Green Energy and Technology

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Climatic and Structural Safety in Multi-Hazard Regime of Cultural and Natural Heritage

Methodological Advances and Case Study Applications

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Indexed in Ei Compendex.

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ISSN 1865-3529 ISSN 1865-3537 (electronic)
Green Energy and Technology
ISBN 978-3-032-11925-4 ISBN 978-3-032-11926-1 (eBook)
https://doi.org/10.1007/978-3-032-11926-1

This work was supported by Università degli Studi Mediterranea di Reggio Calabria.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The protection of a Country's cultural heritage, both architectural and environmental, is a highly relevant political and scientific concern, given its profound implications for the social and cultural fabric of societies.

Safety assessment requires a comprehensive understanding of the various sources of risk (climatic, geomorphological, structural, etc.), demanding interdisciplinary approach to the problem. The topics involved are of considerable interest for the scientific community and constitute a knowledge base for any planning strategy, both for preventive actions (maintenance, building and site safety) and reactive interventions (emergency management, evacuation plans).

This book addresses the issue of climatic and structural safety in multi-hazard regime of cultural and natural heritage, drawing on the outcomes of a three-year technology transfer project, funded by the Italian National Recovery and Resilience Plan -PNRR T4Y PP 4.7.1. In particular, the project is entitled Open Platform *phigital space* (physical and digital) of the type *user-profiling* for the advanced and dynamic codesign of interventions on the built and ex novo.

The book is organized into two main parts collecting peer-reviewed papers from approximately twenty involved researchers and begins with a chapter detailing the methodologies adopted and the final goals of the project.

The first part of the book aims to deepen theoretical knowledge related to cultural heritage analysis, proposing advanced models for damage assessment on structures and their surrounding environments. These models also incorporate uncertainties related to material properties and consider different environmental stressors under three projected climate scenarios for the years 2030, 2050, and 2085.

The second part of the book features some chapters with a more applied focus. Thanks to some large-scale case studies, it proposes a digital platform to support all the meta-files relating to the security data collected. This platform, along with the creation of a Living Lab (physical platform), will provide a methodology for the transfer of digitalized data to different stakeholders: including institutions, professionals, and local communities.

The Editors sincerely thank all the senior and the young researches who have contributed by their outstanding contributions to the quality of this book.

October 2025

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Acknowledgements

This volume is the result of the synergistic activities related to the following National Recovery and Resilience Plan (Mission 4, Component 2 Investment 1.4) Research Project, funded by NextGenerationEU: Tech4You “Technologies for climate change adaptation and quality of life improvement” – “Pilot Project 4.7.1-Open platform ‘phygital space’ (physical and digital) of the type user profiling for the advanced and dynamic codesign of interventions on the built and ex novo” (Spoke 4 - Technologies for resilient and accessible cultural and natural heritage - Goal 4.7- Protection and enhancement of natural and cultural heritage and identity of the inner territories) - CUP C33C22000290006 (ECS_00000009).

The authors sincerely thank the project that funded their research activities and the open access publication of this volume.

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Theoretical and Methodological Approaches

Regenerative Digital Design and Innovative Processes to Define Predictive Models: Workflow on Climate Scenarios

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Abstract. The *phigital* approach – *physical and digital* – to regenerative design represents the best synthesis between theory and practice in the contemporary era, in cutting-edge research particularly focused on the study of climate vulnerability, for the adaptive and transformative design of the built environment. Predictive and declarative design demonstrates its particular effectiveness through the optimisation of scale, the use of parametric and simulation tools, and digital regenerative design. This paper addresses, from a theoretical and methodological perspective, the themes and insights that have guided the PNRR T4Y applied research activities for Pilot 4.7.1 with actions 8, 9. The text is to be considered an advancement of the author's scientific treatise on emerging technologies for regenerative design (2022–2023), with subsequent elaborations of competitive research trajectories (2023–2025). In the application phase, it proposes a particular examination of concepts related to information processes with "workflow" and the use of "predictive parameter tools", in order to provide useful information for technological and environmental innovation actions, in application of regenerative design and in scenarios of declared climate vulnerability. This methodology was applied in the experimental phase of the research for the case studies of Palizzi (*natural heritage*, coastal area) and Bova (*cultural heritage*, urban and building area). In the Design and Prototyping sections of the ABITAlab university laboratory, part of the Department of Architecture and Design at the Mediterranean University of Reggio Calabria, studies and experiments were conducted, producing both digital and physical prototypes (3D printing), described in a high-information Digital Atlas as a decision support system (Lucanto, Hanida, 2025). They where produced images, navigable models, interoperable data and multi-level information for an *open knowledge user profiling platform* capable of translating structural and environmental impacts on natural and historical heritage, developing solutions for the safety of territories and communities, with projections to 2030, 2050 in urban areas and up to 2085, 2100 in coastal areas.

Keywords: Regenerative Digital Design · Advanced Sustainable Design · Innovative Process · Emerging Technologies · Parametric Tools · Workflow · Climate Scenarios

C. Nava et al. (Eds.): *Climatic and Structural Safety in Multi-Hazard Regime of Cultural and Natural Heritage*, GREEN, pp. 150–173, 2026.
https://doi.org/10.1007/978-3-032-11926-1_10

1 Introduction

The quality that can be achieved through the design and construction of the built environment, in accordance with sustainable strategies, must aim to exceed the benefits and requirements of the project in all its components. The performance attributes with which any technological system enables effective processes of operation and response to expressed needs must find scenarios of 'added quality' in which to express their capabilities, at multiple levels and in multiple relationships. Product technologies are required to have their own qualities depending on their physical and material characteristics, durability, efficiency, configuration, operation, etc. process technologies must be referred to in order to interrogate systems on their capacity for innovation and integration, operability and management, competitiveness and improvement (incremental or radical), adaptation to the evolution of socio-cultural models and their aptitude for creating new meanings within advanced design processes. High performance is also assessed in terms of both short-term and long-term response times. For this reason, its function is to act as a yardstick for interventions, both in transition scenarios and in resilience scenarios (Nava 2019). This landscape-infrastructural strategy shifts previous concepts of hyper-sustainability towards a new challenge, innovating on the concept of 'strong sustainability' (a preventive, pre-visionary and predictive vision of radical sustainability) (Nava 2022). The relationship between innovation capable of addressing design and the discussion around sustainability issues is changing in its operational tools, and "advanced design becomes regenerative", as illustrated below (Fig. 1).

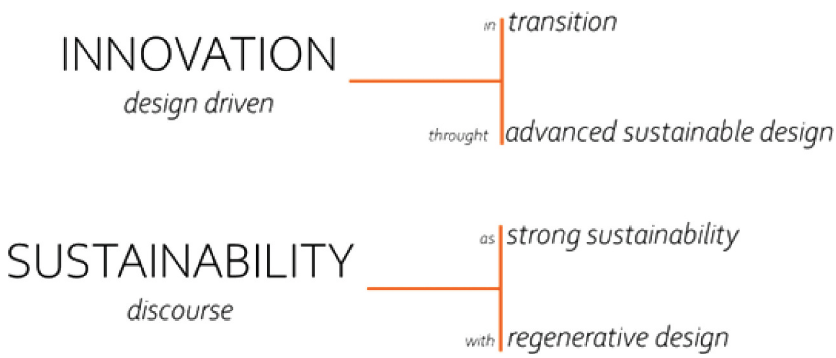

Fig. 1. Relationships between innovation and sustainability in strong sustainability scenarios for regenerative design (C. Nava, 2022)

1.1 Theoretical Background

1.1.1 Transformative Innovation and Climate Risks

This strategy requires a change of approach, looking to the future (future-back) and increasing the opportunities not only for experimentation but also for all options on multiple competing solutions. This involves moving in the opposite direction to incremental innovation, entrusting the future vision with the ability to redefine ecosystems (of innovation action) in order to promote, through a disruptive approach, the launch of initiatives with a strong digital content, with a view to achieving results with an efficient operational method (Fig. 2).

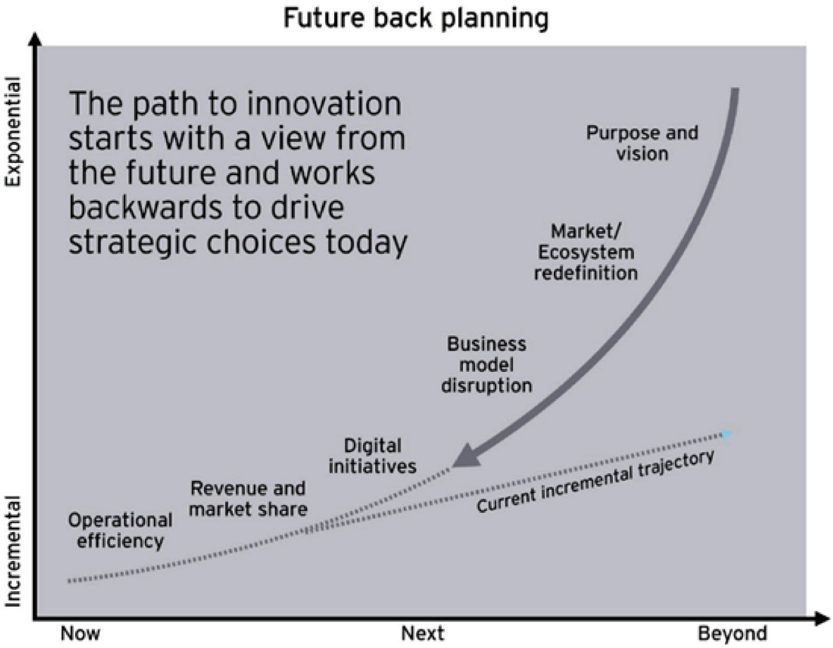

Fig. 2. A vision of future-oriented innovation drives transformation (source: https://www.ey.com/en_uk/consulting/)

The model illustrated, which is recommended for those in the business market who intend to focus on disruptive innovation in order to produce competitive levels of quality in the era of ecological and digital transition, requires an interface in the field of sustainability of built environment transformations, with the ability to pursue 'high performance' objectives. In the context of climate change scenarios, requires the production of levels of quality "beyond performance" in order to aim for a "performance level"; this means working towards scenarios of climate adaptation and/or mitigation and demanding that regenerative design be capable of providing actionable pathways in response to the impact of emerging phenomena. (Fig. 3) This approach is based, also according to the latest IPCC reports (from 2013 to 2022), on the concepts of impact and vulnerability and therefore risk, referring to the "global warming level" (GWL), described as "the increase in the global average air temperature near the surface compared to the pre-industrial period (specifically the period prior to 1750, often approximated by conditions in the period 1850–1900)" (Lionello, Naumann 2022).

The diagram in Fig. 3 is in fact the response generated by the risk categories, which, for example, the IPCC identifies as key risks for Europe, which are susceptible to their level of impact with reference to the increase in global warming (given that the 1.5°

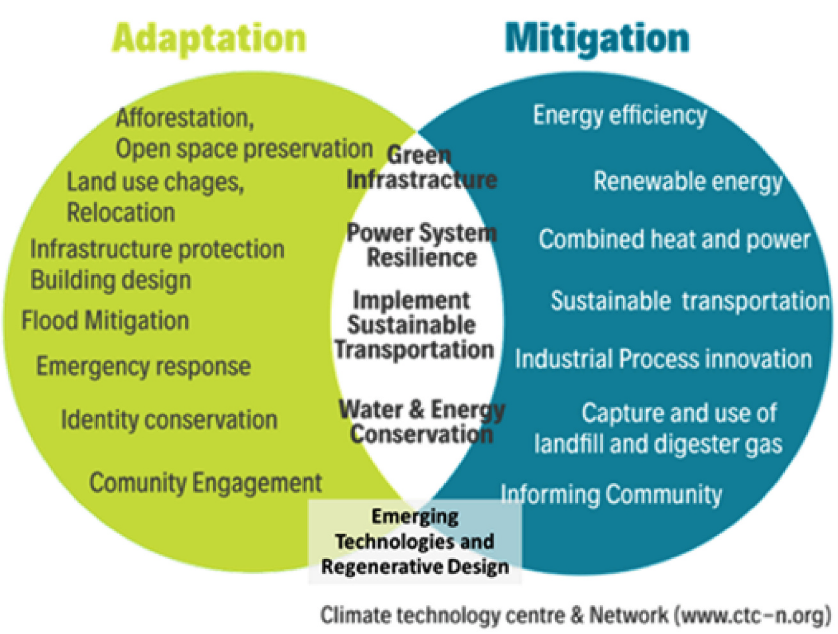

Fig. 3. Schemes on adaptation and mitigation and their areas of application for experimentation (source: www.ctc-n.org)

target of COP 25 has been largely compromised). Even with a 2°C rise in temperature, the risks listed below become more serious and partly irreversible.

The four risk categories to refer to are (Lionello 2022):

– *Risks of heat waves on populations and ecosystems.* The number of deaths and people at risk of heat stress is expected to double or triple for a temperature increase of 3 °C, compared to 1.5 °C. Warming will reduce habitats suitable for current terrestrial and marine ecosystems and irreversibly change their composition, with h us effects increasing in severity above the 2 °C global warming level. Measures to adapt the population to heat stress and mitigate the risks of heat waves require multiple interventions in buildings and urban spaces. These measures must be anticipated in southern Europe, where the risk is greater than in more northern areas.
– *Risks to agricultural production.* Due to a combination of heat and drought, substantial losses in agricultural production are expected in most European areas in the 21st century, which will not be offset by the expected gains in northern Europe.
– *Risks of water scarcity.* In southern Europe, the risk is already high with global warming of 1.5 °C and becomes very high with a 3 °C increase. In these regions, demand for water resources already exceeds supply. This gap is widening due to climate change and socio-economic developments. With a temperature rise of 3 °C, the risk of water scarcity also becomes high in central and western Europe. Even with average warming, adaptation strategies that reduce water demand must be combined with transformations such as diversification of sources and changes in land use. In

the event of high warming, a broad portfolio of measures is required, but this may not be sufficient to prevent water shortages in southern Europe.

– *Risks posed by more frequent and intense flooding*. Due to changes in precipitation and rising sea levels, the risks

The Mediterranean sea, for example, will become a real hotspot for global warming. What caused sea levels to rise by about 1.4 mm per year throughout the 20th century is set to increase and reach about 1 m by 2100. with a 20% increase in sea warming, the ability to absorb carbon dioxide from the atmosphere is already being lost.

It is also essential to understand how the IPCC, in addition to analysing the impacts of climate change, both globally and regionally, on ecosystems, societies, infrastructure, productive sectors, cultures, cities and settlements, and assesses current and future adaptation options, deciphering their risks and limitations, it calls for the promotion of successful practices through the promotion of the SDGs (Sustainable Development Goals) of the UN's 2030 Agenda, in their territorialisation processes at national and local level. The novelty of the latest IPCC report, the sixth, lies not only in its ability to use RCPs (Representative Concentration Pathways), each of which represents a possible pathway characterised by the value of the change in the energy balance in 2100: RCP2.6, RCP4.5, RCP6.0, RCP8.5, also with reference to GWL, but also in its ability to embark on the shared path of the SSP (Shared Socio-Economic Pathways), integrating the RPCs relating to adaptation and mitigation with socio-economic aspects.

"SSPs are based on five narratives describing socio-economic futures characterised by sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil fuel-based development (SSP5) and a narrative that lies between those described (SSP2). The combination of SSP-based socio-economic scenarios and RCP-based climate projections provides an integrated framework for climate impact and policy analysis." (CMCC Foundation, IPCC Focal Point for Italy, 2022).

We are looking for an answer in these times of polycrisis, as defined in all its risks in the latest WEF2023 report, those crises (social, environmental, technological, economic, geopolitical) that see design as a translator of the most complex processes useful for the present and future of ecosystems. A "cognitive and scientific challenge", as referred to in M. Losasso's introduction to issue 23 of Techne Journal, entirely dedicated to 'the possible necessary within the polycrisis' and the need to "play a more effective and proactive social and technological role", as mentioned by E. Mussinelli in the editorial of the same issue. This is an issue that remains the responsibility of all citizens, but which certainly calls for planning action imbued with the scientific research of transfer that is characteristic of the effectiveness and application of technologies, as expressed thus far.

1.1.2 The Innovation of Regenerative Design: From Physical Processes to Digital Processes

Further discussion of the role assumed by the project, between emergency and contemporaneity, might seem anachronistic and, at the very least, ill-suited to the speed with which the technologies themselves, their devices, operational capabilities and methodological approaches can apparently take on a decisive and sufficient character. Indeed, immersion in digital capabilities and the absorption of the human element into the products that make them 'devices' seems to exclude the creative processes of design when they are not directed towards the manufacture of those devices. Design can encounter any device, as its unique ability to configure itself in the dimension of the territory, the city, buildings and even public spaces, if the research that produces it intends to consider, in a sort of operational identification process, the project itself as a true enabling and emerging technology.

The complexity of the project means that it takes on the characteristics of physical processes as well as digital ones. Relational organisations, algorithmic writing, data and information exchange, system and resource hierarchies, information and self-learning capabilities, specialisation and coordination of the governing principles of each phase, platforms for client, production and user structures.

Design thus takes on an organisational character, whose field of action becomes the multiple operational fields of action on the objectives and challenges to be pursued. S. Mecca, in his latest text "Il progetto come azione tra ordine e disordine. Alla ricerca dell'Armonia" (2023), outlines a path of "rational organisation" of this complexity, referring to Thompson's classification of three types of technology (concatenation, mediation and intensive) with reference to procedural and methodological issues. He defines intensive technology as "characterised by a varied set of techniques capable of supporting the process of transformation of a specific object, when the choice, combination and ordering of operations can only be determined through feedback interaction with the object itself. Intensive technology has therapeutic characteristics when the object is of a living nature, or design characteristics when the objects are not living, as in construction and research (…). Intensive technology is therefore the technology of non-repetitive processes, whose success depends 'on the availability of all potentially necessary capabilities and, to the same extent, on an adequate combination of capabilities selected according to the needs of the specific case or project".

This is the position taken in this treatise on the operability of technologies in the 'options' of applied experimentation and on the ability of frontier research to take feedback and calibrate itself to each response in an agile manner. The sustainable environmental project has, in fact, always had within its very nature the ability to understand the need for the evolution of its argumentative and procedural structure, bringing with it the instrumental and linguistic necessity of the advancement of architectural technology as an approach and attitude towards contemporaneity (in accordance with the role that technological culture has always played).

However, the temporal and spatial context of sustainability has been defined by complex indicators based on the concept of objectives/visions, design operations and scientific research progress. The evolution of design, classified according to its states of innovation, was traced in 2016 by Fabrizio Ceschin and Idil Gaziulusoy in their article entitled 'Evolution of design for sustainability: From product design to design for system innovations and transitions'. The two scholars propose an evolutionary framework for Design for Sustainability (DfS) and, following an almost chronological outline, provide an overview of the field of DfS, classifying the design approaches developed in recent decades under four levels of innovation: Product, Product-Service System, Spatial-Social System and Socio-Technical System.

The proposed framework summarises the evolution of the field of DfS, showing how it has gradually expanded from a technical and product-centric focus towards large-scale system-level changes in which sustainability is understood as a highly complex socio-technical challenge. The four approaches are classified according to their levels of innovation:

- *Product innovation level*: design approaches that focus on improving existing products or developing completely new products.
- Level of innovation of the product-service system: in this case, the focus goes beyond individual products to integrated combinations of products and services (e.g., the development of new business models).
- *Level of spatial-social* innovation: here, the context of innovation concerns human settlements and the spatial-social conditions of their communities. This aspect can be addressed on different scales, from neighbourhoods to cities.
- *Level of innovation of the socio-technical system*: in this case, design approaches focus on promoting radical changes in the way society's needs are met, such as food and transport/mobility, and therefore on supporting transitions to new socio-technical systems.

Each level of innovation corresponds to a different type of design, which represents the evolution of its definition over time, also with reference to the application areas of research and experimental design.

In terms of product innovation, design takes on the definition of eco-friendly design in terms of environmental impact, emotionally durable design, design for sustainable behaviour, cradle-to-cradle (CTC) design, natural design, and design for improving people's lives. At the level of product-service system innovation, design takes on the definition of service-product system design for efficiency; at the level of social space innovation, design takes on the definition of design for social innovation, systemic design; at the level of socio-technical system innovation, design takes on the definition of design for innovation and system transitions.

The evolutionary framework examines different types of design for sustainability in the space of innovation in relationships and visions (insular and systemic) and, by connecting technologies to communities and the social dimension, embraces the socio-technical challenge (Fig. 4).

The mapping shows that connected design for innovative systems and transitions belongs to the socio-technical evolution framework and can be linked to practices already experienced over the last twenty years. What emerges in this period is that some types of design have undergone evolution, partly influenced by socio-technical design. There is no doubt that some forms of product design connected to nature have given rise to different experiments in the fields of eco-design or green design, biomimetic design, recycling, etc. Product-service, long theorised mainly in academia, has found its applications with the advent of emerging technologies and their transfer to industrial sectors.

In any case, Ceschin and Gaziulusoy's mapping appears interesting, beyond the objectives set by the researchers, precisely because it deciphers those characteristics of 'organisation' and 'processuality' that we have entrusted to the project.

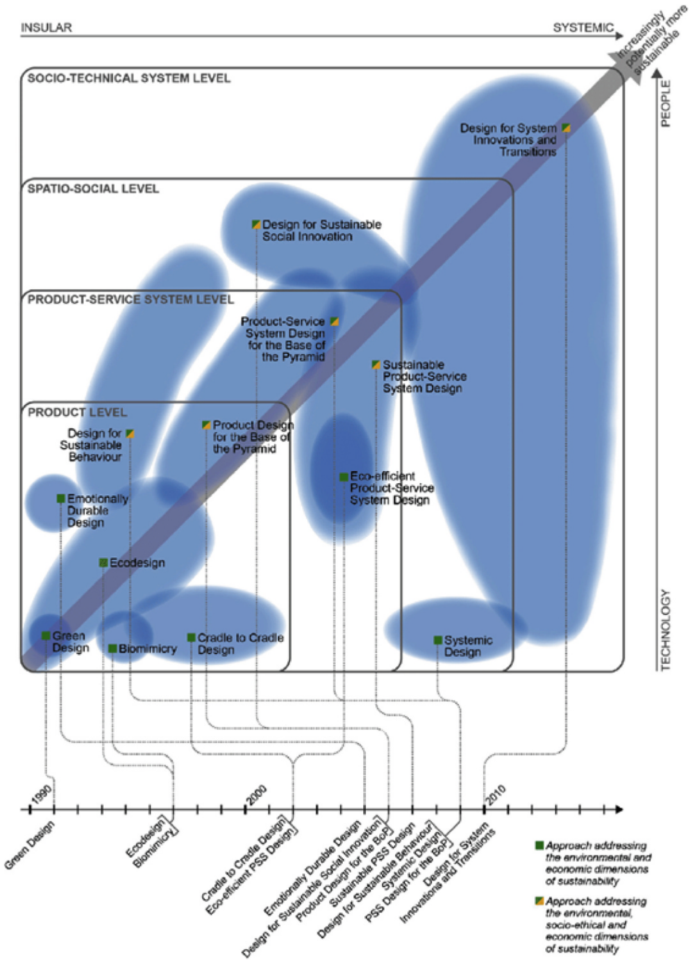

Fig. 4. The evolutionary framework of DfS with existing DfS approaches mapped onto it. The timeline shows the year in which the first key publication of each DfS approach was published (Ceschin, Gaziulusoy 2016)

Regenerative design makes the ecological and social approach 'the distinctive feature' of its transformative and transitional capacity, with a tendency to place the effectiveness of ecosystem services as the theoretical and codification space for a new metric.

Yet it seems that the real challenge towards transition is that of defining new theoretical and applicative frameworks, which are also of interest to technologies as they are understood, working on a regenerative approach based on a socio-ecological (rather than eco-social) approach.

Richard Graves, Bonnie Keeler, Maike Hamann, Elizabeth Kutscke1 and Chris Nootenboom published a scientific paper entitled "A Social-Ecological Approach to Architecture and Planning" in the Journal of Architecture and Construction in 2019, discussing this transition in definitional terms and setting out some necessary conditions for its theorisation.

"First, focus on the future potential of systems within the complexity of the changes occurring in the Anthropocene and abandon romantic notions of nature separate from humans that predate development. Second, start by focusing on the social needs of a healthy and prosperous community, and then consider the ecological limits and technological challenges of design. Third, use a measure of ecosystem services to evaluate design that increases the benefits provided by local ecosystems, in pursuit of more livable, sustainable, and equitable communities".

In fact, the proposal is to transform the design process, going beyond the first-generation regenerative approach (that of the last twenty years), which only considers circular 'single-flow' systems (Lyle 1994) (Fig. 5).

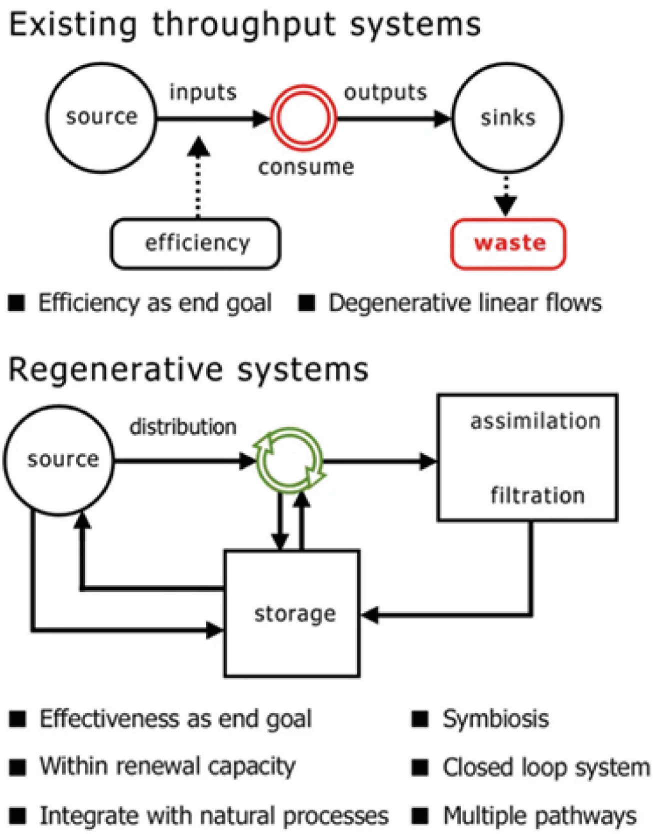

Fig. 5. Adapted from John Tilman Lyle: Regenerative Design for Sustainable Development, 1994

The idea is to go further on the issues of "technological sustainability", which is more directly related to human health. For this latter definition, with a vision that starts from the acceptance of the human and ecological role in the Anthropocene era, the objectives are to integrate social, ecological and technological systems to ensure human well-being, formulating strategies capable of co-evolving towards equity, commitment and capacity building; considering a measurement metric whose indicators are extracted from ecosystem and human services for well-being; with an integral and iterative approach to recognise the complexity of social, ecological and technological systems and their relationships and to promote thinking of complex adaptive systems, with the affirmation of a socio-ecological process [1] (Fig. 6).

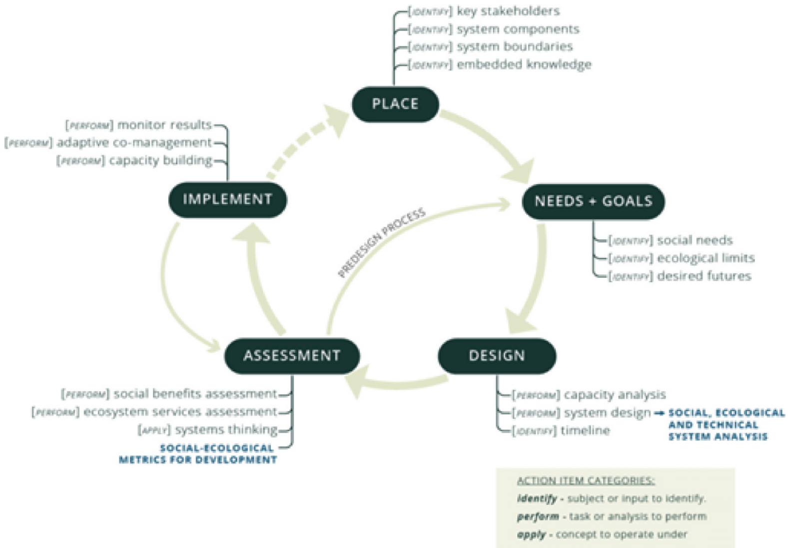

Fig. 6. Socio-ecological process diagram

2 Methodology: Digital Performative Processes

The theoretical path followed so far refers to the scientific positioning assumptions and literature overview that are most consistent with justifying the attempt to construct a method that reconnects the role of enabling and emerging technologies, recognising them in their actions with some differences in the approach to process organisation.

The proposed diagram (Fig. 7) summarises its meaning by identifying a counter-clockwise operational flow for enabling technologies and a clockwise flow for emerging technologies, in defining spaces for innovation in which regenerative and socio-ecological design operates, as previously investigated.

[1] This process has become a benchmark in 15 project experiences for frontier research and communities in transition, in the experiences conducted with ABITALab (dArTe – Mediterranean University of Reggio Calabria) and published in G. Mangano, A. Leuzzo, Co-design and Enabling Technologies, in 2022 by Aracne. With a reinterpretation of the process in seven experiences conducted in inland areas of Calabria and eight experiences conducted in urban areas.

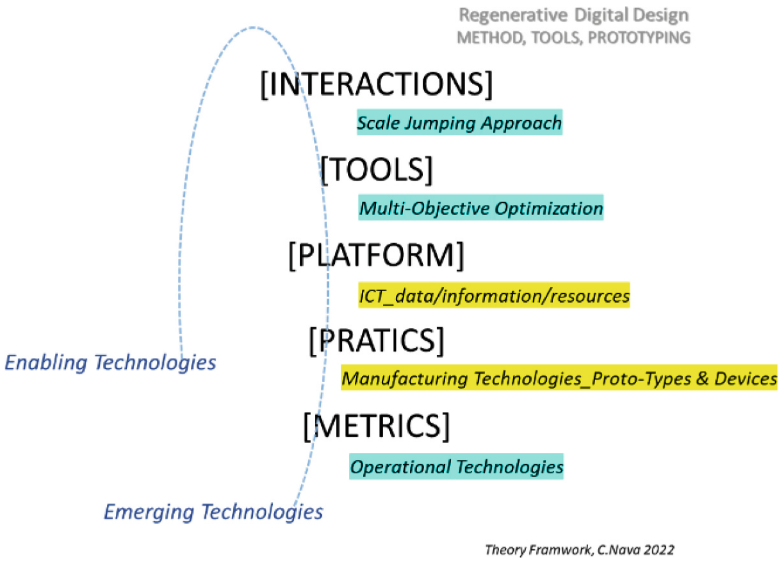

Fig. 7. New operational framework for socio-ecological regenerative design (C. Nava, 2022)

2.1 Scale Jumping and Multi-objective Optimisation

In terms of frontier research, the space for interaction is achieved through the inter-scale approach (Scale Jumping), with the use of tools based on multi-objective optimisation, capable of exchanging data, information and resources on shared and open platforms. Prototypes and devices measure the practices transferred from design experimentation and, by exploiting the operational role of technologies, re-establish a new metric for the organisational action of the regenerative project.

The interscale approach and multi-objective optimisation become the yardstick for the success of practices, supported by digital performance processes.

The extent of interventions in particularly sensitive contexts, such as those relating to natural ecosystems or ecosystems that are fragile due to physical and environmental stress and now also climate change, can always be measured through an inter-scalar process, which must control actions, transformations and impacts, evaluating multiple reference measures. The project and programme that seek to pursue these methods are always ‘multidimensional’. Any transformation of the built environment or an ecosystem with a high natural value produces direct and indirect impacts, which can also be measured at different times. The instruction of design processes, through enabling technologies and dedicated devices, has never a hierarchical operational process, but takes information and data and produces them as a design support system, with the logic of an open platform capable of triggering reversible and assessable activities in progress. The size of the object of the intervention, the resources involved and the reference context already belong to three very different configuration scenarios and therefore, being included in any transformation action (including infrastructural), need to enter the processes as receptive or productive systems, with relationships and operations that take into account their specific characteristics and behaviour throughout their life cycle. Multi-scale design control allows for the activation of controlled response conditions towards high performance results already in the design or model/prototype definition phase. It can therefore be said that, according to hyper-sustainability strategies, there may be conditions of scalability of the problems that the project has to face, but these must be matched by an interscalar and integrated response in terms of project definition and performance quality (Nava 2019).

In digital processes, this characteristic becomes even more influential on project operations, as the simultaneous control of multiple factors and the ability to interpolate certain data require reference spaces that can be assumed by systems located in different detailed configurations. The scale of the city, the building and the device is often questioned by data flows that cross all dimensions of the systems, without distinguishing their boundaries, but only working on response indicators for different categories of impact (mesoscale, macroscale, microscale). A new space-time dimension, immaterial and often virtual, transcends the physical and consequently changes the predetermined boundaries and scope of action, in which often even the proactive role of users defines the variability of contextual conditions.

The pressing need to cope with a disruptive demand such as that requiring the expert contribution of digital skills for the management of such radically changed design processes certainly shifts the discussion of innovation and knowledge to the training and educational levels of learning about digital tools and their use. The performative characteristics of these tools certainly cannot replace the grammar of the approaches and methods we have discussed so far, but in characterising the indicators of their new structure, they provide data and information whose structure has changed significantly compared to 20th-century theory. The relationship between design and construction, between configurative research and expressions of the influence of contextual factors on the project, is changing. In terms of sustainable and regenerative design, this condition is even more sought after in the current forecasting, simulation and predictive scenarios to which we have referred the action of strong sustainability in a regime of ecological and digital transition.

Training in this new instrumental skill can once again come from academia and scientific and transfer research, where imagination and creativity can be pushed to the point of realising what has been imagined, thanks to the skills acquired in advanced laboratories, where research, computation and new technologies are measured against material and construction production, for highly advanced solutions (Paris, 2017) (Kozak, Nava 2024).

2.1.1 From Workflow to Predictive Simulations

Digital operational tools are able to report on these paths, from fundamental concepts to their application. The application of multi-objective optimisation algorithms and methods to achieve the desired levels of efficiency and sustainability is of significant importance. The presence of complex scientific issues leads to the use of optimisation methods to solve the problem at hand, even though some of them require solutions with accurate calculations and adequate time frames. Since classic methodologies cannot be used, artificial computational methods must be employed, which often take examples for their algorithmic writing from the structures of certain natural phenomena (e.g., meta-heuristic algorithms referring to intelligent behaviours in nature) (Sadollah, Nasir and Woo Geem Z 2020). For example, in the energy sector, for efficiency and positive building performance, optimisation processes and systems are becoming fundamental for constructing reference scenarios for consumption rather than production, performance and simulation on projective simulation models and the transition to climate and carbon neutrality (2035, 2050, 2085).

Therefore, digital tools that support regenerative design are themselves based on optimisation methods to provide solutions and interpretative models of the data and configurations sought. For this reason, regenerative design is always "integrated" and digital tools can operate from a single problem to multiple scenarios through the use of parametric processes, which are programmable to address customisation and multi-domain issues.

Parametric design for regeneration becomes the most appropriate set of tools for the use of technical optimisation processes in the energy-environmental field, based on models that can be applied to different scales of architectural systems, but also to natural ecosystems, biology, botany, botanical sciences, climatology, comfort and physiology (Naboni 2019).

In terms of solutions, this approach makes it possible to formulate models and solutions based on co-benefits at different scales, providing integrated digital environments in which tools that model climate, energy, nature, the built environment and human behaviour maximise the strategies and benefits of scaling up through the systemic coupling of physical simulation domains that work on data and information flows.

The construction of demand in the "scripted" transfer of the information workflow effectively realises the operational character that we have entrusted to design tools, whereby the coupling of multiple domains in the scale jump and the process of trial and error effectively simulate the creative processes of design in a manner similar to its natural logical-cognitive expression.

In a holistic approach, high-performance solutions are maximised, and therefore positive, and data, information and resources are returned, which once again become the reference structure for identifying "sustainable technologies".

The construction of the 'workflow' becomes a crucial phase for pre-design activities, in identifying the organisation of the process, such as the ability of operational tools to identify its phases, the validation of the outputs of design activities and in "declarative" mode, and therefore the ability to express expected results in terms of defining the actions to be taken in the design and assessment phase (Fig. 8).

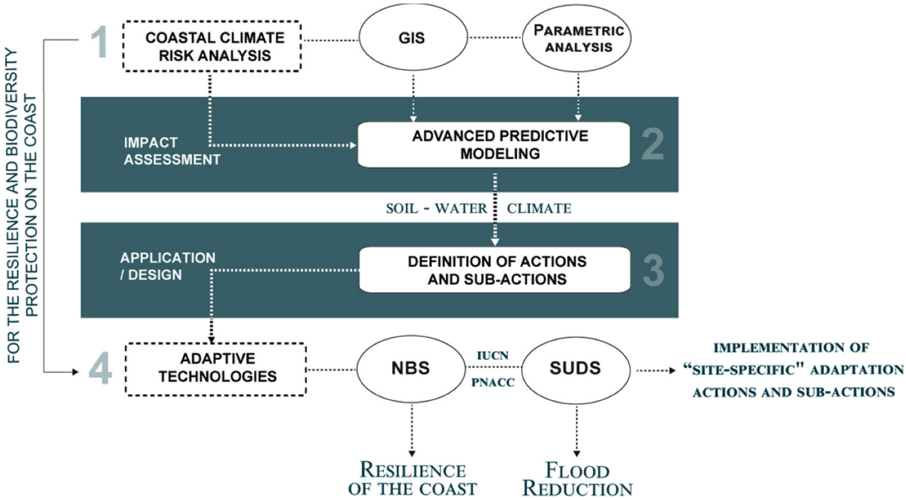

Fig. 8. Adaptive technologies in flooding scenarios through NBS/SUDS. The experimentation of an innovative protocol for resilience and biodiversity protection on the coast of Reggio Calabria (Workflow – D.Laganà, ABITAlab 2024)

Climate vulnerability and resilience analysis, in their procedure for assessing the impacts of climate change, with the selection and classification of multi-risks and hazards, identify the conditions for action through adaptation solutions (Lucanto, Nava, Mangano 2024). The methodology, which can be integrated with the regenerative digital design approach, complies with the provisions of the EU Taxonomy, pursuant to Delegated Regulation (EU) 2023/2486 of 27 June 2023, which supplements Regulation (EU) 2020/852.

Below is a structure of the information, data and resources involved in conducting macro-analysis, starting with climate resilience analysis for all performance levels investigated at the urban cluster and building scale. Studies, types of analysis, simulations and mapping are carried out using digital parametric tools whose outputs can be reported (Table 1).

Table 1. Operational framework for simulations with Regenerative Design tools (E. Catalano, ABITAlab, 2025)

Macro Analysis	Studies	Types of analysis	Parametric tools	OUTPUT
1. Climate resilience analysis	Study of long-term climate change scenarios (temperature increase, variation in rainfall patterns) aimed at assessing the resilience and adaptability of urban and architectural solutions Modelling of the effects of heat waves and extreme weather events (flash floods, hailstorms) on the comfort and safety of spaces	- Urban Heat Island (UHI) analysis - Air Temperature - Humidity - Wind Field/Wind Direction - Heat Stress Index (HSI) - Universal Thermal Climate Index (UTCI) - Mean Radiant Temperature (MRT) Distribution - Cool Island Effect - Simulations of passive cooling strategies at cluster scale (Radiation+Windflow+Evaporation water/Permeable surface) - Analysis of performance development under extreme conditions -Analysis of areas vulnerable to flooding from extreme events	[Rhinoceros+Grasshopper] [Ladybug tools] [ENVI-met] [Forma] [ClimateStudio] [ScalgoLive]	Data Graphs Mapping Project forecast simulations
2. Microclimatic analysis and thermal comfort	Advanced study of urban microclimatic conditions (temperature, humidity, solar radiation, ventilation), aimed at characterising the urban heat island and analysing the thermal gradients induced by impermeable surfaces, building infrastructure and green areas, in order to evaluate design solutions aimed at mitigating local overheating and improving thermo-hygrometric comfort in outdoor spaces Simulations and comparative assessments of different spatial configurations, including the study of impermeable and permeable pavements ( ), the use of materials with high solar reflectance or high thermal emissivity, the optimisation of green surfaces and modelling for the assessment of shading systems to reduce direct solar radiation.	- Predicted Mean Vote index (PMV) - Predicted Dissatisfaction Index (PPD) -Physiological Equivalent Temperature (PET) - Universal Thermal Climate Index (UTCI) -Soil temperature up to 2 metres (Soil Temperature) - Soil moisture content - Solar Reflectance Index -Shadow Analysis -Analysis of impermeable surfaces (asphalt, concrete) vs. draining or vegetated surfaces -Average radiant temperature distribution (MRT) - Cool Island Effect - Analysis of permeable and impermeable surfaces – higher UHI - Direct/diffuse/reflected solar radiation (short-wave radiation) -Long-wave radiation -Albedo analysis	[Rhinoceros+Grasshopper] [Ladybug tools] [ENVI-met] [Shape] [ClimateStudio]	Data Graphs Mapping Project forecast simulations

(*continued*)

Table 1. (*continued*)

Macro Analysis	Studies	Types of analysis	Parametric tools	OUTPUT
3. Advanced analysis of air quality, pollutant dispersion and natural/hybrid ventilation	Analysis of natural ventilation (wind speed and direction) as a key variable in the dispersion of atmospheric pollutants. We assess how the presence of buildings, vegetation or surfaces with different degrees of permeability affects air exchange and the potential formation of areas with high smog concentrations. Mapping and characterisation of air pollutant dispersion using CFD models with scalar transport, assessing the influence of the built environment configuration and ventilation conditions. This analysis aims to identify possible accumulation zones, air exchange paths and the impact on public health. Study to assess the impact of traffic on air quality, aimed at characterising and quantifying the influence of these emission sources on levels of $PM_{2.5}$, PM_{10}, NO_x, O_3 and other pollutants in urban areas, in order to guide effective mitigation strategies and safeguard public health. Comparison of scenarios with different vegetation solutions (trees and green barriers) or optimised urban layouts, aimed at quantifying the effectiveness of these interventions in reducing pollutant concentrations and improving the local microclimate. The analysis focuses in particular on the contribution of vegetation to particulate deposition and the modulation of air flows. Computational fluid dynamics (CFD) modelling allows air circulation to be optimised through the use of r passive ventilation solutions, with the aim of reducing energy consumption and increasing thermo-hygrometric comfort.	-Air quality/Pollutant dispersion -Particulate concentration (PMx PM2.5 PM10), NOx, O3, etc. - Other atmospheric parameters - Effect of vegetation on evapotranspiration - Leaf/canopy temperature - CO2 exchange flux - Wind field/wind direction	[Rhinoceros+Grasshopper] [Ladybug tools] [ENVI-met] [Shape] [ClimateStudio] [OpenFOAM]	Data Graphs Mapping Project forecast simulations

(*continued*)

Table 1. (*continued*)

Macro Analysis	Studies	Types of analysis	Parametric tools	OUTPUT
4. Energy analyses (Building and Urban Cluster)	Analysis of energy flows at building and cluster level, aimed at quantifying overall consumption (heating, cooling and lighting) and evaluating the effectiveness of different design strategies (shading, materials, natural ventilation) for optimising thermal and energy comfort. Energy simulation of buildings, aimed at comparing and evaluating different construction solutions (building envelope) and systems (high-efficiency heating/cooling systems), with the aim of optimising energy consumption and ensuring optimal thermal and hygrometric comfort conditions. Analysis of the overall energy balance through the study of the balance between heat inputs (solar radiation and internal loads) and heat loss (ly through the building envelope and ventilation), aimed at accurately quantifying actual energy requirements. In-depth analysis of passive solar strategies in order to maximise free heat gains and reduce overall energy consumption. Quantitative analysis of the influence of natural and artificial solar protection systems (trees, internal courtyards, sunshades, tree lines) on the reduction of direct solar radiation and, consequently, on the reduction of cooling requirements.	-Energy balance -Energy simulation of buildings -Effect of shading on energy demand -Passive solar analysis - Sensible/latent heat flux - Sum of incoming components (direct, diffuse, reflected, longwave solar radiation) and outgoing components (longwave, reflection) - Effect of shading on energy demand	[Rhinoceros+Grasshopper] [Ladybug tools] [ENVI-met] [CityEnergy Analyst]	Data Graphs Mapping Project forecast simulations

(*continued*)

Table 1. (*continued*)

Macro Analysis	Studies	Types of analysis	Parametric tools	OUTPUT
5. Lighting analysis and visual comfort	Assessment of daylight and artificial lighting in public spaces aimed at optimising the visual well-being of users, reducing energy consumption and improving the usability and safety of environments. The analysis focuses on the correct distribution of light sources, the integration of natural and artificial light, and the choice of materials and finishes that promote adequate light diffusion for the different functions and time of day ( ). Glare analysis and identification of possible solutions to reduce visual discomfort (screening, orientation, etc.) aimed at minimising the perception of discomfort and maintaining adequate levels of visual comfort in urban contexts. Luminance mapping (outdoor) to optimise the distribution of natural and artificial light and improve comfort and safety with simulations that highlight any underlit or overexposed areas.	- Outdoor Glare Analysis - Outdoor Luminance Mapping - Combined Daylight+Thermal analysis. Outdoor glare analysis (visual discomfort) + mapping related to outdoor thermal comfort + UTCI + UHI	[DIALux Evo] [Rhinoceros+Grasshopper] [Ladybug tools]	Data Graphs Mapping
6. Analysis of pedestrian flow and use of spaces	Study of pedestrian flows and passage densities aimed at optimising the urban layout to facilitate mobility and ensure safety standards. Areas of high traffic flow are identified, travel times are assessed and critical points are pinpointed, allowing for the evaluation of shaded walkways and rest areas that facilitate social interaction and improve the quality of urban spaces.	-Pedestrian Flow Analysis	[DepthmapX]	Data Mapping Project forecast simulations

3 Discussions – Predictive Tools for Open Knowledge

The parametric simulation tools described (Grasshopper and all application plug-ins such as Lady Bug Tools Environmental, et al.) allow strategies to be developed in the pre-design phase for biomimicry, positive energy buildings, green and blue infrastructure design, urban space design, and the management of natural resources, soil, air, water, solar radiation, etc. Even more so, by using metrics, data and information from relevant databases, they can create simulation models of projected scenarios, such as those needed to simulate configurations, operations and behaviours across multiple contextual options under climate change. This design and operational methodology is able to superimpose all studies and outputs, producing actual digital prototypes that can 'communicate' during the design phase, with specialised and organised flows of information and data (Fig. 9), to be applied in the pre-design phase, together with workflows dedicated to the operational flow process, accompanying all advanced adaptive design and supporting decision-making throughout the regeneration process, even producing new benchmark indicators extracted from the checks, using assessment tools and strategies. This methodology was implemented in the experimental phase of the research for the case studies of Palizzi (*natural heritage,* coastal area) and Bova (*cultural heritage,* urban and building area). In the Design and Prototyping sections of the ABITAlab University Laboratory, part of the Department of Architecture and Design at the Mediterranean University of Reggio Calabria, studies and experiments were conducted, creating both digital and physical prototypes (3D printing), in order to manage all simulations in climate change scenarios, controlling outputs in an interscalar manner and producing images, navigable models, interoperable data and multi-level information. This is an essential phase in the creation of an "open knowledge" user profiling platform capable of translating and disseminating the conditions and scenarios of structural and environmental-climatic impact on natural and historical heritage, with processing designed to ensure the safety of territories and communities, with projections to 2030, 2050 in urban areas and up to 2085, 2100 in coastal areas (Figs. 10, 11).

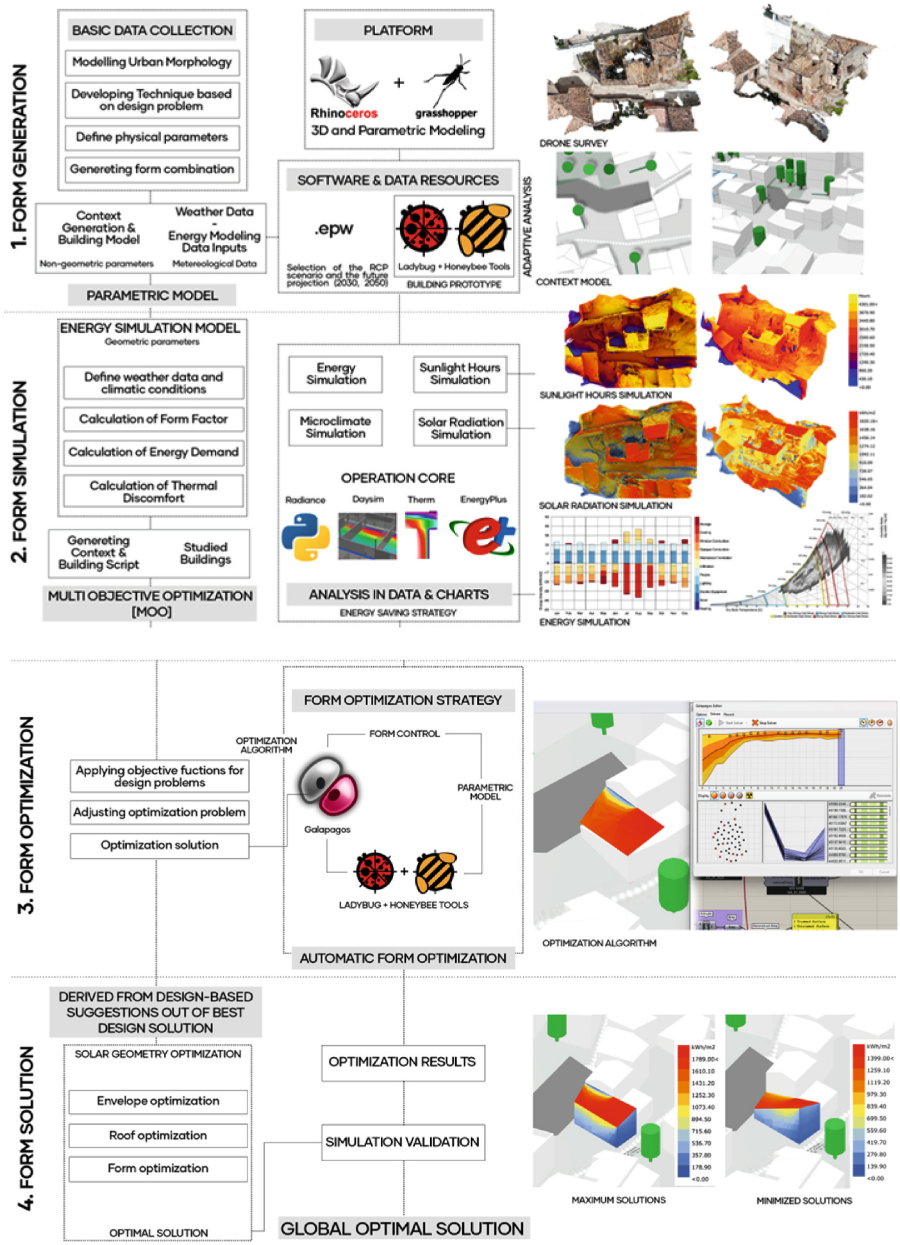

Fig. 9. Energy-environmental pre-design for decarbonisation. Application of a regenerative digital design workflow in the cultural heritage cluster of Bova (RC) (flowchart – E. Catalano, ABITALab, 2024)

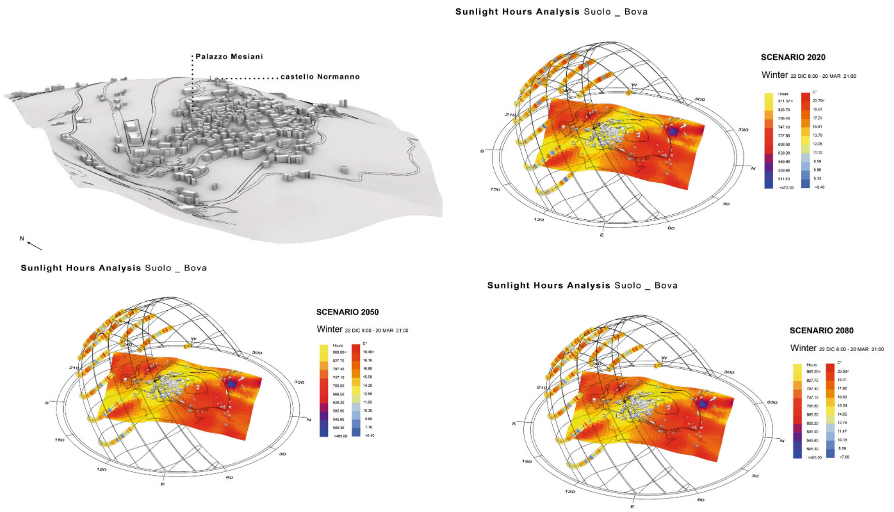

Fig. 10. Climatic Dataset – Soil/Winter_in the cultural heritage cluster of Bova (RC) (D. Laganà, ABITALab, 2024)

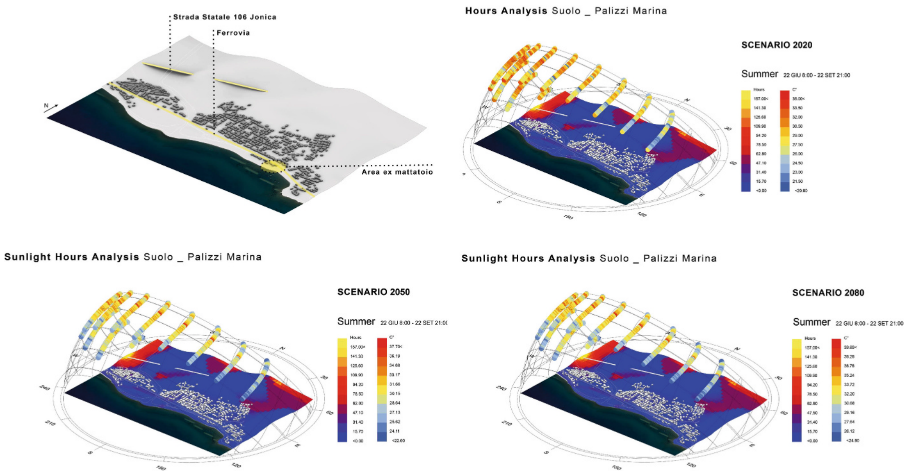

Fig. 11. Climatic Dataset – Soil/Summer in the natural heritage coast of Bova (RC) (D. Laganà, ABITALab, 2024)

4 Conclusions – Beyond *Regenerative Digital Design*

The study proposed in its methodological and applied discussion can express three levels of advancement on the trajectories of digital regenerative design, going beyond the processual nature of the outputs we have presented in this text and preparing its predictive phases for a role of "in and out" information in simulation processes. We consider the possibility of managing the DL (deep learning) of AI's generative capabilities as a further frontier of research, in order to overcome the mathematical and numerical models on which parametric simulation design is based. The discretisation of data and information is a crucial step when using environmental simulation tools (e.g. Lady Bug, ENVI-met), and AI's ability to process large amounts of data offers an interesting opportunity to refine predictive models in the field of climate scenarios (Nava, Melis 2024). **There are three new performance capabilities of a regenerative digital design process** that are truly effective in the field of studies on cultural and natural heritage at risk (Nava 2024), as described below.

First, in parametric design processes, the flexibility to simulate and adjust a wide range of variables allows you to explore latent opportunities within a design space. **The generative capabilities of AI** further enhance this process, allowing designers to explore different permutations and paths that may not be immediately apparent. Through deep learning, AI systems can help recognise patterns of redundancy or untapped potential within data and structures, allowing these elements to be co-opted for new purposes, similar to adaptation in biological systems.

Secondly, through **the construction of workflows that express the complexity** of the methodologies adopted, we propose the construction of a new procedural tool that, by reinterpreting the operational framework adopted for socio-ecological regenerative design, in the circularity of metric, practical, platform, tool and interaction phases (Nava 2022), can work according to the scale-jumping approach, introducing, through DL processes, widespread modelling tools for the production of images, which are inserted into the interactions between the outputs of parametric tools, as a discretisation space for the visualisation of 'scenario options or scenario times', produced with AI.

Third, the regenerative process informed by AI strengthens its phigital profile in an innovative way, because it is capable of guiding the design and discussion of sustainability issues in an "advanced" manner and with "high performance" results in climate adaptation and mitigation scenarios, in order to respond to different states of impact on the physical ecosystem. From a digital point of view, it is capable of producing and exchanging preventive and predictive visions. Regenerative design thus takes on an organisational character to identify options that lead to **new solutions through the use of adaptive technologies.**

Acknowledgement. This study was carried out within the Innovation Ecosystem Tech4You – "Technologies for climate-change adaptation and quality-of-life improvement," Mission 4, Component 2, Investment 1.4 of Italy's National Recovery and Resilience Plan (PNRR), funded by the European Union—NextGeneration EU (project code ECS_00000009, CUP C33C22000290006). The author is pilot project lead, Pilot Project 4.7.1 "Open platform phygital space for advanced, dynamic co-design of built-environment interventions" and scientific responsible for the activities carried out in the Design and Prototyping sections of ABITAlab, Department of Architecture and Design, Mediterranean University of Reggio Calabria.

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