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Luigi Massaro
University of Campania "Luigi Vanvitelli" https://orcid.org/0000-0003-2755-5471
Roberto Serpieri
roberto.serpieri@unicampania.it

University of Campania Luigi Vanvitelli: Universita degli Studi della Campania Luigi Vanvitelli
https://orcid.org/0000-0003-4443-5981

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Struct-Stainability: a metric for Timber Use and Forest Restoration

Luigi Massaro[a], Roberto Serpieri[a]*

[a]*Department of Architecture and Industrial Design, University of Campania Luigi Vanvitelli, 81033, Aversa, Italy*

luigi.massaro@unicampania.it

*roberto.serpieri@unicampania.it

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Purpose. This study introduces an interdisciplinary methodology for defining a sustainability metric supporting the joint engineering design of forestry operations and construction processes reliant on forest-based supply chains. Focusing on forest restoration and sustainable management in ecologically fragile areas like Campania Felix in Southern Italy—where high-density conurbations have almost entirely replaced ancient lowland forests—the framework aims to harmoniously balance the quantification of environmental regeneration needs with the demand for structural construction materials.

Methods. The methodology is tested through a case study assessing restoration opportunities for Campanian coastal psammophilous ecosystems and *Pinus pinea* habitats—and the related land resource requirements—to support the prospective solid-wood reconstruction of the *columna-capreoli* A-trusses in the *Aula Magna* of the Department of Architecture and Industrial Design at the University of Campania, hosted by the Monastery of San Lorenzo *ad Septimum* in Aversa.

Proceeding from the metric determination of dimensional and volumetric requirements of structural timber and through growth and yield (alsometric) analyses, the computed bill-of-quantities figures are converted into an equivalent estimated land-time metric for reforestation and land-use planning. This conversion is achieved via the recently proposed *struct-stainability* axiom, which equitably pairs anthropic transformation demand with anthropogenic ecosystem restoration and preservation needs.

Results and discussion. The main outcome of this study is the definition of the San Lorenzo space-time Unit (SLU), ultimately quantified to be 8,200 m² over a time range of 70 years, representing a twofold contextual reforestation plan that implements, on the obverse, land allocation and forest operations exclusively destined to ecosystem restoration and, on the reverse, land allocation and sustainable forest engineering for the timber supply chain (short-wood supply chain). The resolution of an SLU-based optimality model design problem is also illustrated.

Although this quantitative outcome depends on several specific assumptions adopted in the present case study, the knowledge gained provides an encouraging proof of concept of the convergence of the proposed algorithmic schemes and

experienced geographically informed design-individuation processes into well-defined actions of built environment regeneration.

Conclusion. Overall, the illustrated general methodology of *Struct-stainability design*, in its *Construction-driven* and *Biodiversity-driven* variants, offers a multidisciplinary approach scalable to other regional case studies with a promising potential of contributing to the harmonization of structural needs, forest planning, and long-term sustainability goals.

Keywords: Biodiversity Heritage, Wooden structures, Cultural heritage, Sustainability, Forest Restoration and Management, Mitigation practices.

Introduction

Sustainable forest management, ecosystem restoration, and the responsible use of timber resources have become central drivers in contemporary forest engineering. Today, these policies are increasingly intertwined with global climate-mitigation strategies and with the rapid expansion of demand for timber-based construction materials, both for cultural heritage preservation and for maintenance and construction of ordinary buildings.

The rising demand for structural wood products, together with growing interest in low-impact construction solutions, calls for a substantially larger-scale rethinking of design paradigms so that construction-site engineering decisions can appropriately incorporate ecological metrics, sustainable supply-chain considerations, and long-term, wide-area regeneration goals. Recent research (Kühmaier et al. 2025) has indeed underscored the need for an integrated framework able to simultaneously address structural design, forest planning, biodiversity conservation, and socioeconomic development, reflecting the evolving role of Sustainable Development Goals (SDGs) (United Nations General Assembly 2015) within forest operations and engineering practice, as well as the primary importance of applying sustainable forest harvesting methods while supporting reforestation and restoration (SDG 15.2). In response to this design-paradigm rethinking, recent contributions have emphasised the importance of

forest ecosystems as functional infrastructures within urban and peri-urban landscapes, calling for smart forest management strategies that reinforce ecological connectivity and human-nature interactions (Iaderosa et al. 2024).

Parallel developments across several research fields today are paving the way for more viable, sustainable integration of forestry-engineering parameters with structural and architectural design. Just to mention few more recent developments, mechanical characterisations of small-diameter stems have demonstrated that this lower-impact raw material, often underutilised in traditional supply chains, can serve as a suitable feedstock for engineered wood products (EWP), with performance levels comparable to those of standard structural timber (Heräjärvi et al. 2004; Frunzio et al. 2022; Massaro et al. 2026). Concurrently, studies on traditional timber carpentry and wood-to-wood joints – frequently examined within heritage preservation case studies (Cennamo, Di Gennaro, Frunzio, et al. 2025; Cennamo, Di Gennaro, Massaro, et al. 2025) – confirm the long-term durability of structural wood and suggest that traditional steel-free joining techniques can comply with both structural requirements and conservation-oriented provisions, allowing minimal introduction of non-renewable materials (Massaro et al. 2023). Smart strengthening methods, such as post-tensioned wire-rope reinforcement of timber floors, which can significantly enhance stiffness while preserving the architectural integrity of heritage structures (Di Gennaro et al. 2025), can also help reduce the envisaged structural-wood supply demand associated with specific restoration interventions.

As hereafter discussed, a road map for integrating forest engineering decisions with structural engineering decisions can conveniently proceed by a research path aiming at an integration of the selected design-driving variables and resource demand metrics between the two sectors of forest engineering and structural building engineering.

On the side of reforestation and forest harvesting engineering, research is still currently active on the proposal of operational metrics receptive to quite different processes. Among more recent contributions with a focus on improving sustainability criteria and machinery efficiency, one can mention for instance, on the one hand, the elaboration of demand metrics which quantify environmental impact associated with harvesting activities under the lens of soil disturbance measured in terms of soil rutting depth (Salmivaara et al. 2018). These demand metrics can find employment in logistic models aiding the search for optimal placement of forest biomass terminals as well as for evaluating mitigation practices in operational forestry (Berg and Athanassiadis 2020). Still in forestry-harvesting engineering, albeit on the opposite machinery- and tool-oriented side, metrics evaluating time-consumption of forestry equipment have also recently been the object of research concerned with forest operations in conservation-sensitive areas (Fernandez-Lacruz et al. 2023).

Turning to the building construction side of the metric problem, concerning the engineering performance-metrics which ordinarily orient in a structural project the demand for building materials, and in particular wood products, design metrics in structural engineering seem to have not experienced, in contrast to forest engineering metrics, a comparable updating trend. Besides still ongoing attempts to find credible metrics able to find balance between CO_2 consumption and CO_2 storage related to building materials (Marcea and Lau 1992; Roijen et al. 2025; United Nations Environment Programme 2025), in several countries, among which Italy, the performance metrics more frequently employed tend to remain grounded, traditionally – or perhaps inertially – on mechanical performance indicators alone, such as stiffness, strength, and demand-to-capacity ratios assessing the compliance with structural requirements (Ministero delle Infrastrutture e dei Trasporti 2018) and in metrics of construction costs

primarily concerned with economic variables (ISTAT 2026). Without denying the everlasting anthropic groundedness of these traditional performance indicators, it can be observed that use of these two metrics alone leaves unresolved the engineering performance analysis with respect to those dimensions of the design problem which must delve into the assessment of the '*safe operating space*' (Butera 2021) concerned with the larger-scale biodiversity-protection design problem (not undelegated to the responsibility of construction engineers) and to what can be perhaps defined as the 'mother of all anthropic risk mitigation problems' which is that of finding a logic of proportionate allocation of land use and solar energy fixed annually by photosynthesis by terrestrial producers (Vitousek et al. 1986). Traditional construction metrics also leave unresolved the problem of duly quantifying and 'charging' to the local on-site project its land-time resources required to restore forest ecosystems used as a source for raw construction material.

In light of the considerations above, and in an attempt to contribute to rethinking the design paradigms rooted at the intersection of forestry-engineering design and structural engineering design, the authors of the present study have explored methodologies for quantifying the relationship between the demands for structural wood employed as construction materials and forest ecosystem restoration opportunities in Central and Southern Italy, with specific consideration of the Campania region context and of its 2000-year-old documented environmental fragility. These studies have elaborated and formally proposed interdisciplinary metrics which comprehensively account for cultural heritage conservation criteria, dendrometric and alsometric variables, and ecological variables gained from high-resolution regional-scale biotope maps (Bagnaia et al. 2017) capable of supporting simple, yet effective, sustainability-driven rule-of-thumb design-criteria (Massaro et al. 2023; Massaro et al. 2024). This

multidisciplinary effort has allowed the concept of *struct-stainability* to emerge, a neologism proposed by the University of Campania research group as a lexical blend in English of the words *structural* and *sustainability* (L. Damiani et al. 2024; Damiani et al. 2025).

The struct-stainability principle postulates that a relevant metrically equal anthropogenic ecosystem-regeneration action must dually accompany any structural-engineering anthropic intervention that relies on forest-derived materials (or, more generally, ecosystem-derived resources). The implementability of this general principle has been confronted by this research group with the real-world problem of the potential reconstruction of the historic trusses in solid timber of the Aula Magna of the monastery of San Lorenzo ad Septimum. The monastery is a historic site in Aversa currently hosting the Department of Architecture and Structural Design (DADI), which emblematically tells a thousand-year history of both agonistic and antagonistic interaction between anthropic development and anthropogenic modification of natural resources in the Campania plain and of hospitality to institutes for vocational education and training, mostly of professionals and workforce tasked with acting as transformers and regenerators of the built and natural environment (Jacazzi 2009). The present article thus describes a forest-engineering-oriented methodology which attempts to translate, via the struct-stainability axiom, a construction-driven timber demand, tailored to the San Lorenzo's Aula Magna reconstruction problem, into corresponding requirements of land-use forest resources allocation for the sustenance of biodiversity thresholds and of the wood supply chain.

As this study will describe, quantification of the required structural timber volume, informed by dendrometric and mechanical analyses, ultimately yields the *San Lorenzo land-time Unit* (1 SLU), equally divided between land for biodiversity-oriented

regeneration and for productive coppice forestry. The SLU metric is finally deployed into a minimalistic, yet still instructive, optimization problem which consists in the design of the transverse section dimensions of the frame elements of San Lorenzo's A-trusses under gravitational, seismic and wind actions, targeting the maximization of a Struct-Stainability Performance Metric (SSPM) while keeping the same wire-frame geometry of the current installation.

The article is organized as follows. After presenting the methodology in a general abstract formalization, the premises of the San Lorenzo ad Septimum case study are described. The consequential elaborations and results finally leading to the computation of the SLU are then illustrated together with the results of the optimization problem. Discussion and conclusions follow.

Methods

Abstract general procedure

The proposed forest-engineering-oriented methodology herein described places its focus on the opportunity of joining forest engineering design and construction design to provide a contribution to the ongoing common effort, catalysed by the 2030 UN Sustainable Development Goals, towards a resolution for the duality between environment sustenance and construction sustenance.

The methodology proceeds from acknowledging the binomial necessity of equipping engineering design science with analysis methods and design criteria that can prove to be effective in equally guaranteeing safety with respect to the bidirectional actions:

- of the effects of construction for anthropogenic purposes on terrestrial and aquatic ecosystems;
- of natural actions on the anthropic built environment (typically, safety to gravity, wind and earthquake loads).

The procedure applies the '*struct-stainability*' principle to translate a construction-driven timber demand and an environmental fragility (or procured damage) scenario into corresponding forest-restoration resource requirements and forestry operations. *Struct-stainability* is a neologism proposed by DADI groups of Science of Design and Construction as a portmanteau between the words "structural" and "sustainability". The principle, progressively elaborated as recorded in several publications (Massaro et al. 2023; L. Damiani et al. 2024; Luca Damiani, Massaro, et al. 2024; Massaro et al. 2024; Damiani et al. 2025), can be reduced in essence to the following minimalistic postulate.

Every instance of redesign of the built environment must start from: 1) An instance of anthropic transformation, and 2) an anthropogenic preservative or reintegrative instance, the two placed in binomial, joint, and equitable form.

From the above premises, the 'struct-stainability-inspired' metric problem is more simply formulated herein as the objective of developing appropriate metrics formulated in terms of land, time and ecosystem resources by allocating such terms in two equal parts:

1. one for ecosystem restoration to replenish biodiversity thresholds (S_{V}) (also indicated in the sequel as *separate management*);
2. a second equal and independent part exclusively destined to the construction materials supply chain (S_{A}).

In testing the applicability of the struct-stainability postulate against a real empirical problem to be selected from those offered by the construction industry, wood appears as a most natural and simple choice for a building material, given the eminent, certainly unique, features of renewability and circularity of plant products.

The proposed methodology converts the wood quantity required by a given building project (say of restoration, renovation or new construction) into corresponding requirements for land allocation, forest operations, and forest resources. These resources are designed so as to be equally partitioned between the two complementary purposes of: 1) ecosystem restoration, aimed at supporting the recovery of selected biodiversity targets (S_{V}), and 2) silvicultural activities aimed at supplying the timber resources required by the construction project (S_{A}).

In its simplest implementation, assuming unrestricted availability of allocatable land and feasible forest operations and giving prominence to building restoration over renovation or construction, the general algorithm is illustrated by the flowchart in Figure 1 and Figure 2. The algorithm proceeds from the assignment of a binomial problem of regenerative co-

restoration (ecosystem restoration + building restoration). The binomial assignment requires the definition of an action (or of a homogeneous technological task, unit or component) of building restoration destined to anthropic purposes.

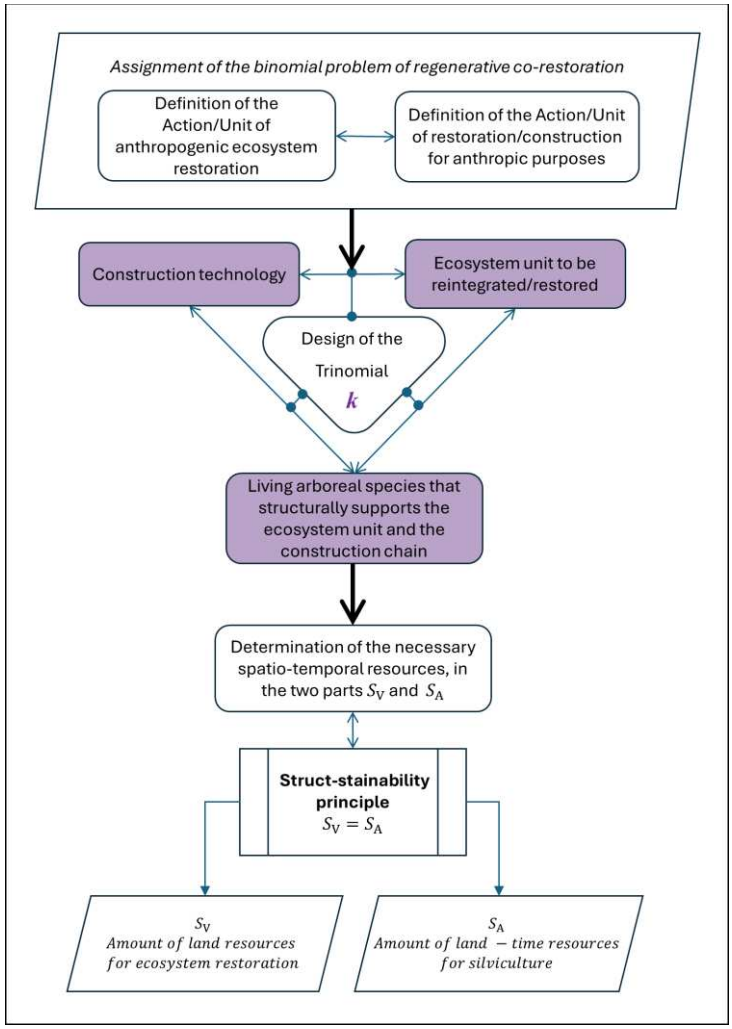


Figure 1: General abstract struct-stainability analysis-design methodology (simplest form with assumed unrestricted availability of allocatable land and feasible forest operations).

Therefore, by making the choice of the construction problem for anthropic purposes fall on an architectural restoration action (specifically considered in the diagrams of Figure 1 and Figure 2), it is necessary, in order to complete the valorization of the regenerative input binomial, (upper slanted rectangle of Figure 1 and Figure 2) to identify a design problem of a biodiversity restoration/replenishment action to be placed in a dual, binomial and equitable

form to the anthropic design problem. The problem can be accordingly denominated to be of *co-restoration*.

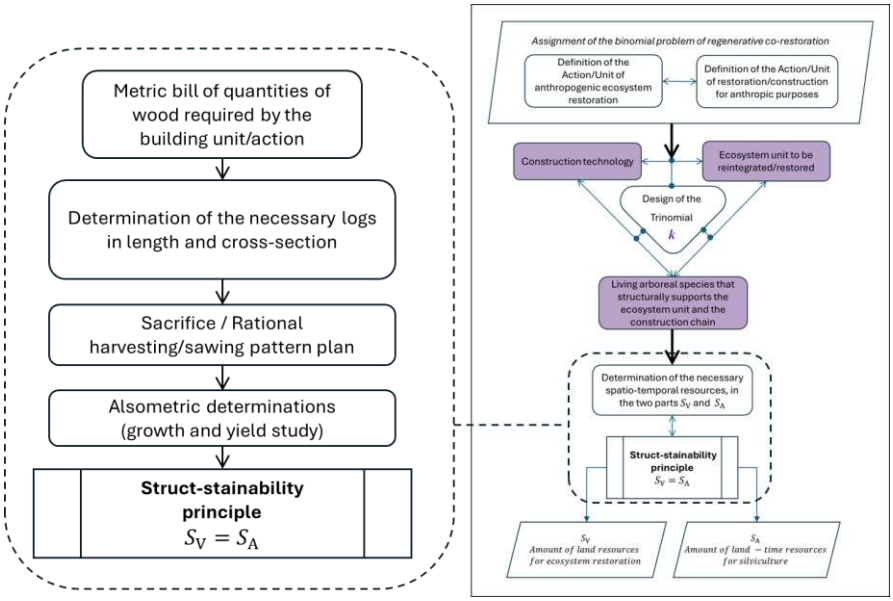


Figure 2: General abstract struct-stainability analysis-design methodology. Detail of the simplest computation branchless sub-algorithm with no conditional blocks, assuming unlimited resources.

The biodiversity restoration/replenishment action is set to be designed in a form specular to seismic mitigation on buildings, proceeding from a proper identification in the reference geographical context of ascertained territorial issues of environmental fragility and vulnerability (or of already procured environmental damage, if the case applies) in a way mirrored, in the context of structural engineering, to post-shock damage-scenario surveys, like post-earthquake damage assessment.

The central idea of the method is to elaborate and identify the environmental restoration target from the inspection of the actual conditions of damage and environmental fragility and proven ecosystemic emergencies, according to an intervention rationale which parses target ecosystemic actions by following a decreasing order of priority.

As shown in the higher detail flow-chart of Figure 3, this dual side of the design input can be conveniently elaborated on the basis of available Geographic Information Systems (GIS)

providing higher resolution maps of ecosystem fragilities and incurred damage, up to the scale of biotopes of the target geographical context.

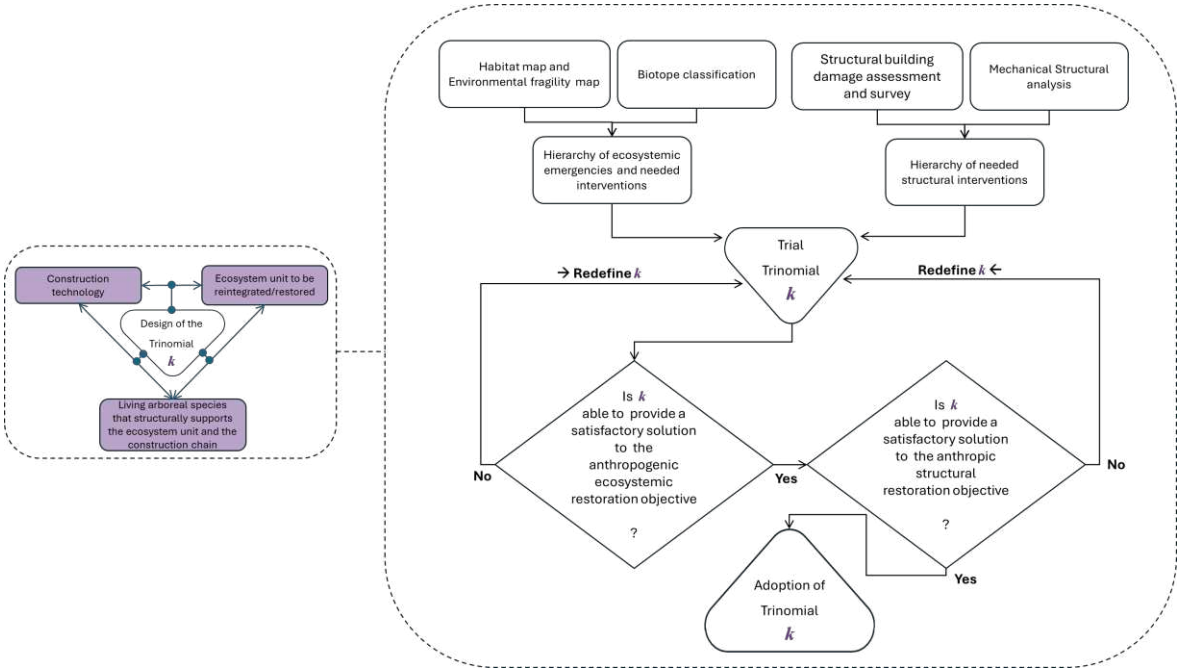


Figure 3: Detail of the procedure for the design of trinomial ***k***.

A pivotal step of the procedure is the proper identification of the living arboreal species that can optimize the benefit in terms of co-restoration of the binomial (anthropic construction) - (anthropogenic reintegration) and onto which calibrate the quantity of resources needed to balance ecosystem restoration with the production of the quantity of materials necessary for the construction hypothesis.

As shown in Figure 1, Figure 2, and Figure 3, at the centre of the design algorithm stands the *trinomial* ***k*** *of primary struct-stainability design variables*, serving for the input binomial co-restoration purpose. This trinomial design step (illustrated in the form of a triangular shield-shaped process block) joins the three elementary processes/functions of:

1) design of the target ecosystem unit to be replenished;
2) design of the arboreal living species having structural function for the ecosystem unit;

3) design/selection of the construction materials and construction technology for the targeted anthropic action.

The trinomial process ***k*** has the function of joining the three processes so as to identify an engineering solution granting the requirement of *sustainable sustenance*. This requirement points to the capability of equitably supporting anthropogenic and anthropic restoration targets. As illustrated in Figure 4, the function of this trinomial can be set in analogy to the static function performed in a standard A-truss by the Kingpost beam joint, of equitably supporting the left and right principal rafters through the kingpost-struts connection.

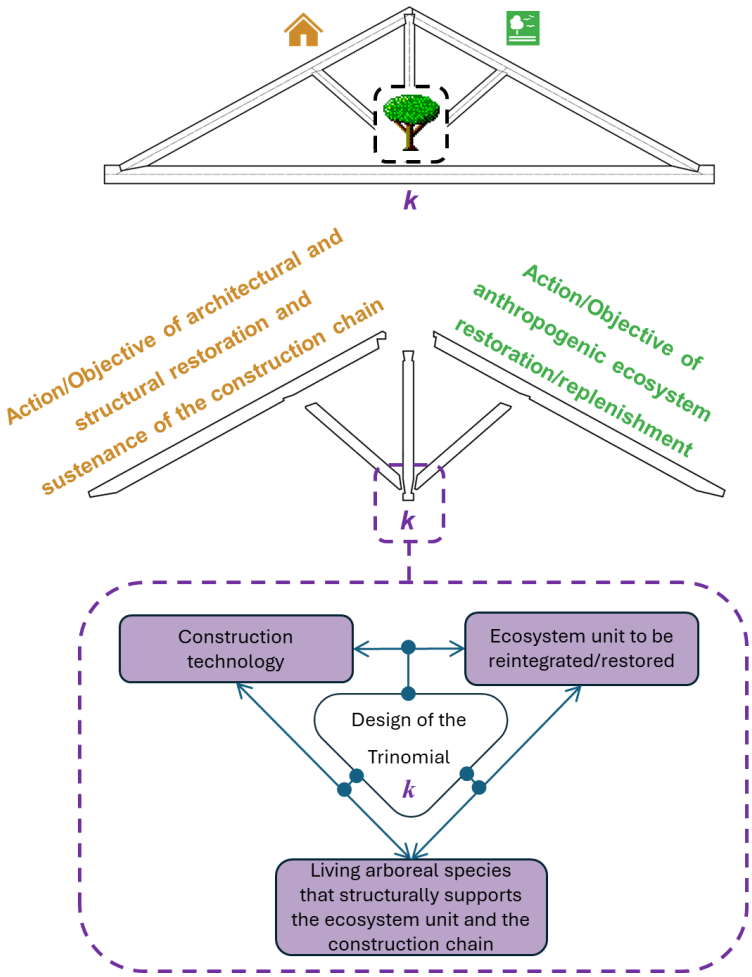


Figure 4: Illustration of the concepts of *sustainable sustenance* and of binomial co-restoration.

As set forth by Damiani et al. (Luca Damiani, Massaro, et al. 2024; Damiani et al. 2025) the methodology proposes to ponder the choice of the living arboreal species ‘‘*dando pienamente a questa […] il significato di valorizzazione di un grado di libertà progettuale primario, ovvero di elemento di scelta progettuale non soggetto ad altri vincoli se non a quello di massimo beneficio in termini di co-restauro del binomio costruito-ambiente, responsabilmente valutato e mediato dai progettisti incaricati del problema progettuale di co-restauro*’’.

The choice of the reference tree species is therefore to be regarded as a primary design process and the identified tree species as a key design variable, rather than as a predetermined input. Its selection should thus be guided by the objective of maximising the overall benefits associated with the co-restoration of the built and natural environments, as assessed by the designers responsible for the integrated restoration process. Accordingly, the optimality of a specific architectural, structural and forestry operational intervention becomes part of a broader systemic optimisation problem, in which both ecosystem resilience and the long-term sustainability of the construction supply chain are considered.

Starting from the definition of the geographical reference context, the general abstract procedure requires the sequential identification and characterisation of the following fundamental design variables:

- a selected sample construction unit,
- a selected sample renewable and circular construction material (wood, engineered wood or other plant-derived products for construction, among circular building materials),
- a selected sample construction-driven transformation process,
- a selected sample natural resource,

- a selected sample ecosystem unit,
- a selected sample living unit, defined as an elementary regenerative unit through which the resources required for ecosystem restoration are balanced against those required to produce the quantity of material needed for the construction project.

The San Lorenzo co-restoration case study

Assigned geographical context and anthropic restoration action

The geographical context chosen for the formulation of the present 'struct-stainability-based' case study on regenerative co-restoration focuses on the territories of the Volturno plain crossed by the Via Antica Consolare Campana, situated along the Capua-Aversa-Pozzuoli axis, (Luca Damiani, Massaro, et al. 2024), with DADI serving as an ideal center of gravity. Today this area has been almost entirely transformed into high-density conurbations and agricultural land at the expense of a virtually complete destruction of ancient lowland forest ecosystems, which on the coastal area once consisted mainly of ancient holm oak (*Quercus ilex*) wood.

The assigned action of restoration for anthropic purposes contemplates a future new solid-wood installation of the gable roofing structures of the Aula Magna of San Lorenzo ad Septimum, supporting the clay tile covering. The existing installation consists of 16 glued-laminated timber A-trusses that support the roof of the great plenary hall which has approximately dimensions 13.20 m × 23.55 m. The trusses, placed at a spacing of 1.4 m, belong to the open-noded Vitruvian canon with kingpost and struts. A survey of the installation could enable reconstruction of the geometric model shown in Figure 5, with element section dimensions and wood volume summarised in Table 1, taken from (Damiani et al. 2025). Upon adding to the overall volume of Table 1 the volume of planking and purlins, a total amount of about 50 m^3 is obtained.

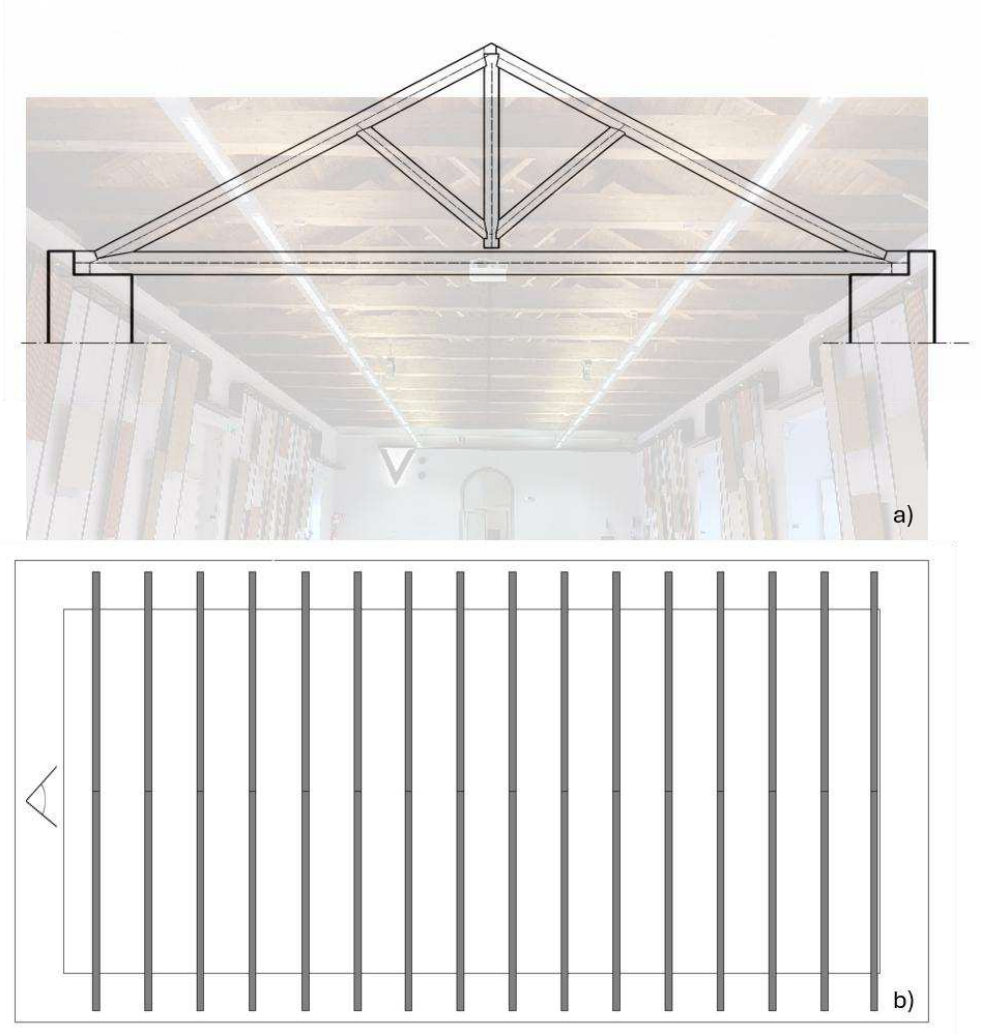


Figure 5: a) Front view of the trusses of the lecture hall of San Lorenzo ad Septimum with photo of the interior of the Aula Magna in background transparency; b) plan view.

English name	Latin name	Width × Height	Length	Volume for 1 truss unit	Volume for 16 units
		[m] × [m]	[m]	[m^3]	[m^3]
Tie	*Transtrum*	0,20 × 0,40	13,95	1,12	18,86
Kingpost	*Columna*	0,20 × 0,24	3,55	0,17	2,73
Roof beams (×2)	*Cantherii*	0,20 × 0,30	7,60	0,91	14,60
Struts (× 2)	*Capreoli*	0,20 × 0,24	2,70	0,26	4,16

Table 1: Section dimensions, lengths and computed wood volumes of the elements of the A-trusses of San Lorenzo's Aula Magna with English and Latin technical denominations.

As a first step, seeking a simplest settlement of the structural engineering design problem, the assigned anthropic restoration action contemplates the solid wood reconstruction employing exactly the same geometry of the existing installation of San Lorenzo's Aula Magna. Such action of reconstruction of San Lorenzo's A-trusses is also indicated by the abbreviation *SLA*. In Section *Results Summary and Discussion* a less simplistic version of such design problem, formulated as a redesign sectional optimization problem, is also briefly discussed.

Design of the anthropogenic ecosystem restoration action

The territorial analysis aimed at the identification of the dual ecosystemic action of the co-restoration design-binomial of Figure 3 similarly proceeds by attributing to San Lorenzo ad Septimum and to DADI of Vanvitelli's University the role of an ideal generative stem center. Such dual action is also referenced in short by the dual abbreviation SLV. The SLV action has been elaborated proceeding from a survey of ecosystem fragilities and incurred damage by consulting dedicated technical reports released from Italian institutions and agencies, and available GIS databases. The approach to the regional scale problem has been preceded by a brief contextualization at the global level over a temporal scale covering the last two millennia (Williams, 2003; Ritchie, 2021) and at the national Italian level (Red List of Ecosystems of Italy, Blasi et al., 2023) (RLEI), to ultimately focus on the regional emergencies of the targeted territories of Campania (Carta della Natura della Regione Campania) (CNRC), and specifically of Piana Campana, up to the refined scale of biotopes (Bagnaia et al., 2017, Corine Biotopes, 1991).

According to the 2023 update of the Red List (Blasi et al. 2023) Piana Campana belongs to the Tyrrhenian ecoregion. This ecoregion comprises 34 elementary ecosystems and covers

about 29% of Italy, including Sicily and Sardinia. The Red List assigns a risk-of-collapse category to the ecosystems within each ecoregion based on a multi-criteria assessment considering:

- multi-temporal assessment of ecosystem distribution and future projection;
- higher detail surveys focusing on conditions of worsening conservation status or exceptional scarcity on the most restricted ecosystems;
- loss of quality, observed over time, of the environmental parameters that characterize the ecosystem due to pressure factors that include ecosystem land consumption, coastal erosion, intensive agriculture, forest fires and the chemical state of surface waters.

Outstanding figures retrievable from the list and deserving attention are the following. At the national scale, 46.3% of the Italian territory is classified as being at risk, while 29 ecosystem classes are identified as being at risk or *critically at risk*, approaching thresholds associated with *irreversible environmental degradation* or loss of ecosystem quality (Blasi et al. 2023).

For the Tyrrhenian ecoregion comprising Campania, the Red List accounts of a decidedly worrying condition, which can be numerically summarized into:

- 82% of ecosystems at risk,
- one ecosystem in critical danger condition,
- 8 ecosystems in danger conditions,
- 19 vulnerable ecosystems,
- and 5 possibly incurring future risk.

In particular, the main critical emergency condition concerns psammophilous peninsular ecosystems, characterized by a prevalence of plants specialized in living in coastal areas on

the surface of the wet sand and on the dunes (coded F2). The eight ecosystems in endangered conditions are the psammophilous ecosystems of the major islands, different categories of ecosystems with a prevalence of oak and beech species, and the ecosystems of the major islands with a prevalence of chestnut (*castanea sativa*).

On the basis of this Tyrrhenian priority list, an intelligent approach to the design of the struct-stainability trinomial ***k*** (entering the flowcharts of Figure 1, Figure 2, Figure 3 and Figure 4) can conveniently proceed, as recommended by Damiani et al. (Luca Damiani, Massaro, et al. 2024; Damiani et al. 2025), along the identification of suitable 'struct-stainability-inspired' factors of synergistic and equitable sustenance of:

- the supply chain of construction materials to be optimally selected for the assigned SLA,
- and of the assigned target replenishment of the endangered biodiversity thresholds placed at the top of the priority list.

By adopting such design rationale, a decision-making process leading to the identification of a suitable ***k***-trinomial can be supported by the following argumentations.

Should the elaboration of trinomial ***k*** be governed only by the anthropogenic environment-restoration component of the problem assignment (SLV), the choice might be straightforwardly placed over species having structural function for psammophilous biotopes whose critical endangerment leads the list of primarily required reintegration actions. However, in the present problem formulation, such choice must be counterbalanced by the dual SLA assignment leaded by the structural building-constructive requirements.

Due consideration of the vegetation zonation in coastal and riparian zones of the Thyrrenian ecoregion must be taken (Strumia 2004; Acosta et al. 2007) keeping a dual focus on both SLA and SLV restoration objectives.

In the foredune zones (embryonic and shifting dunes), the structural ecosystem function is primarily performed by pioneer plant communities with herbaceous, hemicryptophytic, and geophytic growth forms. Characterized by flexible and trailing stems, these species exhibit specific ecomorphological adaptations to withstand wind action and continuous sand burial. Consequently, their above-ground biomass lacks significant arboreal components or lignified tissues, what makes them unsuitable as a source of structural construction timber destinable to the SLA action.

Tall trees that perform a fundamental structural ecosystem function and that have traditionally provided suitable timber for structural components of building construction are instead found in the adjacent area of the fixed dune (or inner dune) such as the holm oak (*Quercus ilex*), the stone pine (*Pinus pinea*), and the maritime pine (*Pinus pinaster*), the last two species having been largely employed for reforestations, although currently suffering reduced ecosystem stability and increased outbreaks of insects and pathogens due to global climate change and increased human activities (Calandrelli and Migliozzi 2023).

Tamarisks (*Tamarix Gallica, Tamarix africana*) show very interesting properties which can make this species synergistically deployable for both the structural function in the restoration of threatened psammophilous coastal or riparian mediterranean ecotones and for supplying construction materials for building applications. Although sometimes having been indicated in non-Mediterranean areas as invasive against autochthonous psammophilous species, their at least bimillennial presence in Italy is already documented in literature by Vergilius and Pliny the Elder *(Virg., Buc.; Plin., Nat. Hist. Libri XIII XVI)* "*Myricen et Italia, quam tamaricem vocat,*" (transl.: Italy also has the myrica, which is there called the tamarisk) (Plinio il Vecchio 1906). Tamarisks, which grow spontaneously on the coasts, on the humid subsaline sands and in the riverbeds of almost the entire Italian territory, have been

efficiently employed in soil bioengineering techniques for Mediterranean coastal dune restoration and in reforestation interventions in mediterranean coastal areas (Braschi 1951; Mareschi 2014; Romano et al. 2022).

Although strictly classified under riparian and brackish classes within the CORINE database (such as the Nerio-Tamaricetea communities) (Biondi et al. 2012), *Tamarix gallica* acts as an important ecotonal species bridging the gap between strictly psammophilous dune systems and coastal wetlands, providing cross-habitat structural stability

Turning attention instead to the dual anthropic-side face of the co-restoration assignment, tamarisks are included in the alphabetical catalogue by Cavalieri San Bertolo of the main species of trees from which working timber adapted to the different architectural uses is obtained (Cavalieri San Bertolo 1831), although their twisted-trunk habit and moderate height, reported by various sources to not exceed 7 meters, make the species not specially indicated for the construction of long trusses as those for the assigned SLA action.

If, on the other hand, under a more anthropic-centered perspective, the design problem were entirely focused on the other key issue in cultural heritage protection of the conservation of the constructive techniques most frequently found in traditional roofing systems of Campania, the newly built structure could be designed in chestnut trunks and the selected arboreal species could fall on the chestnut tree (*castanea sativa*) playing, as reported in the red list, structural function in some of the endangered Thyrrenian ecosystems of the major islands.

Maritime pine (*Pinus pinaster*) and stone pine (*Pinus pinea*) are also to be included among the candidate living arboreal species at the centre of trinomial ***k***. Actually, among the vulnerable/fragile Tyrrhenian ecosystems, category C35 includes coastal, hilly, and peninsular forest ecosystems characterised by the prevalence of these tree species. These species thus deserve a higher detail scrutinization for being placed as the trial living arboreal species at the base of the trial trinomial ***k***, (shield-shaped box in Figure 3), given their high potential to structurally support both the San Lorenzo ecosystem-centred action (SLV) and the SLA action.

To enhance the practical significance of the ***k***-trinomial design exercise, this study aims to calibrate such trinomials focusing attention on species having structural functions within ecosystems facing intermediate risk levels – specifically, species that are neither critically endangered nor entirely secure. The reason for this choice is the following. Selecting a critically endangered species, such as *Tamarix gallica* or other structural components of psammophilous ecosystems, would make the individuation of the ***k*** -trinomial exceedingly complex and of questionable feasibility within a reasonable timeframe. Conversely, choosing an entirely risk-exempt species would strip the exercise of its core utility, reducing it to a detached, overly simplified reconfiguration of a forest resource supply chain. This latter scenario would fail to account for the local and global dynamics of the timber market.

After scrutinization at national scale, the problem of identifying candidate target ecosystems is delved into also at a regional scale.

Candidation of *Pinus pinea* at the base of the ***k*** trinomial requires a more detailed assessment at regional scale of its distribution and environmental fragility at the habitat scale. For this purpose, the Campania Habitat Map provided by ARPAC (Bagnaia et al. 2017), based on

the CORINE (Coordination of Information on the Environment) biotope classification developed by the Commission of the European Communities (Corine Biotopes 1991), has been examined. Within this classification, stone pine forests are associated with habitat codes 42.83 and 42.83A, the latter including ancient *Pinus pinea* stands and populations considered potentially natural along the Tyrrhenian coast of the Italian peninsula and on the major islands.

Analysis of the 1:25,000-scale raster dataset (Bagnaia et al. 2017) indicates a highly restricted distribution of *Pinus pinea* habitats within the Piana Campana. Acrually, in the study area, only three raster cells associated with stone pine habitats were identified, all located near the left bank of the Volturno River mouth, within the Oasi dei Variconi nature reserve. This remarkably limited spatial occurrence provides quantitative evidence of the critical local scarcity of the selected habitat in the territories selected to host the targeted SLV ecosystem-restoration action and resolves the final election of *Pinus pinea* as the living arboreal species at the kingpost node of the ***k*** -trinomial, allowing to consequently assign solid *pinus pinea* trunks as the selected construction technology, and reintegration of coastal pinus pinea habitats (C35) of the Domitian coast as the associated anthropogenic action (Figure 6).

The last algorithmic step is checking the fulfillment of the validation condition in the right diamond step in Figure 3 on whether ***k*** can provide a satisfactory solution to the SLA action under a mechanical, structural and building performance perspective. This check is positively passed as specified hereafter. Concerning mechanical and durability properties, the superior qualities of pine wood as a factory material are attested by several authoritative sources among which Plinio (Plin. Nat. Hist., XVI), Jean-Baptiste Rondelet (Rondelet 1834), and Cavalieri San Bertolo (Cavalieri San Bertolo 1831). Reported working stresses of this wood species turn out to be only moderately lower (within a maximum reduction of 30% for

shear strength) than the values of other conifers such as spruce (Tassinari and Calzecchi - Onesti 1951). A recent structural engineering study by this research group could also show that the truss geometries in the S3 ensure work rates ordinarily below 8% when the employed essence are spruce or fir (Massaro et al. 2024) having not significantly dissimilar structural properties.

An obstacle to the hypothesis of using the Pinus pinea for the SLA action might therefore exclusively be impelled by metric factors, a critical design requirement being the tie length of approximately 14 metres, which requires logs of sufficient length and adequate straightness. Dendrometric tables for stone pine published by the Italian Experimental Institute for Forestry Settlement and for Alpiculture (Gasparini et al. 2016; Gasparini et al. 2022), several other sources (Morelli and Raimbault 2011; Lorenzini and Nali 2013; Morelli and Raimbault 2014) and on field surveys around San Lorenzo ad Septimum abbey (Damiani et al. 2025) confirm the possibility of reaching this requirement upon giving the plants enough time to grow and resorting to appropriate silviculture technical expertise. Successful pass of this last validation step allows to conclusively adopt the trinomial ***k*** in Figure 6.

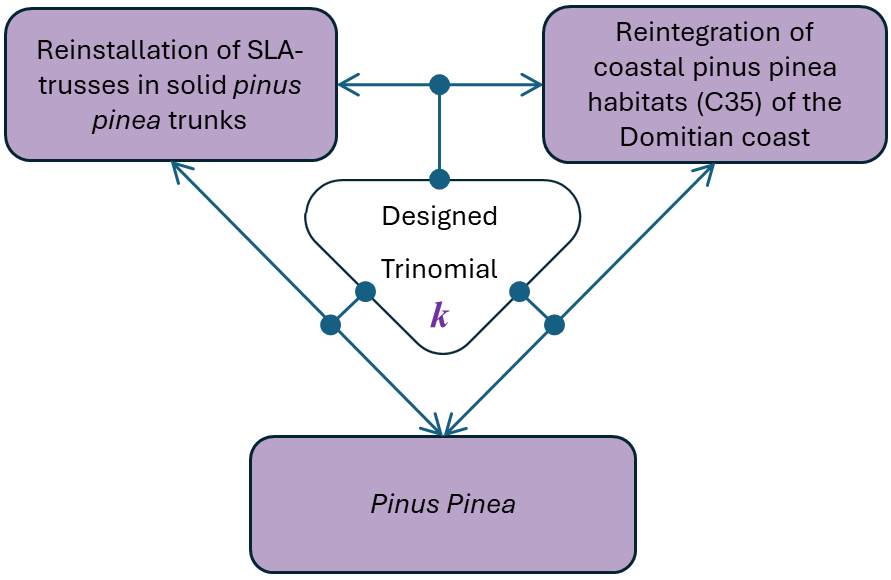


Figure 6: Outcome of the design of trinomial ***k***.

Design of the anthropogenic ecosystem restoration action

Assignment of $\boldsymbol{k}$ allows to move on to undertaking the problem of computing the resource-demand land-time ecosystemic metrics for reforestation and coppice activities corresponding to quantities S_{V} and S_{A} entering the flow-chart of Figure 1, which have to be equitably determined based on the struct-stainability principle.

This computation can be approached with the aid of the following synoptic symbolic ratio assignment:

$$\frac{Ecosystem\ metric}{Construction\ metric} := \frac{Pinus\ pinea\ habitats\ in\ the\ Volturnus\ Plain}{A-trusses\ of\ San\ Lorenzo\ ad\ Septimum's\ Aula\ Magna}. \qquad (1)$$

This ratio assignment can be developed by expanding its numerator into the two dual land allocations required for the SLV action and the SLA action. This results into the following synoptic prescriptive land-allocation design rule:

$$\frac{Ecosystem\ metric}{Construction\ metric} := \frac{\begin{pmatrix} Land\ for \\ reforestation \\ of\ Pinus\ pinea\ habitats \end{pmatrix} + \begin{pmatrix} Forestry\ land\ destined\ to \\ Pinus\ pinea\ silviculture\ for \\ the\ timber\ supply-chain \end{pmatrix}}{\begin{pmatrix} timber\ for\ wooden\ covers \\ of\ the\ Aula\ Magna\ di\ San\ Lorenzo \end{pmatrix}}. \qquad (2)$$

Indicating the soil quantities in the numerator by S_{V} and S_{A}, respectively, and the denominator by T, the design principle of struct-stainability translates into the following more compact writing:

$$\frac{Ecosystem\ metric}{Construction\ metric} := \frac{S_{\mathrm{V}} + S_{\mathrm{A}}}{\mathrm{T}}. \qquad (3)$$

The struct-stainability principle imposes the constraint of equitable distribution of resources which, in the present exercise, is simplified to a joint equal assignment of a same amount of land Λ, viz.: $S_{\mathrm{V}} := \Lambda =: S_{\mathrm{A}}$. Such an assignment implies $S_{\mathrm{V}} + S_{\mathrm{A}} = 2\Lambda$, so that Eq. (3) provides:

$$\frac{Ecosystem\ metric}{Construction\ metric} := \frac{2\Lambda}{\mathrm{T}}. \tag{4}$$

The operational rule for allocating soil resources, stemming from the algorithmic assignment procedure jut described, can be summarized into the following algorithmic steps:

Step 1. architectural-engineering metric calculation of T;

Step 2. technical-industrial-agronomic metric calculation of Λ as a function of T;

Step 3. assignment of land-time extension resources destined to anthropogenic restoration (separate management) $S_{\mathrm{V}} \coloneqq \Lambda$;

Step 4. allocation of land-time resources destined to coppice forestry $S_{\mathrm{A}} \coloneqq \Lambda$.

Resort to empirical and statistical dendrometry formulas for stone pine (Tassinari and Calzecchi - Onesti 1951) and use of empirical formulas and notions (Luca Damiani, Massaro, et al. 2024) lead to consider a model work log of truncated-cone shape (net of debarking, presumably between 3 and 6 cm thick) with a height of 14 m and end diameter of 75 cm corresponding to a taper of approximately 1 cm per metre of height. On the basis of this trunk model, the rational cutting plan can proceed from the contemplation of the sacrifice of two stone pine individuals in the coppice-allocated land. From two of these idealized work logs it is possible to esteem production of the elements in Table 1as well as of purlins and planking in sufficient quantity and adequate dimensions according to the specifications of the architectural metric calculation. Overall, for the Aula Magna, 32 trunks of Pinus pinea are required. The total work wood produced amounts to 71.4 m^3, while the waste wood amounts to 74.9 m^3, with a yield of approximately 49%. It should be noted that the waste volumes are still usable for other sectors of the wood supply chain, and that production surpluses of approximately 220% for planking and 310% for purlins are achieved compared to design needs.

The outcome of the struct-stainability-guided sizing for the San Lorenzo case study assignment is summarized in Figure 7.

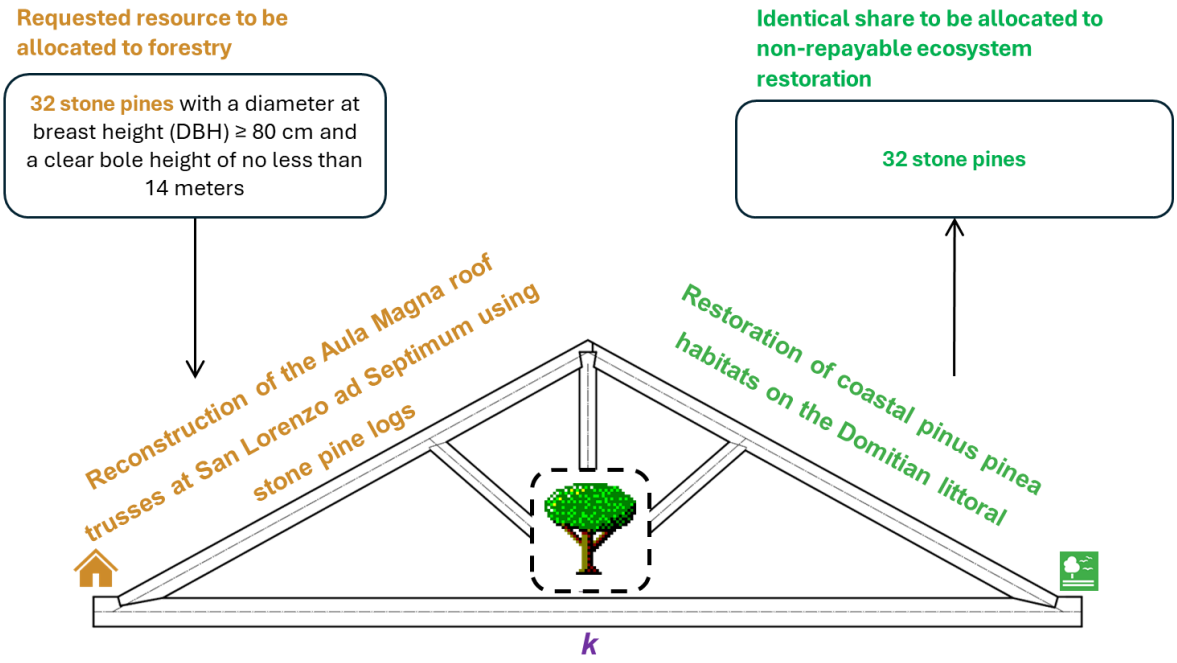


Figure 7: Outcome of the struct-stainability-guided sizing for the San Lorenzo case study assignment.

Forest planning parameters

To complete Step 2 it is necessary to proceed with the required sizing of the soil quantity 2Λ on agronomic and eco-metric bases. Herein, a simple pre-sizing is carried out of a quantity of soil Λ sufficient to produce 32 domestic pines in 60-80 years ensuring, at the end of this growth period, geometric and qualitative characteristics suitable for the budgeted cutting plan and adequate for the expected structural performance.

Such computation must take due account of the probability that, over the 60-70 years of growth, possible adverse events such as diseases and differences in pine growth parameters, or even calamities, such as lightning strikes or other natural events and external causes, can damage the pines and reduce the number of specimens meeting the design requirements. Applying a safety coefficient of 2, the quantity of soil to be placed for coppice forestry is

accordingly sized on a basis of 2×32=64 pines (

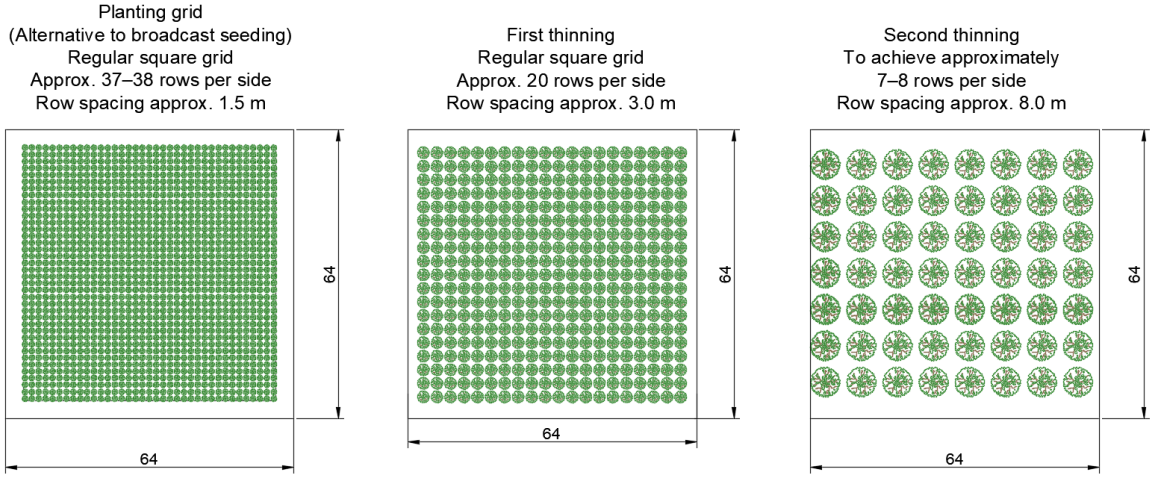


Figure 8). From this value, it is possible to schematically consider a regular 8 m × 8 m planting layout. Starting from broadcast seeding or grid planting with 30×30 rows at a spacing of approximately 1.5 m, it is possible to obtain 900 pines with a stem diameter of an average of 5 cm. After broadcast seeding, downstream of two thinning seedlings taking care of an appropriate selection of the best specimens, it is possible to finally achieve a grid with an average distance of 8 metres. This figure can be deemed sufficient to ensure full sun exposure for the tree canopies and for the transit of small mechanical vehicles and machinery. This approximate pre-sizing allows to end up with an estimated soil quantity of 64×64≅4100 m^2. The first thinning may occur after about 15 years, and a second after another 15 years.

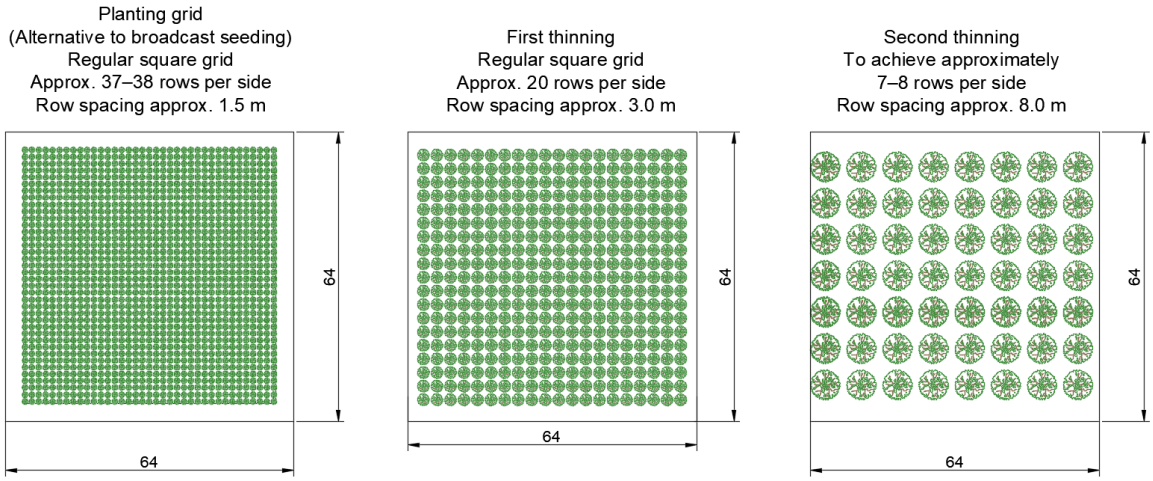


Figure 8: Designed spatial distribution of trees in a silvicultural pine stand following first and second thinning operations, from initial broadcast sowing on a 4,100 m² plot (Luca Damiani, Massaro, et al. 2024).

Turning the first aliquot Λ of soil, S_V, destined to anthropogenic ecosystem restoration (under separate management), while referring to specific botanical and zoological competences for ecosystem restoration and forest management specific to reforestation, it is recommended, on the basis of consultation of the CORINE database (Corine Biotopes 1991), the opportunity to privilege the location of the new pine forest in coastal or lake areas, in synergy with the restoration of aquatic and coastal habitats and psammophilous ecosystems of Campania, which, as registered in the Carta della Natura della Regione Campania, suffer from a condition of high if not very high fragility

Reforestation destined to the SLV action must involve direct seeding, the most widespread system for the stone pine, and plan for the fixation of shifting sands and the protection of the coastal dune on dunes and littoral sands. This should be achieved using live barriers (psammophilous herbaceous and shrub species by seeding or planting) and, where necessary, palisades, retaining structures, and coastal defense works. The management of soil S_V will have the primary objective of ecosystem restoration. Field experience from forestry operators in Calabria confirms that the pine is a highly rustic plant that takes root everywhere and that, except in very specific cases, does not require pre-treatment of the soil where it will be planted. Ecosystem restoration must also address with particular care the ecotonal transition zones between back-dune areas and coastal riparian and psammophilous habitats. This should be achieved by introducing species capable of providing cross-habitat structural stability, such as Tamarix gallica, in combination with other native species that can be effectively deployed in soil bioengineering techniques for coastal dune restoration

and reforestation interventions in coastal Mediterranean environments (Braschi 1951; Mareschi 2014; Romano et al. 2022).

Regarding the second soil portion, S_A, designated for silviculture, a reasonable choice for managing the designed high forest may favor the compound coppice system. This is recommended by Tassinari (Tassinari and Calzecchi - Onesti 1951) as a choice 'highly suitable in Mediterranean climates for heliophilous species' like the stone pine, also considering that the seed (pine nut) holds food and economic interest. A compound coppice management regime offers the advantage of greater soil protection (in terms of fertility and hydrogeological stability) while ensuring fewer pest attacks; however, it carries the disadvantage of producing structural timber of lower quality compared to other management systems.

Budgeting for specific agronomic and forest management expertise, along with the necessary labor force, will be required to plan intermediate cuttings, cleanings, weedings, and thinnings. These operations will simultaneously protect soil quality and biodiversity over the years, while preserving the quality of the produced timber. Furthermore, thinning operations must ensure that all seeded plants receive light primarily on their crowns and to a lesser extent on the trunk, in order to limit branching along the stem and the formation of knots, which are recognized as defects for structural timber applications. In the event of initial transplanting, particular care is recommended to avoid mutilating the root system, as this can cause plant stress and compromise height growth.

Results Summary and Discussion

The overall quantity of land determined by the design process illustrated in the previous sections for the assigned San Lorenzo's struct-stainability sustenance program amounts to 8200 m^2 destined to plantation of Pinus pinea, corresponding to 4100 m^2 allocated exclusively for reforestation for the sole purpose of ecosystem regeneration, plus

4100 m^2 allocated for coppice forestry activities with the necessary size expected to be reached after 70 years. This space-time metric of 8200 m^2 for 70 years is denominated the *San Lorenzo Unit* (SLU).

Figure 9 shows the 'resolved flowchart' providing the SLU, i.e., the flowchart showcasing the final values of the project variables which, downstream of the above illustrated design trade-off processes and agronomic and engineering computational subtasks, define the solution obtained for the San Lorenzo ''assignment'' as fine-tuned in the present case study.

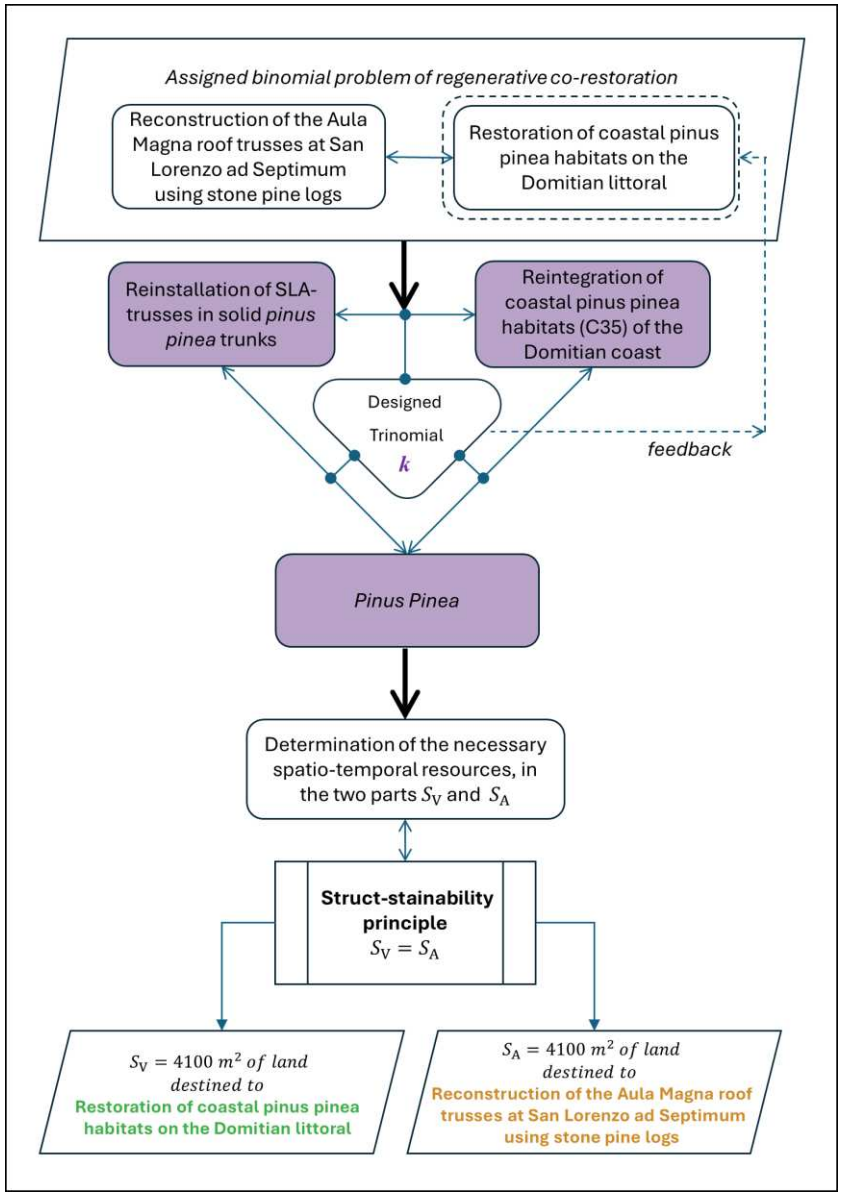


Figure 9: Resolved flowchart for the San Lorenzo assignment.

It must be acknowledged that the investigation path experienced in this case study leading to Figure 9 has implicitly relied on the creation of a feedback loop, in particular during the trinomial ***k*** design stage, that has directly influenced the same initial input design variables established at the baseline statement of the 'assigned' binomial problem of regenerative co-restoration. Actually, while this feedback (represented in Figure 9 by a dash-dot arrow) has substantially left unaltered the SLA action (San Lorenzo's roofing reconstruction), the SLV action, ultimately targeted on the restoration of pinus pinea habitats over the Domitian area, has been the result of a convergence process orbiting around the San Lorenzo gravitational pole (also definable, allowing for a broader lexicon within engineering language, individuation process or individuation journey). The scheme of the design process actually experienced in the present case study can accordingly be denominated *Construction-driven struct-stainability design*.

It is thus possible to conceptualize an exactly symmetrical design flow scheme which, starting from a predetermined and non-negotiable set of ecosystem goals and ecosystemic volume of structural species to be reintegrated, establishes a process for fine-tuning subordinate structural building engineering objectives. It appears natural to give the latter the name of *Biodiversity-driven struct-stainability design* or *Environment-driven struct-stainability design*.

Clearly, intermediate variants of these two complementary and bipolar design process-flow schemes can be also contemplated as well as design problems in which the structural building construction material volume or the ecosystemic volume of structural species are not a-priori assigned quantities and are instead the outcome of a process of optimization under different and less relaxed project constraints.

A first exercise pointing towards this typology of problem statements has been carried out in (Damiani et al. 2025) where a simplistic computational optimality model-problem based on metrics that evaluate performance in terms of synergistic anthropic and environmental benefit (Damiani et al. 2025) has been formulated and solved. The design problem considered consists in the determination of the transverse section dimensions of the frame elements of San Lorenzo's A-trusses (under seismic, wind and gravitational actions) which target the maximization of a Struct-Stainability Performance Metric (SSPM) by reducing cross-sectional dimensions while keeping the same wire-frame geometry of the current installation in the Aula Magna. The SSPM specifically employed by Damiani et al. (Damiani et al. 2025) is selected to be a balanced blend between a structural performance rate and a metric of required land extent to be preventively regenerated/transformed before construction. The structural performance rate is kept ordinarily defined as a demand/capacity work stress rate (WSR), based on the polytope transversely isotropic strength criterion proposed in (Luca Damiani, Di Gennaro, et al. 2024; Massaro et al. 2024) accounting for several failure mechanisms of wood, upon suitably tailoring such criterion on Italian stone pine. The complementary performance metric pondering the natural resources to be regenerated is determined as a demand/capacity ratio where the demand is computed after the scaled amount of wood necessary for the redesign of the A-truss geometry, and where the capacity is set to be 1 SLU (8200 m^2 and 70 years). Figure 10 illustrates the outcome of the exercise conducted in (Damiani et al. 2025). The horizontal axis reports the percentage reduction in the wood volume of one truss, achieved by uniformly scaling its transverse dimensions. On the vertical axis three performance metrics are reported. The first performance rate, w_{land}, is the metric of required land extent, defined as a demand/capacity ratio. Demand is computed as the scaled amount of soil required for the redesigned A-truss installation. The second one is a structural performance factor, w_s, normally defined as the

truss work rate. The third metric, denominated 'synergic performance factor', f_{sp}, is set as the product $f_{sp} = k \cdot (1 - w_s) \cdot (1 - w_{land})$ between the complement to unity of the two individual work rates, so that whenever any of the two individual performances is compromised the performance rating is zero. The quantity k is a constant irrelevant for the optimisation outcome. The optimality point found by Damiani et al. (Damiani et al. 2025) is attained at 30% reduction of structural sections.

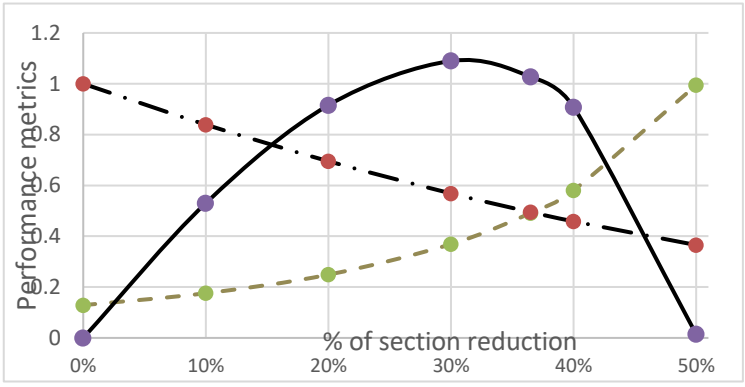


Figure 10: Dimensionless performance metrics: demanded land extent metric (dashdot line); structural Work Stress Rates (dashed line); synergic performance factor (solid line) (Damiani et al. 2025).

Conclusions

This study has proposed an interdisciplinary methodology, denominated *struct-stainability design*, for defining a sustainability metric supporting the joint engineering design of forestry operations and anthropic construction processes relying on forest-based supply chains.

The methodology has bridged design methods and geographically informed individuation processes and has integrated quantification of environmental regeneration needs and construction material demand starting from the *San Lorenzo's assignment*, which is the prospective solid-wood reconstruction of the *columna-capreoli* A-trusses of the

assembly hall of the Department of Architecture and Industrial Design of the University of Campania in Southern Italy. Proceeding through the relevant metric determination of dimensional and volumetric requirements of structural timber, and through alsometric analyses, the computed bill-of-quantities has been converted, via the *struct-stainability axiom*, into an equivalent estimated land-time metric for reforestation and land-use planning. The axiom equitably pairs anthropic transformation needs with anthropogenic ecosystem restoration and preservation needs.

Upon illustrating the methodology in its abstract form, confrontation with the SL assignment and with ecological restoration needs of the fragile habitats of *Piana Campana* have guided through an assessment of Pinus pinea restoration opportunities and land resource requirements in these territories, and have ultimately led to the definition of the *San Lorenzo land-time Unit*: $1\ SLU = 8200\ \mathrm{m}^2 \times 70$ years.

Although this quantitative outcome clearly depends on the specific assumptions adopted in the case study – namely, the San Lorenzo assignment, the use of solid timber elements, the ecological focus ultimately landing on Pinus pinea habitats in the Domitian Littoral – the knowledge gained in this study provides an encouraging proof of concept of the convergence of the proposed algorithmic schemes and experienced processes of design-individuation into well-defined actions of built environment regeneration.

The illustrated general methodology of *Struct-stainability design*, in its *Construction-driven* and *Biodiversity-driven* variants, appears naturally adaptable and scalable to other regional and wide-area case studies and to different interdisciplinary land design problems. It also appears to be deployable in design experiences aimed at reaching long-term sustainability goals, within the fields of forest and construction engineering, architecture, and urban planning. This deployment should ideally proceed through the

convergence of necessary complementary expertise from the mathematical, physical, and natural sciences, with a particular emphasis on botanical and zoological disciplines.

Future research will further expand the applicability of the struct-stainability paradigm by investigating additional case studies of Campania Felix's heritage-protection, having ecosystemic, architectural and engineering relevance, examining other structural typologies such as engineered wood and timber floor systems.

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Data Availability Statement

The authors declare that the data supporting the findings of this study is available within the article and in the cited references.

Compliance with Ethical Standards

Disclosure of potential conflicts of interest

All authors declare that they have no competing interests.

Research involving Human Participants and/or Animals

All authors declare that this research did not involve human participants or animals.

Informed consent

This statement does not apply.

References

Acosta A, Ercole S, Stanisci A, Pozzi J, Blasi C, Izzi CF. 2007. Coastal sand dune vegetation under human pressure under the Mediterranean macrobioclimate. J Coast Res. 3(23):751–761.

Bagnaia R, Viglietti S, Laureti L, Giacanelli V, Ceralli D, Bianco P, Loreto A, Luce E, Fusco L, Resicato B, et al. 2017. Carta della Natura della Regione Campania: Carta degli habitat alla scala 1:25.000. ISPRA, 2017. [Internet]. [accessed 2024 Jun 17]. https://www.isprambiente.gov.it/it/servizi/sistema-carta-della-natura/cartografia/carta-della-natura-alla-scala-1-50.000/campania.

Berg S, Athanassiadis D. 2020. Opportunity cost of several methods for determining forest biomass terminal locations in Northern Sweden. International Journal of Forest Engineering. 31(1):37–50. https://doi.org/10.1080/14942119.2019.1616424

Biondi E, Blasi C, Burrascano S, Casavecchia S, Copiz R, Del Vico E, Galdenzi D, Gigante D, Lasen C, Spampinato G, et al. 2012. Italian Interpretation Manual of the European Union Habitats.Ministero dell'Ambiente e della Tutela del Territorio e del Mare, editor. Ministero dell'Ambiente e della Tutela del Territorio e del Mare, Roma.

Blasi C, Zavattero L, Capotorti G, Bonacquisti S, Copiz R, Del Vico E, Falcioni L. 2023. Lista Rossa degli Ecosistemi d'Italia.

Braschi B. 1951. Piante arboree arbustive e perenni da usare nelle località marine. In: TASSINARI G, editor. Manuale dell'Agronomo. Roma: Ramo Editoriale degli Agricoltori.

Butera Federico. 2021. Affrontare la complessità : per governare la transizione ecologica. Edizioni Ambiente. Milano.

Calandrelli M, Migliozzi A. 2023. History of degradation and rebirth of a coastal pine forest. Forest@ - Rivista di Selvicoltura ed Ecologia Forestale. 20(5):73–80. https://doi.org/10.3832/efor4386-020

Cavalieri San Bertolo N. 1831. Istituzioni di Architettura, Statica e Idraulica. Mantova.

Cennamo C, Di Gennaro L, Frunzio G, Massaro L. 2025. Modeling a Double-Shell Dome Inter-connected with a Wooden Structure: San Gennaro Chapel in Naples. International Journal of Space Structures. https://doi.org/10.1177/09560599251333277

Cennamo C, Di Gennaro L, Massaro L, Frunzio G. 2025. Domes and Earthquakes of Naples: A Comparative Study of Baroque and Neoclassical Structure. Buildings [Internet]. 15(12):2008. https://doi.org/10.3390/buildings15122008

Corine Biotopes. 1991. EUR 13231 - The design, compilation and use of an inventory of sites of major importance for nature conservation in the European Community. Luxembourg.

Damiani L., Di Gennaro L, Frunzio G, Massaro L, Sallicandro E, Serpieri R. 2024. Enhancing past rules of the art for sustainable design of columna-capreoli wood trusses. In: Proceedings of XXVI AIMETA Conference 2024. Naples. https://doi.org/https://doi.org/10.1007/978-3-032-17231-0

Damiani Luca, Di Gennaro L, Frunzio G, Massaro L, Sallicandro E, Serpieri R. 2024. A transversely-isotropic polytope strength criterion for wood and multipurpose optimal design. In: Proceedings of XXVI AIMETA Conference 2024. Naples. https://doi.org/https://doi.org/10.1007/978-3-032-17231-0

Damiani Luca, Massaro L, Frunzio G, Serpieri R. 2024. Scienza del progetto, della costruzione e della natura sulle orme di Plinio per il sostenta-mento della Campania Felix – Un percorso di indagine. In: Valtrend Editore, editor. Rivista di Studi Pliniani (A cura di ALuciano), ISSN 2785 5856. Vol. 4. Napoli.

Damiani L, Sallicandro E, Massaro L, Frunzio G, Serpieri R. 2025. STRUCT-STAINABILITY ASSESSMENT OF THE COLUMNA-CAPREOLI A-TRUSSES OF THE SAN LORENZO AD SEPTIMUM MONASTERY AULA MAGNA. :2772–2782. https://doi.org/10.7712/120125.12608.25345

Fernandez-Lacruz R, Grönlund Ö, Johannesson T, Djupström LB, Söderberg J, Eliasson L. 2023. Harvester time consumption in nature conservation management operations. International Journal of Forest Engineering. 34(2):112–116. https://doi.org/10.1080/14942119.2023.2174353

Frunzio G, Rinaldi S, Guadagnuolo M, Massaro L, Di Gennaro L. 2022. Use of engineered wood for the retrofitting of existing structures. WIT Transactions on the Built Environment. 210:225–236. https://doi.org/10.2495/ARC220191

Gasparini P, Di Cosmo L, Floris A, De Laurentis D, editors. 2022. Italian National Forest Inventory–Methods and Results of the Third Survey. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-98678-0

Gasparini P, Di Cosmo L, Floris A, Notarangelo G, Rizzo M. 2016. Guida per i rilievi in campo. INFC2015 – Terzo inventario forestale nazionale. [Internet]. [accessed 2024 Apr 11]. https://www.inventarioforestale.org/it/statistiche_infc/

Di Gennaro L, Faella G, Guadagnuolo M, Frunzio G, Massaro L. 2025. Dynamic Assessment of Timber Floor Strengthening with Post-tensioned Wire Rope. Protection of Historical Constructions: Proceedings of Prohitech 2025 (Lecture Notes in Civil Engineering #596). 2. https://doi.org/https://doi.org/10.1007/978-3-031-87312-6_34

Heräjärvi H, Jouhiaho A, Tammiruusu V, Verkasalo E. 2004. Small-Diameter Scots Pine and Birch Timber as Raw Materials for Engineered Wood Products. International Journal of Forest Engineering. 15(2):23–34. https://doi.org/10.1080/14942119.2004.10702494

Iaderosa R, Massaro L, Frunzio G. 2024. Forest management for urban environment-nature connection. DISEGNARECON. 17(33). https://doi.org/10.20365/disegnarecon.33.2024.12

ISTAT. 2026. Indice ISTAT costo di costruzione fabbricato residenziale: Aprile 2026 [Internet]. [accessed 2026 Jul 10]. https://www.rivaluta.it/aggiornamento-calcolo-indici-costruzione.asp

Jacazzi D. 2009. Il sito di San Lorenzo ad Septimum sulla via Campana. In: Le Vie dei Mercanti Cielo dal Mediterraneo all'Oriente. Capri, Naples, Italy: Edizioni Scientifiche Italiane.

Kühmaier M, Schweier J, Sibiya Z, Marchi E, Laschi A, Grünberg J. 2025. The connection between Sustainable Development Goals (SDGs) and forest operations research. International Journal of Forest Engineering. 36(2):222–236. https://doi.org/10.1080/14942119.2025.2469199

Lorenzini G, Nali C. 2013. Il pino domestico. Elementi storici e botanici di una preziosa realtà del paesaggio mediterraneo. Giardini e paesaggio. Firenze.

Marcea RL, Lau KK. 1992. Carbon Dioxide Implications of Building Materials. Journal of Forest Engineering. 3(2). https://doi.org/10.1080/08435243.1992.10702637

Mareschi L. 2014. Interventi di riforestazione nelle aree costiere: analisi dell'impiego di Tamarix spp. nel litorale ravennate. Silvae (Rivista tecnico-scientifica ambientale dell'Arma dei Carabinieri - ex Corpo Forestale dello Stato) [Internet]. [accessed 2026 Oct 30]. https://www.carabinieri.it/media---comunicazione/silvae/la-rivista/aree-

tematiche/monitoraggio-del-territorio/interventi-di-riforestazione-nelle-aree-costiere-analisi-dell-impiego-di-tamarix-spp.-nel-litorale-ravennate

Massaro L, Di Gennaro L, Frunzio G, Sallicandro E, Serpieri R. 2024. Understanding past rules of the art in columna-capreoli wood trusses. Developments in the Built Environment. 19. https://doi.org/10.1016/j.dibe.2024.100472

Massaro L, Di Gennaro L, Guadagnuolo M, Frunzio G, Faella G. 2026. ENGINEERED WOODS FOR SUSTAINABLE USE OF LOCAL RESOURCES. International Journal of Conservation Science [Internet]. [accessed 2026 Mar 23] 17(1):291–306. https://doi.org/10.36868/IJCS.2026.01.17

Massaro L, Serpieri R, Frunzio G, Di Gennaro L. 2023. Timber carpentry without steel connectors. COMPDYN Proceedings [Internet].:3203–3212. https://doi.org/10.7712/120123.10633.20422

Ministero delle Infrastrutture e dei Trasporti. 2018. Norme tecniche per le costruzioni (D.M. 17 gennaio 2018). Gazzetta Ufficiale della Repubblica Italiana, 42, Suppl. Ord. n. 8. [Internet]. [place unknown]; [accessed 2026 May 19]. https://www.gazzettaufficiale.it/eli/id/2018/2/20/18A00716/sg

Morelli G, Raimbault P. 2011. Pino domestico in ambito urbano. Un cittadino sconosciuto. In: Vol. 3/2011. Bresso: Acer; p. 20–30.

Morelli G, Raimbault P. 2014. Il pino domestico (Pinus pinea L.). Un cittadino sconosciuto. In: Monza: Arbor, 2, Società Italiana di Arboricoltura; p. 14–26.

Plinio Secondo, G. 1982. Storia naturale. Einaudi (Original work published 77–79 AD).

Roijen E Van, Miller SA, Davis SJ. 2025. Building materials could store more than 16 billion tonnes of CO2 annually. Science (1979). 387(6730). https://doi.org/10.1126/science.adq8594

Romano G, Ricci GF, Leronni V, Venerito P, Gentile F. 2022. Soil bioengineering techniques for Mediterranean coastal dune restoration using autochthonous vegetation species. J Coast Conserv. 26(6):71. https://doi.org/10.1007/s11852-022-00912-0

Rondelet J. 1834. Trattato teorico e pratico dell'arte di edificare. [place unknown].

Salmivaara A, Miettinen M, Finér L, Launiainen S, Korpunen H, Tuominen S, Heikkonen J, Nevalainen P, Sirén M, Ala-Ilomäki J, Uusitalo J. 2018. Wheel rut measurements by forest machine-mounted LiDAR sensors – accuracy and potential for operational

applications? International Journal of Forest Engineering. 29(1):41–52. https://doi.org/10.1080/14942119.2018.1419677

Strumia S. 2004. Contributo alla conoscenza delle cenosi forestali ripariali del fiume Volturno (Campania). Delpinoa ns. 46:63–70.

Tassinari G, Calzecchi - Onesti A. 1951. Manuale dell'agronomo, Ramo editoriale degli agricoltori, Roma. Roma.

United Nations Environment Programme. 2025. United Nations Environment Programme (2025). Global Status Report for Buildings and Construction 2024/2025: Not just another brick in the wall: The solutions exist - Scaling them will build on progress and cut emissions fast. Global Status Report for Buildings and Construction 2024/2025. https://doi.org/10.59117/20.500.11822/47214

United Nations General Assembly. 2015. United Nations, The 2030 Agenda and the Sustainable Development Goals.

Vitousek PM, Ehrlich PR, Ehrlich AH, Matson PA. 1986. Human Appropriation of the Products of Photosynthesis. Bioscience. 36(6). https://doi.org/10.2307/1310258

Williams M. 2003. Deforesting the Earth: From Prehistory to Global Crisis. University of Chicago Press, Chicago, 2003.