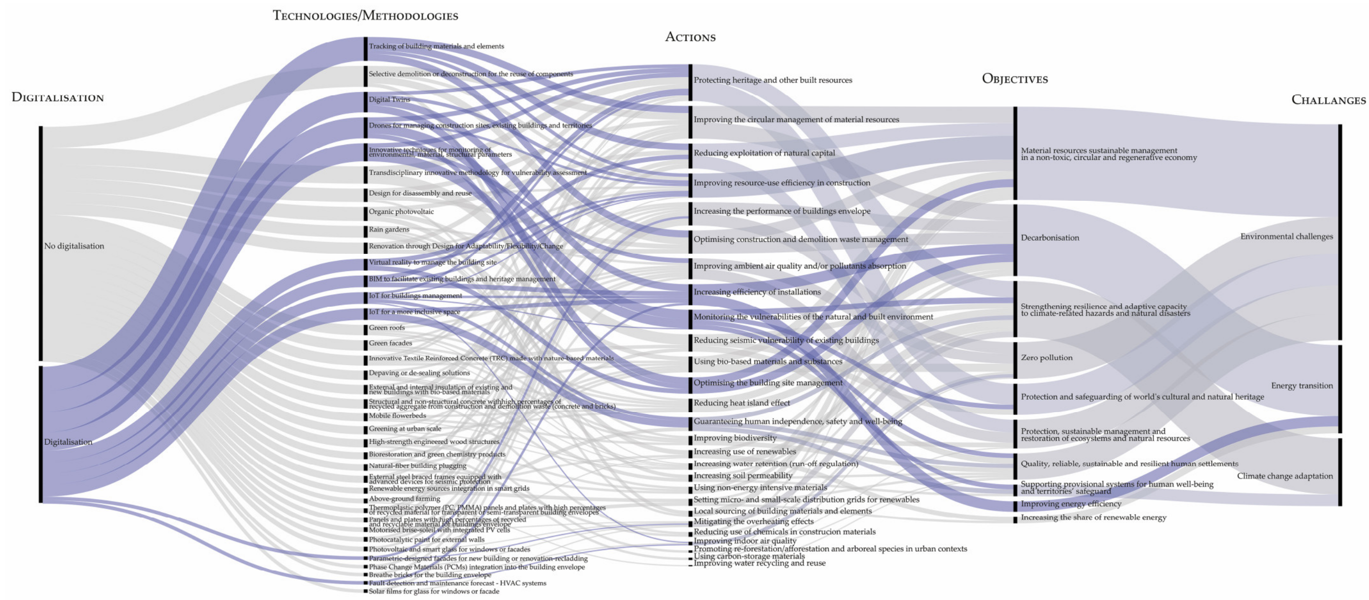

Figure 8. Alluvial diagram depicting the relationship between the identified technologies and methodologies and the cross-cutting digital challenge.

Table 11 summarises the technologies and methodologies which are relevant to the digital challenge, to date. They are ordered according to the descending order used for the first diagram (Figure 7), although it is not a ranking nor is related to a degree of effectiveness.

Table 11. List of the technologies and methodologies currently connected to the digital challenge.

Technology or Methodology
Tracking of building materials and elements
Innovative techniques for monitoring of environmental, material, structural parameters
Drones for managing construction sites, existing buildings, and territories
Digital twins
Virtual reality to manage the building site
IoT for buildings management
IoT for a more inclusive space

Table 11. *Cont.*

Technology or Methodology
Building Information Modelling to facilitate existing buildings and heritage management
Parametric-designed facades for new building or renovation (recladding)
Fault detection and maintenance forecast (HVAC systems)

The number of technologies or methodologies that make use of digital systems, or that are digital per se due to their methods of implementation, corresponds to the 26% of the total identified.

4. Discussion

Based on the results database, graphically represented by the diagram in Figure 7, it is possible to define (Table 9) a ranking of the 38 solutions, listed according to their effectiveness in addressing the challenges through the actions they support and the objectives they contribute to reaching. It is to be noted that the graphical output considers the four targets as well (Envelope, Structure, Urban Space, Indoor Space), as the rank of the technologies/methodologies is affected also by the number of targets each action could address. The target most addressed by the technologies and methodologies is the envelope [E], followed by structure [S], urban space [U], and indoor space [I]. Many of the identified solutions are ranked ex-aequo: this is due to the limited range of both actions supported (between 3 and 10 per technology/methodology) and of targets addressed (between 1 and 3 per solution). The order of three challenges reveals that Environmental Challenges is the one most confronted by the identified solutions, followed by Energy Transition and Adaptation to Climate Change. This depends on the overall number of actions indirectly supporting the challenges. Table 9 shows that only in one case a technology or methodology supports more than 20 actions (included); 11 solutions support a number of actions between 10 (included) and 20; 26 solutions support less than 10 actions.

The most promising solutions are "Tracking of building materials and elements" and "Selective demolition or deconstruction for the reuse of components", the first two methodologies in the ranking supporting a huge number of actions (21 and 18 respectively), contributing to Energy transition and Environmental challenges, and covering three targets each (envelope; structure; urban space). The following solution in the ranking is the "Transdisciplinary innovative methodology for vulnerability assessment", which reached the third position supporting 15 actions, contributing to Environmental Challenges and Adaptation to Climate Change, and addressing three targets (Envelope; Structure; Urban space). These first three positions denote how the concepts of sustainability, environmental preservation, and climate change adaptation are increasingly connected to operations focused on existing buildings, whether they are to be preserved or demolished, understood in their value as cultural and/or material resources. It is hence no surprise that, concerning different thematic areas and addressing the management of complex processes, operative methodologies, rather than technologies, hold the podium. Such perspective emerges as well by examining the whole list: seven out of 10 methodologies support between 10 and 21 actions and are ranked among the first and seventh place, confirming their wider scope.

A further observation reveals how the most promising solutions are not innovative per se, nor specifically designed with the sole aim of contributing to address the environmental challenges. On the contrary, they can be described as methodologies originally created to support construction and design processes with other purposes, such as optimisation of the building sites, implementation of urban mining strategies, efficient management of construction materials, and securing and preserving heritage. Nevertheless, the results highlight how their benefits also concern the environmental and energy issues, making these solutions particularly effective in supporting the sustainable evolution of the built environment and the construction sector precisely because of their wide application potential. This also demonstrates how, in the Italian construction sector, traditionally slow in absorbing technological innovation due to both operational and cultural reasons, innovation lies in using traditional and already consolidated technologies, techniques, and procedures in an original and alternative way.

The solutions' extensive application by supporting the actions is not the only reason determining the ranking. The number of addressed targets also influences the technologies and methodologies effectiveness. This is probably the reason placing all the entries belonging to the "Passive solutions for buildings" strategy in the lower part of the list, along with a high number of the "Renewable energy sources and installation" ones—with the exception of Organic photovoltaic technology. In fact, most of these solutions only concern one target—the building envelope or the indoor space, and, in addition, are technologies meant to strictly solve an issue, not devised to undertake a complex process.

Based on the alluvial diagram depicted in Figure 8, digitalisation currently concerns only 10 solutions (three methodologies and seven technologies). Several remarks can descend from the diagram analysis:

- Although most of the solutions making use of digital processes or devices are technologies, the percentages are in line with the overall ones. Hence, both technologies and methodologies appear suited to contribute to addressing the digital challenge, fostering at the same time sustainable innovation in the built environment.
- The adoption of digitalisation seems to be evenly distributed along the diagram, implying that the effectiveness ranking (determined based on the actions and the targets) does not affect the potential to use digital processes.
- All the three challenges are addressed by technologies or methodologies that also concern the digital challenge, with no preference emerging. Digitalisation hence proves to be a cross-cutting enabler in supporting objectives linked to energy transition, environmental challenges and adaptation to climate change.

A critical observation deriving from the results is the one concerning their close dependence on the qualitative methods adopted. Data collection and interpretation are strictly determined by the elements (objectives and actions) considered to draw the correlations between the four challenges, on the one hand, and the innovative technologies and operative methodologies, on the other hand. In fact, the objectives and actions identified in this investigation are not univocal nor complete. Concerning the objectives, they derive from the specific examined policies, which were chosen according to the goals of the whole research project—ultimately, supporting the transformation of the built environment and building sectors in the Italian North-East territory, increasing its sustainability and resilience. Although this can be considered a discretionary factor, it represents a big strength of the developed methodology: its replicability as a multidisciplinary approach conscious of the geographical field of application. Regarding the actions, their choice strictly depends on the researchers' know-how, and they do not have to be considered as a complete and defined list, but rather a collection to be integrated.

The choice to rely on the researchers' disciplinary know-how and experience entailed that the identified solutions pertained to their own fields of interest and, casting a critical eye, it can be argued that they lack a more comprehensive perspective or innovative aspects. Apart from the already highlighted benefits deriving from a multidisciplinary approach, this choice supported three other positive outcomes, hereby illustrated:

- The emerging solutions are cross-cutting not only in terms of fields of study, but also in scale of application (from a specific building aspect to the urban area) and of potential building stock targets (from restoration to new construction).
- As the involved researchers feature a consolidated knowledge on the Italian North-East territory, their investigation was in line with the constructions and urban areas' features, criticalities, and needs. In this sense, the suggestion of the technologies and methodologies considered their potential ease of implementation, avoiding a focus on specific solutions discussed in up-to-date literature that, although innovative or effective, might not be appropriate for the targeted built environment.

- The identification step also benefited from the interactions with the stakeholders the researchers have been implementing in time, allowing the suggested solutions to be in line with the existing local supply chain. Starting from this, the investigation outputs could guide the North-East production sectors and SMEs towards innovating their current technologies and products. On the contrary, adopting a perspective more detached from the territory would not have considered this site-specific aspect, leading to solutions alien to the current local supply chain.

5. Conclusions

The research described in this contribution was carried out in the framework of the "Interconnected Nord-Est Innovation Ecosystem" (iNEST) project funded by NextGenEU through the Italian National Recovery and Resilience Facility (NRRF). The general aim of iNEST is to outline a strategic plan for the development of the construction and sustainable design sectors in the North-East of Italy. The goal of the investigation described, carried out by a multidisciplinary research team coordinated by the authors, is to propose innovative technologies and operating methodologies (T/M) capable of fostering the sustainable evolution of the built environment and the construction sector. Such solutions should specifically act within four key thematic areas recognised as strategic by the research programme: Energy transition (ET); Environmental challenges (EC); Adaptation to climate change (CCA); and Digitalisation (D).

The paper describes in depth how a conceptual research framework was specifically devised to reach the goal of the task, an instrument replicable both as a methodology and, if applied in similar territorial contexts, for the results achieved. After illustrating the methodology development and features, the contribution describes the results obtained by its application:

- A definition of the four challenges (ET, EC, CCA, D) in light of the built environment and construction sector.
- A conceptual research framework devised to connect the innovative technologies and methodologies and the challenges, a link identified through the actions the T/M implement, and the objectives the actions contribute to reaching.
- A preliminary list of innovative technologies and operative methodologies supporting the sustainable innovation in the Italian North-East built environment and building sector.
- A ranking of the most promising solutions according to their degree of contribution in addressing the challenges, also considering their potential application to one or more targets pertaining to the built environment (indoor space, urban space, envelope, structure) and their current contribution to digitalisation.

In addition, from the results analysis, several observations emerge:

- Within the studied context, the potential to undertake the four challenges mainly lies in the original application of an existing technology or methodology, rather than in an ad hoc developed solution.
- The technologies and methodologies most effective in delivering sustainability and resilience are the ones operating in the built environment by preserving the built resources.
- Digitalisation proves to be an even cross-cutting enabler, rather than a challenge per se.

Nevertheless, several improvements could be made in the research next steps:

- The qualitative nature of the methods entails some discretionary factors.
- The list of technologies and methodologies identified is not to be considered an exhaustive catalogue of solutions, but rather a work in progress to be implemented and enriched by an ongoing process to be supported by the research community.
- Although the local existing productive fabric was taken into account in identifying the solutions, costs were not examined: further investigation could be carried out to improve the effectiveness of the results.

The contribution illustrates an investigation representing the first phase of an ongoing research that, although subject to improvements, devises and makes use of an original methodology. Its replicability lies both in its being an instrument useful for other multidisciplinary research and in its potential application to similar contexts, as a means to deliver the sustainable innovation of the built environment and construction sector by supporting research and production decision making.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13122920/s1, Table S1: Conceptual research framework summarising the results of the methodology application to the Italian North-East context; Figure S1: Alluvial diagram depicting the relationship between targets, solutions, actions, objectives, and challenges, ranking them according to the number of actions supported and targets addressed (HQ); Table S2: Dataset used for generating the alluvial diagram depicted in Figure S1; Figure S2: Alluvial diagram depicting the relationship between the identified technologies and methodologies and the cross-cutting digital challenge (HQ); Table S3: Dataset used for generating the alluvial diagram depicted in Figure S2.

Author Contributions: Conceptualization, M.C. and E.Z.; methodology, M.C. and E.Z.; software, R.R. and M.C.; validation, E.Z., M.C. and R.R.; formal analysis, E.Z., M.C., R.R. and V.T.; investigation, E.Z., M.C. and R.R.; writing—original draft preparation, E.Z.; writing—review and editing, E.Z., M.C., R.R. and V.T.; visualization, R.R.; supervision, M.C.; project administration, M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research and the APC were funded by RFF NextGenEU, grant number ECS00000043—CUP F43C22000200006, through the Italian Piano Nazionale di Ripresa e Resilienza (PNRR), Mission 4 «Education and Research», Component 2, Investment 1.5, Interconnected Nord-Est Innovation (iNEST) Ecosystem, Spoke 4 (research coordinator: L. Fabian).

Data Availability Statement: The data presented in this study are available in the Supplementary Materials.

Acknowledgments: The authors thank the professors and researchers of Università degli Studi di Udine and Università degli Studi di Trieste involved in the research team of iNEST RT1.3.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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