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STRUCT-STAINABILITY ASSESSMENT OF THE COLUMNA-CAPREOLI A-TRUSSES OF THE SAN LORENZO AD SEPTIMUM MONASTERY AULA MAGNA

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Abstract

Original methodologies are proposed for formulating and solving optimization design problems concerned with the hazard assessment of a hypothetical solid wood replacement of the restored columna-capreoli A-trusses of the Aula Magna "Alfonso Gambardella" of the ancient monastery complex of San Lorenzo ad Septimum in Aversa, currently hosting the Department of Architecture and Industrial Design of the University of Campania "Luigi Vanvitelli". The study addresses a twofold struct-stainability performance evaluation contemplating both the structural hazard originated from natural combined gravitational and dynamic actions, and the demand related to dynamics of anthropic/anthropogenic ecosystem consumption/transformation, in a scenario of short wood supply chain within the Piana Campana area. Both the contemplated hazard scenarios appear meaningful since: 1) the complex has suffered significant earthquake damage between 1456-1457, and 2) dedicated environmental studies by ISPRA/ARPAC elucidate a worrying condition of very high fragility for most of the lake, river and coastal ecosystems of the Piana Campana as well as an 'endemic' fragility condition for most of its territory.
Encompassing both hazard perspectives, the optimization problems considered herein address the optimal choice between open- and closed-node solutions for the kingpost-strut A-trusses of the installation. Performance analyses have been carried out with the aid of an object-oriented in-house-developed multipurpose structural analysis code (MORES), employing finite-element formulations with a transversely isotropic structural model for wood based on a polytope strength criterion which has been calibrated from data made available from the military aeronautic industry and which has been suitably experimentally and numerically validated.

Keywords: Struct-stainability Dynamics, Optimal Design, Structural Design, FE Method.

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1 INTRODUCTION

For civil engineering design purposes, construction science typically confronts with dynamic actions in terms of effects of wind and earthquake excitations entering as input data in computational problems concerned with the prediction and optimization of structural response under established design performance metrics which usually critically affect the project outcome as much as functional and architectonic project requirements. In the past, along the trend of primarily framing planetary resource consumption in an anthropic development perspective, the metrics assigned for design optimization have more frequently essentially pointed to human profit/benefit maximization alone, such as minimization of human economic costs. Evidence from evergreen system-dynamics computational studies of the seventies of the past century on the limits to human growth in relation to planetary resource bounds [1] and recent updates to Article 9 of the Italian Constitution [2] (which today places environment, biodiversity and ecosystems protection altogether in the interest of all timeline generations jointly with landscape, historical and artistic heritage protection and development of culture and scientific and technical research) have stimulated the groups of science of design and construction of the University of Campania Luigi Vanvitelli to computationally investigate novel sustainability metrics for the development of the built environment of the territories of Piana Campana [3] based upon the concept of *struct-stainability* [4]. Struct-stainability (a neologism proposed as a lexical blend in English of the words structural and sustainability) deploys in design problem analysis suitable optimization metrics formulated in terms of soil, time and resources to be allocated, in one partition, to ecosystem restoration in order to support the reintegration of suitably selected biodiversity thresholds and, in a second equal partition, to support the material supply chain destined to the designed anthropic construction work [5,6].

In [3], the identification of a meaningful struct-stainability metric has been achieved as the outcome of an interdisciplinary investigation. By proceeding from global scale to Italian and Tyrrhenian scales to focus in greater detail on some regional Campanian emergencies, analyses of records of fragility conditions of ecosystems, biotopes and habitats [7-10], have allowed to identify *pinus pinea* habitats in Campania as a meaningful ecosystemic target to ponder an endangered or trespassed threshold requiring anthropogenic restoration.

Concerning the secondary term, which is the anthropic transformation object of design, in [4] a model problem has been defined by contemplating the case study of the replacement in solid wood of the A-trusses bearing the roof San Lorenzo's Aula Magna of the Department of Architecure and Industrial Design (DADI) of the Università degli Studi della Campania "Luigi Vanvitelli" of Fig.1 [12]. Keeping a primary focus over the following ratio assignment:

$$\frac{Ecosystem\ metric}{Construction\ metric} = \frac{\substack{Italian\ Stone\ Pine \\ Habitats\ in\ Campanian/Volturnus\ plane}}{\substack{A\text{–}trusses\ of\ San\ Lorenzo's \\ Aula\ Magna}}, \tag{1}$$

a determination of the volume and dimensions required, in length and section, of the trunks for the San Lorenzo design model problem has been carried out, followed by technical, dendrometric and cormometric analyses, and by computer-aided structural and stress analyses. These research activities have permitted to gather sufficient evidence ultimately leading to the identification the use of solid Italian stone pine (*pinus pinea*) wood as a meaningful term for proposing a schedulable land-regeneration program hinged on the allocation of one partition of soil for reintegration of biodiversity thresholds in *pinus pinea* habitats in the Campanian/Volturnus plane, and of another equal partition to forestry activities in coppice supplying the construction material for a far future replacement of the A-trusses of San Lorenzo's Aula Magna (former Aula S3, recently named after the first faculty dean Alfonso Gambardella).

The computed amount of soil quantified in [3] for this planned joint sustenance program amounts to 8200 m^2 allocated for pinus pinea plantation, corresponding to 4100 m^2 destined to reforestation for ecosystemic regeneration purposes alone, plus 4100 m^2 destined to forestry activities in coppice. This 8200 m^2 soil area has been baptized as *one San Lorenzo's soil unit* and is henceforth referred to in short as 1 SLu.

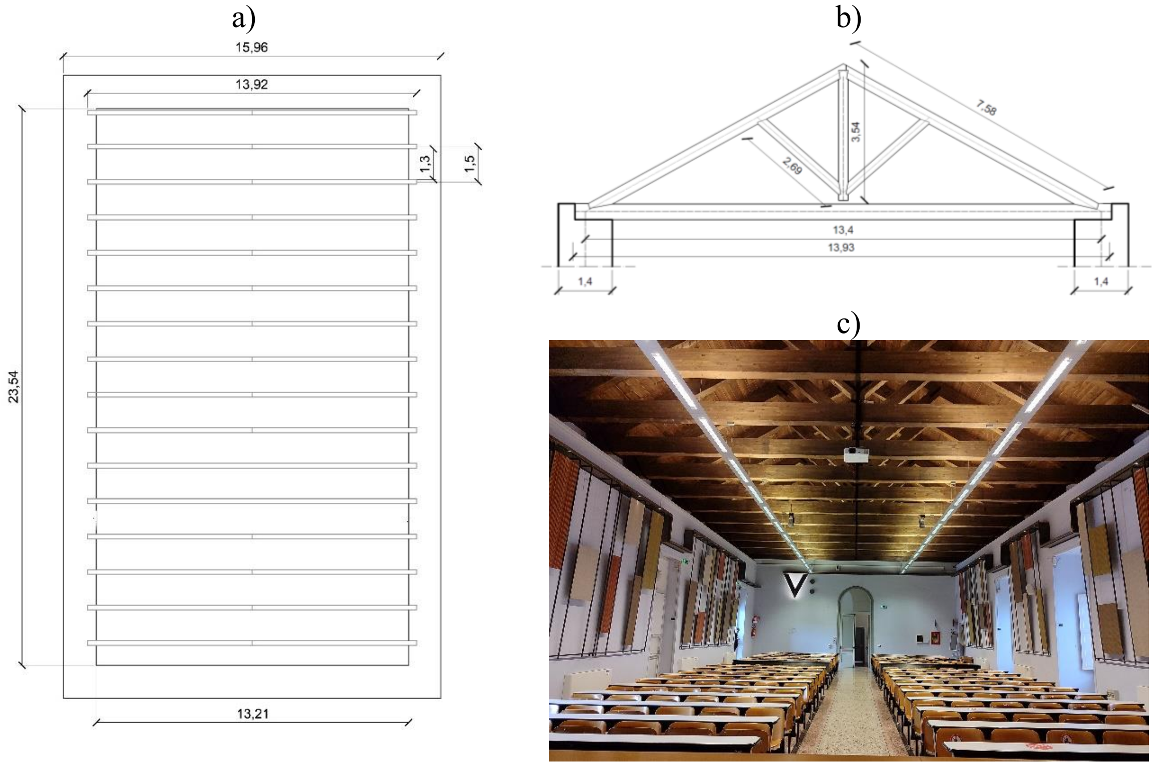

Figure 1: Trusses of the lecture hall of San Lorenzo ad Septimum; a) plan view of the current glulam installation; b) front view sketch of one truss; c) view of the Aula Magna.

In this contribution a computational optimization problem is proposed, consisting of the design of the transverse section dimensions of the frame elements of San Lorenzo's A-trusses under 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 SSPM specifically employed in the present study is set as a balanced blend between a structural performance rate and a metric of required land extent to be preventively regenerated/transformed before construction. The proposal herein investigated is to keep the structural performance rate ordinarily defined as a demand/capacity work stress rate, specifically based on the polytope transversely isotropic strength criterion proposed in [4] upon suitably tailoring such criterion on Italian stone pine, and to define the latter metric determination as a demand/capacity ratio where the demand is computed after the scaled amount of wood necessary for the redesigned A-truss installation, and where the capacity is set to be 1 SLu.

In the following, after briefly recalling the geometric model of the current installation and the employed strength and stiffness models, and after presenting the data employed for Italian stone pine strength, sizing of dynamic inputs is briefly reported. After proposing the specific choices for the parametric analyses, the optimization rationale is described, and relevant results are illustrated and discussed.

2 STRUCTURAL MODEL

The installation selected as case study is located on the second floor of San Lorenzo ad Septimum, a benedictine monastery complex in the municipality of Aversa situated along the ancient Via Campana, founded around 1000 A.D., currently hosting DADI. The installation consists of 16 glued laminated timber A-trusses bearing the roof of the great plenary hall which serves today as Aula Magna of DADI. The trusses belong to the open-noded Vitruvian canon with kingpost and struts.

Survey of the installation could allow to reconstruct the geometric model of Figs.1a and 1b with element section dimensions and wood volume summarized in Table 1.

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 in [4], the employed stiffness and strength models are respectively constructed, as a first step, as a transversely isotropic conservative adaptation of the full set of orthotropic stiffness data that is comprehensively supplied in [13] for spruce, light mahogany, ash and walnut, and of orthotropic strength data that the same source supplies for spruce. As a result, for spruce the longitudinal Young modulus is $E_L = 13.44$ GPa and the adapted input strength data are in MPa: $\sigma_{R+} = \sigma_{T+} = 2.76$, $\sigma_{L+} = 124.11$, $\sigma_{R-} = \sigma_{T-} = -4.14$, $\sigma_{L-} = -34.47$, $\bar{\tau}_{RT} = 2.07$, $\bar{\tau}_{TL} = \bar{\tau}_{LR} = 7.58$. As a second step, a conservative adaptation to Italian stone pine of this basic spruce model is obtained accounting for data reported in [14] from which a ratio (Italian stone pine)/spruce 0.937 can be computed for compressive axial strengths and corresponding ratios of 0.888 and 0.778 can be computed for tensile axial strengths and shear strengths, respectively. Material stiffness reduction has been deemed irrelevant for the outcome of this preliminary stress analysis study, given the linearity of the structural model, the adoption of uniform material properties in all frame elements, and the absence in the analysis herein presented of an evaluation of the deformability performance.

Latest Italian technical standards for construction [15] have been considered as a primary, yet non-exclusive, reference for load sizing.

Concerning gravitational actions, truss self-weight has been modeled by uniformly distributing the entire truss weight over the roof beams. Such load combined with permanent loads over the roof beams amounts to 2.775 kN/m. Snow actions, though also computed as per standard definition, have not been included in the load combination selected for the optimization problem herein discussed to give prominence to the analysis of dynamic actions with permanent gravitational loads alone.

For dynamic inputs, wind and seismic loads have been modeled, as provided by NTC 2018 [15], in terms of static equivalent actions upon conventionally setting a nominal lifetime of

2000 years for the site of San Lorenzo, assumed to be inheritable by any key installation of structural and architectonic importance in the perimeter of the abbey. This life requirement is prescribed for several reasons. On the one hand such value stems from the simple perspective of compliance with standards: aside to considerations of the significant crowding the facilities are subjected to, for the important public school educative, academic as well as religious function that the structure holds and has held for centuries. On the other hand, aside to engineering technical norms, such lifetime is clearly motivated by the historical, cultural, architectonic, and religious merit of San Lorenzo ad Septimum abbey. The credibility of such long lifetime for the preservation of a wooden roof also seems not unrealistic, considering that there exists evidence of the fully-preserved sixth-century trussed wooden roof of the church of St. Catherine monastery at Mount Sinai [16], and believing that careful ordinary maintenance and technological development can support such a provision (which is also mostly desirable for sustainability in a planned land-use in a long time-range perspective).

For wind, according to chapter 3.3 of NTC 2018, the input data considered for unit load computation, as per technical code specifications, are: 1) Campania being situated in zone 3 of the relevant Italian zonation for determining wind actions, yielding to a baseline reference velocity at sea level of 27 m/s, and 2) the average altitude above sea level of Aversa of 39 m. Further figures are: 1) a conventional return period for wind actions set to the default value $T_R = 50$ years (common to all environmental actions, as per norm specifications); 2) a ground roughness category 'A'deemed attributable given the quite dense urban fabric of San Lorenzo district; 3) the distance the territory of Aversa from the Campanian coast ranging between 20 and 30 km. This data and information allow to attribute to the site an exposition category 'IV' which, combined with the roof ridge height estimated in 25 m, yields an exposition coefficient of 2.45. Retrieval of formulas for aerodynamic and pressure coefficients, now available in ministerial circular 2019 21/01/2019 n.-7, allows to bound exposition pressure coefficient between a minimum downwind value of -1.0 and a maximum upwind value of 0.5 respectively corresponding for unit pressures to bounds of 0.558 kN/m^2 positive pressure and a negative pressure -1.116 kN/m^2 (see Fig. 2) while frictional tangent actions appear negligible, as far as the purpose of this study is concerned, for being less than 0.05 kN/ m^2

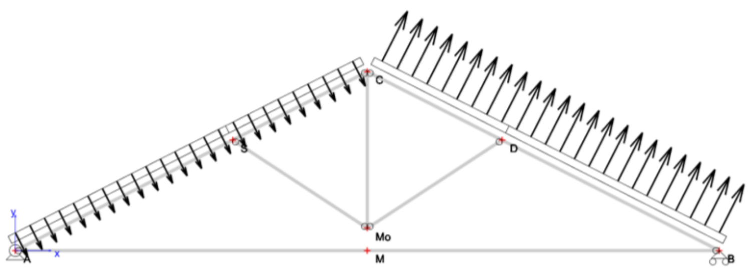

Figure 2: Wind load case.

The determination of earthquake actions for San Lorenzo ad Septimum site deserves sufficient attention, aside for the simple matter of applying engineering procedures in compliance with currently applicable laws and ever changing-technical standards, for the prominence of protecting a historical site, since the abbey has suffered significant earthquake damage between 1456-1457 [17]. Unit seismic loads have been also primarily sized upon NTC 2018 technical procedures. This investigation has ascertained the unavailability of direct quantitative records for ground acceleration over a time period meaningfully comparable to the nominal lifetime of

2000 years required for the project. Examination of the presumably extremal seismic event over the Campanian plane territory, the earthquake in south-central Italy of December 1456 (deemed by some sources to be the strongest earthquake recorded in Italy during the second millennium) could not allow, in the opinion of the authors, retrieval of sufficient information to express any quantitative inference. Historical reports also provide mixed judgements of the extents of damage caused by the 1456-1457 earthquake over places directly or indirectly relatable to the territory of Aversa. Just to report two short excerpta in Italian and Latin by Giannozzo Manetti one may quote hereafter: *à fatti varii danni, secondo la varietà de' siti e lla qualità d'edificii, e grande e innistimabile 'vasione degli abitanti*"; [18] "*A Caieta itaque initium sumentes: eam ipsam cum Nola ac Suessam, duas vetustas urbes, et Theanum quoque ac Calenum; et Casinum pariter, antiqua opida, eos ipsos terremotus cum paucorum damnorum susceptione, per universam agrum audivisse dicimus*" [19].

The considerations above point out the difficulty which is encountered when, for the purpose of the present study, one attempts to obtain from the somehow fragmentary and partially inconclusive information retrievable from historical records, quantitative inferences which may allow to attribute, in a scientifically meaningful way, either an excess probability P_{V_R} or a conventional return period T_R to a determination of ground acceleration for the site of Aversa over a time window meaningfully comparable with the assigned structure lifetime of 2000 years.

Based on the above considerations, the same common 50-year return period, specified as default value by NTC 2018 for all other environmental actions (wind, snow and temperature), has been applied to size earthquake actions.

As per seismic design prescriptions in chapters 3 and 7 of NTC 2018, which also refer to annexes of DM of Infrastructures 14/01/2008, consultation of Table 2 in annex B at rows ID 32756 and 32534 (corresponding to detailed geographic determination of two reference grid points closest to the site of San Lorenzo) and at the column associated with the default value of $T_R = 50$ years yields a maximum horizontal acceleration expected at the site $a_g < 0.06\,g$.

Adopting the simplified approach, the subsoil category A "Outcropping rock masses and very stiff soils" is determined based on topographic surface features (though without specific geotechnical inspections), based on the essential consideration that Aversa is built on the plain on tuff deposits from ancient eruptions, and that the monastery is founded below 3 meters, above semilitoid Pozzolana banks and tuff banks. On this basis, the stratigraphic amplification coefficient S_S which accounts for the subsoil category is determined into a unitary value. Similarly, the coefficient of topographic amplification is also given by the norm a value $S_T = 1.0$ since Aversa is situated in the Campanian plane and the site of San Lorenzo is a flat area. Accordingly, being $S = S_S S_T = 1$, the condition posed by NTC 2018 $a_g S \leq 0.075$ is satisfied so that determination of horizontal force F_H is ultimately led to $F_H = 0.10W\lambda$ where λ can be conservatively set to the supremum value of 1.0 among the several computation options provided by the Italian norm.

It is worth observing that this final determination of unit seismic actions appears to remain conservatively bounded within ranges inferable for the site of Aversa from some past Italian technical recommendations, such as the Ministerial Decree 16/02/1996 technical regulations for construction in seismic zones.

Table 2 summarizes all the above determined unit input values. These values have been employed in the structural analyses for the struct-stainability optimization problem reported in the following section.

Action		Unit Input Values		Selected coefficient of combination
Gravitational permanent	G_1+G_2	2,775	kN/m	1,0
Snow	Q_2	0,720	kN/m	0,1
Wind (positive pressure)	Q_{1+}	0,837	kN/m	0,6
Wind (negative pressure)	Q_{1-}	-1,674	kN/m	0,6
Seismic	E	0,277	kN/m	1,0

Table 2: Unit Input Values considered.

In the struct-stainability problem investigated in this contribution a single load combination is considered suitably devised to synthetically account for both effects of wind and seismic loads acting in the truss plane alone. A linear static 2D model of the truss response to wind loads (Q_1) and seismic loads (E), plus permanent loads G_1+G_2 is considered, representing all actions in terms of uniform vertical and pressure loads over the pitch beams. This combination, which is tailored from the several ones provided by Italian technical regulations and required by a full engineering design of the installation, is expressed by:

$$Load\ combination\ of\ the\ present\ study = G_1 + G_2 + E + \psi \cdot Q_1, \qquad (2)$$

where coefficient ψ is deliberately given the value of 0.6 irrespective of any norm provision or statistic consideration. A comparison between an open node truss model and a closed node model has been also carried out. Figure 3 illustrates the loads of combination (2) over the closed node model.

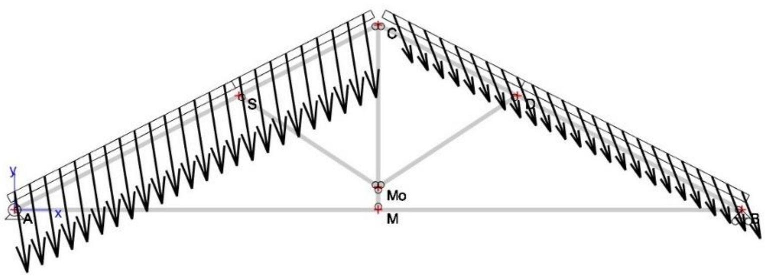

Figure 3: Combination of the load cases analyzed.

3 RESULTS

Figs. 4 and 5 respectively show the bending moment diagrams over the open- and closed-node structures corresponding to the basic currently installed geometry. Albeit the additional flexural demand of the tie in the closed node typology is clearly appreciable, the computed Work Stress Rates (WSR) show an almost identical maximum WSR of about 13% in the two typologies. Figure 6 exemplifies the deformed shape of the open node solution.

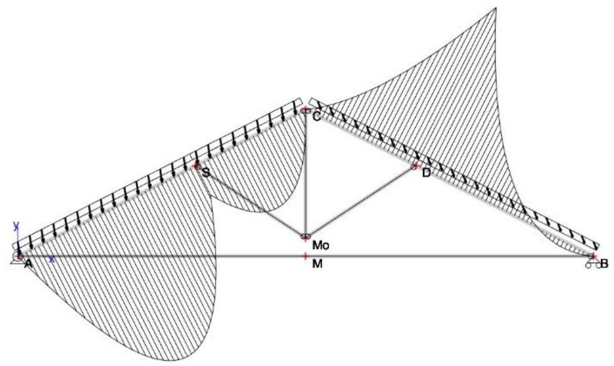

Figure 4: Open-node, bending moment.

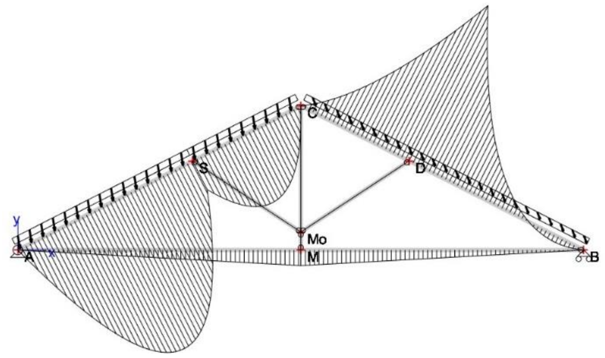

Figure 5: Closed-node, bending moment.

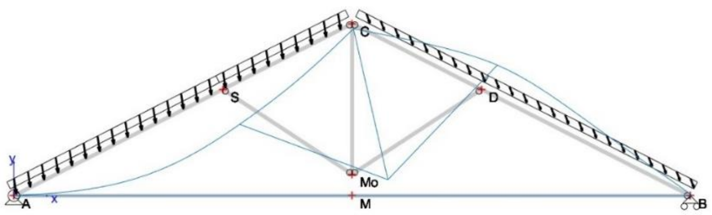

Figure 6: Deformed open-node structure.

Figure 7 shows the results of the optimization problem. The horizontal axis is associated with the percentage of section reduction of the wood volume of one truss by uniformly scaling the transverse dimensions of its elements. 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. The demand is computed after the scaled amount of soil destined to pinus pinea plantation necessary for the redesigned A-truss installation, while the capacity at the denominator is conventionally set to be one San Lorenzo unit, i.e., to 8200 m^2. The second one is an ordinary structural performance factor, w_s, normally defined as the truss work rate. The third metric, denominated 'synergic performance factor' f_{sp} is defined as the product $f_{sp} = k \cdot (1 - w_s) \cdot (1 - w_{land})$ as the product between the complement to unity of the two individual work rates (k being a constant irrelevant for the optimization outcome), so that whenever any of the two individual performances is compromised the performance rating is zero. In this model problem optimality is found to be achieved at a 30% reduction.

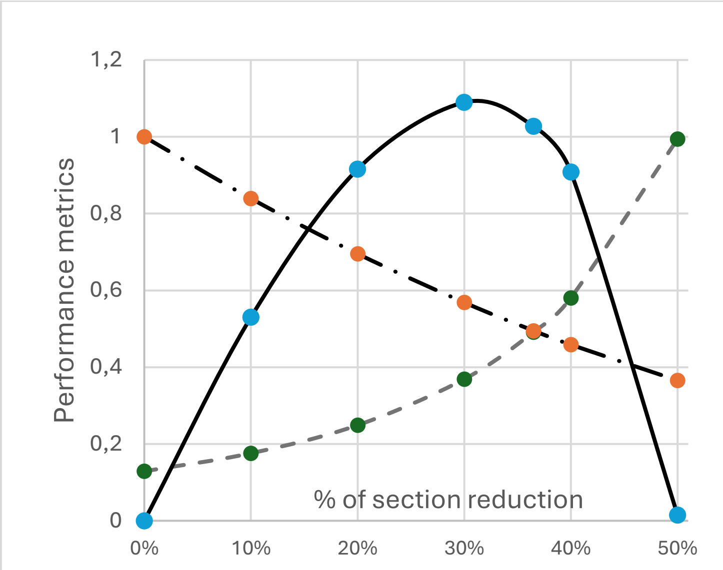

Figure 7: Dimensionless performance metrics: demanded land extent metric (dashdot line); structural WSR (dashed line); synergic performance factor (solid line).

4 CONCLUSIONS

- In the struct-stainability model problem herein considered, optimality is found to be achieved at a 30% section reduction of the structure.
- While this result is obviously sensitive to the specific choices made for the investigated case study, and thus primarily to the choices made on constructive material resources (solid wood elements), on the specific contemplated ecosystem resources (pinus pinea habitats), and on the selected constructive problem of San Lorenzo's Aula Magna roof truss replacement, the rationale and philosophy explored in this contribution is believed to be meaningfully extendible to other case studies concerned with the application of computational approaches to the evaluation of synergic performance metrics in problems suitably coupling the structural response to environmental dynamic excitations with land regeneration dynamic response to current ecosystemic emergencies and sustainability emergencies.
- The structural performance analysis, herein exclusively made in terms of stress work rates with no account of deformability does not allow to appreciate different performances between the open- and cosed-node structures. To reach full credibility of the structural judgement, the atomic character of this investigation should thus be consolidated and corroborated addressing also a due verification of performance to deformability and should comprehend a larger set of load combinations.
- The authors are planning to expand this research also by examining other meaningful case studies including San Gennaro Chapel in Naples [20, 21], Palazzo Ducale in Parete and the church of Santa Maria delle Grazie in Ischia and [22-24] and considering other structural elements like timber floors [25].

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