Optimization of steel web core sandwich panel with genetic algorithm

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Abstract

In civil engineering there is a need for lightweight structural elements, specifically in applications such as the rehabilitation of degraded floors in existing buildings and modular construction. Metaheuristic search procedures are suitable to tackle optimization problems concerning material efficiency, but their use in real design applications is still limited. This paper presents the preliminary design in terms of structural, thermal, and acoustic performance of a floor system based on steel web core sandwich panels with polyurethane (PUR) foam core and a new genetic algorithm (GA) procedure developed to optimize its mass. The optimization study also addresses the minimization of cost and environmental impact and includes a wide range of practical engineering requirements. The constraints stemming from the building codes are incorporated in a new adaptive penalty function whose formulation and performance are thoroughly investigated. Examples of how to formulate the optimization problem in terms of Eurocode verifications are provided to foster the use of optimization procedures in current design practice. The results are presented in terms of design variables and constraints search histories as well as optimal feasible and unfeasible solutions. General conclusions and specific recommendations are drawn based on the case study presented for the design of sandwich floor panels and steel web core sandwich panels, respectively.

Keywords: lightweight, sandwich panel, optimization, genetic algorithm, penalty function.

1 Introduction

Weight is becoming increasingly important as a key factor in the design of civil engineering structures [1]. Low mass structural elements offer advantages such as i) reduced use of raw materials and energy, ii) rapid installation, iii) limited foundation works, iv) diminished production of waste due to on-site construction activity, and v) safe working environment [2]. Current weight-sensitive applications are the rehabilitation of degraded floors in existing buildings and modular construction. The former requires a lightweight floor system with a mass comparable to those of degraded timber floors in masonry buildings which are often found in city centers of Europe. This gives an additional advantage in seismic-prone areas where a low dead weight diminishes the inertial forces generated by the earthquake [3]. The latter imposes constraints on the structural module, which has to be transported to the construction site [4].

In the context of lightweight floor systems, research is focused on the development of sandwich floor panels due to their high strength-to-weight ratio. Sandwich panels are made of two thin and stiff face sheets separated, usually, by a low-density core material [5]. Reinforcement systems for the core are necessary due to its considerable shear deformation resulting from the high values of permanent loads imposed on civil engineering structures. For what concerns core reinforcing techniques, the introduction of webs to increase the shear stiffness of the core and to reduce the vertical deflection appear to be one of the most promising solutions [6].

A great many alternative shapes may be obtained combining different material and geometrical properties resulting in a high number of design variables. Furthermore, the sandwich panel is subjected to a wide range of requirements set out by the building codes. In this context, metaheuristic search procedures such as genetic algorithms (GAs) are well suited to address the design optimization of sandwich panels [7]. These optimization procedures have been researched extensively in the literature, but they are not frequently applied in practice [8]. A more problem-oriented approach focused on the need of structural designers is required to introduce optimization methods in daily engineering practice.

Within the scope of the Lightslab R&D Project the preliminary design of a sandwich floor panel in terms of structural, thermal, and acoustic performance is carried out. The design is based on the analytical provisions currently available in the international standards and building codes. An experimental campaign to mechanically characterize the sandwich panel and validate the results of the preliminary design is envisaged in a later stage of the project and, therefore, is out of the scope of this work. The panel comprises steel face sheets with polyurethane (PUR) foam core and steel reinforcement webs. The material efficiency of the floor panel is optimized by using a GA procedure. Additionally, minimization of cost and environmental impact is also addressed.

The objective of the current study is to develop an optimization procedure that may be accessible to non-experts. Therefore, the GA should be straightforward to implement, flexible, and computationally efficient. Examples are presented of how to include the Eurocode-based structural requirements into the penalty function. Consequently, the versatility of the optimization tool is shown, and the possibility of extending its use to the design of any structural member covered by the Eurocodes. The constraint handling technique is the adaptive penalty function, derived from the idea of Smith and Tate [9], which can include both structural, thermal, and acoustic requirements. The influence of the penalty coefficients is described and a simplified methodology to define them is suggested to avoid cumbersome tuning procedures.

The obtained results are presented in terms of search histories of constraints, optimal feasible and unfeasible solutions, and parametric studies on the main design parameters of the sandwich panel. The search histories provide the ultimate governing constraints, thus, establishing a set of priorities that could help the structural designer in the preliminary stage of the design. The optimal solutions as well as the parametric studies show how certain features of the sandwich panel may be achieved providing useful information to sandwich panel manufacturers based on the particular case study. Indeed, the final layout of the sandwich panel to be manufactured in the scope of the Lightslab R&D Project is selected among the solutions retrieved by the GA.

2 Genetic algorithms in structural design applications

A GA is an optimization and search procedure based on the Darwinian principle of the survival of the fittest [10]. An initial population, which represents the potential solutions to the optimization problem, is randomly initialized. The best individuals, evaluated using a predefined fitness (objective) function, are favoured and combined together to create better individuals in the next generation.

Structural design and optimization problems often present i) variables of different nature (continuous, discrete, integer, and/or categorical), ii) objective and constraint functions whose derivatives are too complex or impossible to calculate, and iii) noisy and multimodal solution space [11]. GAs are particularly suitable to address these types of problems as i) they can handle different types of variables, ii) they require no auxiliary information but the value of the objective function itself, and iii) they are a population-based approach making them less likely to be trapped in local optima. However, GAs are unconstrained optimization procedures, and it is necessary to devise a way of incorporating the constraint in the objective function [7]. The most common way is the adoption of penalty functions.

GAs have been used in civil engineering applications firstly in the structural optimization of 2D and 3D truss structure [12,13]. Hasançebi and Erbatur [14] studied the optimization of a truss system subjected to generic material strength and nodal displacement constraints to benchmark the performance of a new crossover technique introduced in their GA. Tang et al. [15] addressed the issue of dealing with multiple constraints with static penalty function in a combined shape, size, and topology optimization problem of trusses.

Metaheuristic optimization procedures are also employed in real engineering applications such as the reduction of the cost of large steel frame structures [16,17] as well as reinforced concrete ones. El Semelawy et al. [18] studied the cost optimization of a concrete floor slab system according to different methods, including GA. The requirements imposed to the floor system were strength and serviceability limit states (SLS). Sahab et al. [19] aimed at reducing the cost of a three-story flat slab concrete building using GAs. The slab had constraints related to the bending moment resistance and quantity of the steel reinforcement. Each constraint violations assigned a penalty according to a static penalty method.

GAs have been successfully employed to optimize the design of sandwich panels for various applications in the aerospace and naval industries [20,21,22,23]. For what concern civil engineering applications, Studzinski et al. [24] computed the optimal span length from the economic point of view of a soft-core sandwich panel. A static penalty function accounted for the constraints imposed by the structural requirements at the ultimate limit states (ULS) and SLS. The plot of the penalty function against the span length shows the part of the Pareto optimal front which is meaningful since it is satisfying all the constraints deriving from the mechanical performance. Escusa et al. [25] studied the minimization of weight, cost, and environmental footprint of a sandwich floor panel composed of PUR foam core, fibre-reinforced polymer (FRP) bottom layer and webs, and a fibre-reinforced mortar top layer. The design variables involved not only the geometric characteristics of the panel but the stacking sequence of the FRP material as well. The GA retrieved four optimal solutions but only two of them were fulfilling all the constraints. The minimum weight of an FRP web core sandwich bridge deck system was sought by He and Aref [26]. Similar to the previous work, geometric characteristics and stacking sequence were simultaneously optimized using a GA. To avoid the tuning of the penalty parameters for the stiffness constraint, the authors devised a tournament selection scheme that favours sandwich panels with lower deformations if their design is not feasible. A comprehensive study on the relation between design variables, objective functions, and requirements of sandwich floor panels was presented by Garrido et al. [27] although it used a different optimization procedure, namely the Direct Search Method. The authors suggested that characteristics such as weight, cost, or thermal performance may as well be defined as constraints depending on the design priorities. Another meta-heuristic optimization procedure, namely the simulated annealing, was used in the study of Martínez-Martín and Thrall [28]. The FRP sandwich panel for rapidly deployable shelters must be lightweight and have a good thermal resistance. Single objective searches were used to tune the parameters of the genetic operators and define the extremes of the Pareto front of the multi-objective search.

The academic literature often emphasizes the optimization algorithm rather than its application [29]. Furthermore, optimization studies focus on a limited set of requirements, whereas in realistic structural optimization problems all relevant building standards must be considered [30]. These constraints must be incorporated in the fitness function of the GA. However, optimization studies provide little information about handling constraint techniques as well as tuning procedures for the calibration of algorithmic parameters. Therefore, it is concluded that more comprehensive studies based on real engineering applications are required to foster structural optimization tools among practitioners.

3 Sandwich panel characteristics

Sandwich panels with steel face sheets and rigid polymeric foam core are cost-competitive and are widely used as secondary or non-structural elements in cladding systems for roofs and façades [5]. Promising research results emerged recently in view of a possible primary structural use [31,32]. Within the scope of the Lightslab R&D Project, a steel web core sandwich panel for applications in the rehabilitation of degraded timber floors in existing masonry buildings and modular construction was preliminarily designed. The target of the prefabricated modular floor system is to offer an economical solution that is lighter and less polluting than traditional ones available in the market such as reinforced concrete slabs or steel-concrete composite slabs. At the same time, the sandwich floor panel must fulfil the structural safety, thermal and acoustic requirements set out by the building codes. Therefore, in this optimization study, the weight, cost, and global warming potential (GWP) of the panel are set as the objective functions whereas the structural safety, thermal and acoustic requirements represent the constraints imposed on the solutions.

3.1 Geometry

The layout of the sandwich panel considered in this work is illustrated in Figure 1. Two steel face sheets are separated by a low-density PUR foam core. Within the core material, cold-formed steel (CFS) C- and Z-shape thin-walled profiles are inserted in the longitudinal direction to increase the shear stiffness. The face sheets and webs are constituted by hot-dip zinc-coated structural steel sheets with a design yield strength and Young's modulus of 220 MPa and 210 GPa, respectively. The connection between the top and the bottom face sheets is accomplished through adhesive and mechanical joints, respectively. The use of self-drilling screws connecting the bottom face sheet to the webs is due to manufacturing constraints. They ensure that the CFS profiles maintain their position while the bottom face sheets are passing along the conveyor belt where the PUR foam is injected on top of them. The lightweight floor system based on sandwich panels envisages the design and mechanical characterization of the connection between panels and between the panel and the vertical structure. However, these connection systems fall outside the scope of this work.

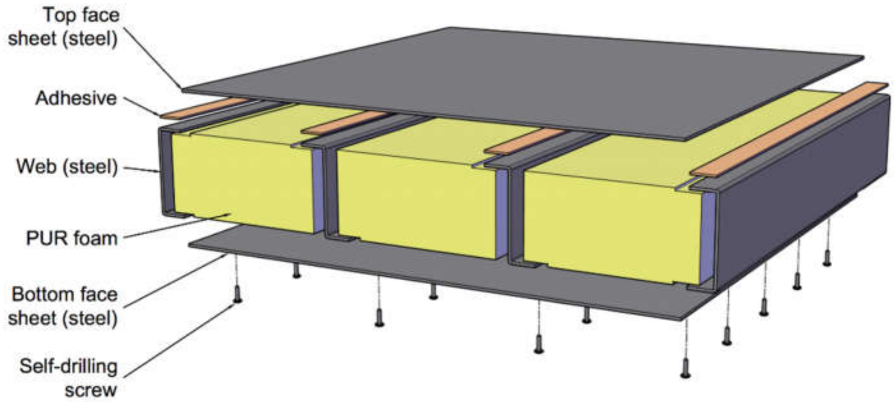
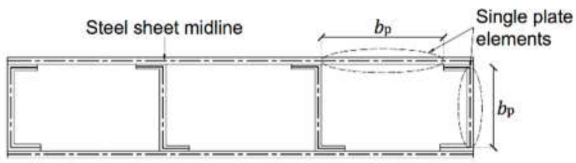


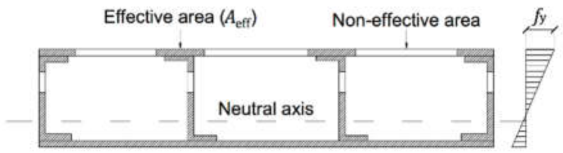
Figure 1. Layout of the proposed sandwich panel

3.2 Structural behaviour and requirements

The steel web core sandwich panel may be considered as a CFS built-up structural member infilled with PUR foam. Several experimental and analytical studies show that the presence of the foam increases the resistance to local instability phenomena [33,34]. However, there are neither guidelines nor codes which set out design procedures for this novel structural element. Therefore, a conservative approach is adopted for the calculation of the load-carrying capacity and deformations of the sandwich panel which neglects the contribution of the PUR foam. The structural model adopted is a simply supported beam subjected to a uniformly distributed load. Such boundary conditions, corresponding to high stresses and mid-span deflections, represent the worst-case scenario in terms of design. The span length between the supports is set equal to 5 m which is a considerable value regarding the literature on sandwich panels for civil engineering applications [35,36]. It is kept constant in the design and optimization procedure since it is slightly above the average span length found in old masonry buildings across Europe, which is approximately 4.0 m [37]. The width of the panel, which is equal to 1.0 m, is also fixed due to constraints related to the sandwich panel manufacturer. The load combination is estimated according to EN 1990 [38] and EN 1991-1-1 [39]. The permanent loads considered are the self-weight of the panel and an additional value of 1.5 kN/m^2 to consider the presence of floor finishing, permanent partition walls, and suspended ceilings. The live loads are set equal to 2.0 kN/m^2 which is the value for residential buildings [39]. The resistance of the CFS cross-section alone is based on the concept of the effective width. When a plate element supported along all edges is compressed, out-of-plane bending occurs in its central region, and the entire load is carried by the strips along the sides. An iterative procedure, whose formulas are given in detail in Annex A, is required to calculate the effective width of all the plates composing the section which carries the longitudinal stresses after local buckling arises. The linear method proposed by Hancock et al. [40] is adopted in this work as the thickness of the cross-section is assumed to be constant. The area of the plate elements composing the cross-section is assumed to be concentrated along their midlines as illustrated in Figure 2(a). It is assumed that at the ULS the yield strength f_y is reached in the top fibre. The neutral axis position is updated through an iterative procedure until a compatible stress field and effective cross-section are obtained as shown in Figure 2(b). A similar procedure is used for the SLS, although the stress in the top fibre is updated at each iteration.



(a)



(b)

Figure 2. Structural model: (a) Schematic representation of the cross-section and (b) its effective parts at the ULS. Note: b_p stands for the flat width of the single plate element

The resisting bending moment (M_{Rd}) and shear force (V_{Rd}) are then calculated according to the following expressions:

$$M_{Rd} = \frac{W_{eff} \times f_y}{\gamma_{M0}} \tag{1}$$

$$V_{Rd} = \frac{{}_{w} \times t_w \times f_{bv}}{\gamma_{M0}} \tag{2}$$

where W_{eff} is the effective section modulus, h_w and t_w are the height and thickness of the web respectively, f_{bv} is a reduced value of the yield strength to account for the effect of local buckling and γ_{M0} is the partial factor for the resistance of the cross-section which is set equal to 1.00. Finally, the vertical deflection at midspan is calculated using Equation (3).

$$\delta_{max} = \frac{5}{384} \times \frac{qL^4}{EI_{eff}} \tag{3}$$

where q is the uniformly distributed load and it is calculated according to the characteristic combination established in the Portuguese National Annex in NP EN 1993-1-1 [41], E is the steel Young's modulus and I_{eff} is the effective moment of inertia of the cross-section.

The verifications of the resistance of the cross-section to the effect of the design actions at the ULS is carried out according to EN 1993-1-3 [42] and EN 1993-1-5 [43] for the most common failure mechanisms of thin-walled CFS profiles: bending moment considering local buckling of the single plates and shear buckling of the webs. It is imposed that the load-carrying capacity of the sandwich panel with respect to bending moment (R_{Md}) and shear (R_{Vd}), whose formulas are reported in

Annex A, must be equal or greater than the value of the effect of the actions according to the fundamental combinations at the ULS:

$$R_{\mathrm{Md}} \quad (\gamma_{\mathrm{G}} \times G_{\mathrm{k}} + \gamma_{\mathrm{Q}} \times Q_{\mathrm{k}}) \geq 0 \; [\mathrm{kN/m^2}] \tag{4}$$

$$R_{\mathrm{Vd}} \quad (\gamma_{\mathrm{G}} \times G_{\mathrm{k}} + \gamma_{\mathrm{Q}} \times Q_{\mathrm{k}}) \geq 0 \; [\mathrm{kN/m^2}] \tag{5}$$

where G_k and Q_k are the permanent and live loads, respectively. The terms γ_G and γ_Q are the partial safety factors for actions that are set equal to 1.35 and 1.5 accordingly [38].

For what concerns the SLS, the Portuguese National Annex in NP EN 1993-1-1 [41] establishes a limit in the vertical deflection (δ_{max}) for a generic type of floors which is given by

$$\delta_{\mathrm{max}} \leq L/500 \; [\mathrm{mm}] \tag{6}$$

For what concerns the verification against excessive vibrations, it can be avoided if the vertical deflection is within a less stringent limit, namely 28 mm [41].

3.3 Thermal behaviour and requirement

The thermal resistance (R_{tot}) defines the thermal insulation properties of the sandwich panel considering heat transfer by conduction through the thickness of the element and convection and radiation on the surfaces of the floor. The value of the thermal transmittance at particular locations, namely the connections between the panels and between the panel and the structure, are not considered since they are out of the scope of this work. It is calculated by the following expression:

$$R_{\mathrm{tot}} = R_{\mathrm{si}} + R_1 + R_2 + \quad + R_{\mathrm{i}} + R_{\mathrm{se}} \tag{7}$$

where R_{si} and R_{se} are the internal and external surface resistance, R_i is the thermal resistance of each thermally homogeneous layer which depends on the thermal conductivity of the material. The thermal transmittance (U) is then determined using Equation (8).

$$U = \frac{1}{R_{\mathrm{tot}}} \tag{8}$$

The effect of the thermal bridges constituted by the metal webs through the insulation layer of the PUR foam core is considered. A correction factor, whose formula is given in Annex A, is added to the thermal transmittance of the sandwich panel as provided for in Annex F of ISO 6946 [44].

To ensure a good thermal performance of the building or an autonomous part of it, with respect to the energy consumption, the efficiency of the technical system, and the minimization of condensation phenomena, a maximum limit is imposed on U of each building element. The value, according to the Portuguese code for the thermal characteristics and behaviour of buildings [45], is set equal to 0.30 W/m^2K considering a horizontal opaque element subjected to a vertical heat flow and the most rigid climatic zone.

3.4 Acoustic behaviour and requirements

The acoustic comfort in a building depends on the airborne and impact sound insulations offered by the construction elements. It is preferable to evaluate the sound insulation based on laboratory and in-situ tests. However, in lack of experimental data, the sound index reduction (R) and the normalized impact pressure level (L_n) can be estimated according to the methods included in Annexes B of EN 12354-1 [46] and EN 12354-2 [47]. Although they are analytical procedures for heavyweight construction elements, they can give a rough idea of the acoustic behaviour of the sandwich panel. The model assumes that the sandwich panel behaves like an infinite isotropic plate with homogeneous mechanical properties. Therefore, a transformed section made of a single material is obtained through a homogenization procedure which is related to the ratio n_E between the Young's moduli of steel and PUR foam (see Figure 3).

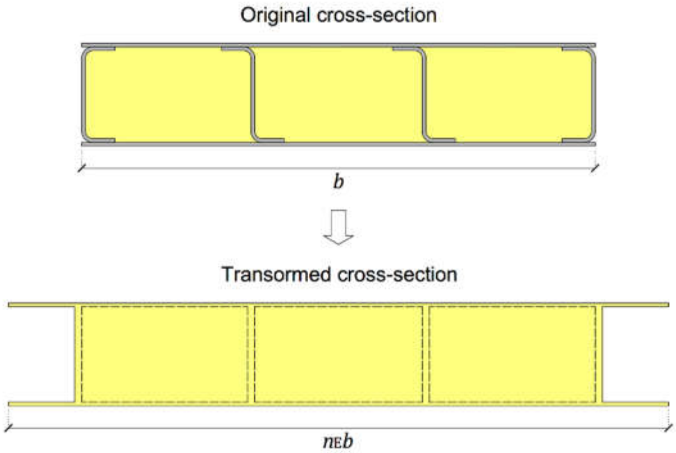


Figure 3. Original and transformed cross-section of the sandwich panel made of a single homogeneous material

The equivalent Young's modulus E_{eq} is obtained from Equation (9) imposing the equality of the bending stiffness between the transformed cross-section and a homogeneous plate with a section with the same thickness as the original sandwich panel and a unitary width

$$E_{eq} = \frac{12 \times E_t \times I_t}{I_{eq}} \tag{9}$$

where E_t, I_t, and I_{eq} are the Young's modulus and the moment of inertia of the transformed cross-section and the moment of inertia of the homogeneous plate respectively. E_{eq} is used to calculate the critical frequency of the slab with homogenous mechanical properties equivalent to those of the sandwich panel on which the sound transmission coefficient τ depends. If the sound transmission coefficient is given, R and L_n can be calculated over a frequency spectrum ranging from 100 to 3150 Hz according to the equations reported in Annex A.

To simplify the design, a single number quantity of the sound insulations values can be estimated through the comparison with reference curve in ISO 717-1 [48] and ISO 717-2 [49]. The detailed procedure is described in Annex A as well as the conversion of the obtained values from laboratory to in-situ conditions considering the volume and reverberation time of typical residential rooms. Indirect airborne and flanking transmission are neglected since they depend on the specific construction details of each building.

The target application of the sandwich panel, e.g. the rehabilitation of degraded floors in existing buildings, does not envisage any requirements. However, minimum sound insulation is desirable for the prototype. Thus, reduced values of the acoustic requirements, in the amount of 60% of those established in the Portuguese acoustic code for new buildings [50], are considered: 30 dB for the airborne sound insulation and 100 dB for the impact sound insulation. It is also worth noticing that the requirements in new buildings are imposed to construction elements separating different dwellings. Therefore, the sandwich floor panel may still be used as a floor system in a multi-floors single dwelling.

4 Formulation of the optimization problem

The GA operators, which will be explained in detail in the next section, manipulate the genetic information of the candidate solution to produce improvement in the next generation. Therefore, the variables which define the geometric and material properties of the sandwich panel must be translated into a chromosome-like structure. The procedure through which the observable characteristics of the sandwich panel, defined as phenotype according to the specific terminology for GAs, are converted in its corresponding genetic constitution, i.e. the genotype, is called encoding and is illustrated in Figure 4.

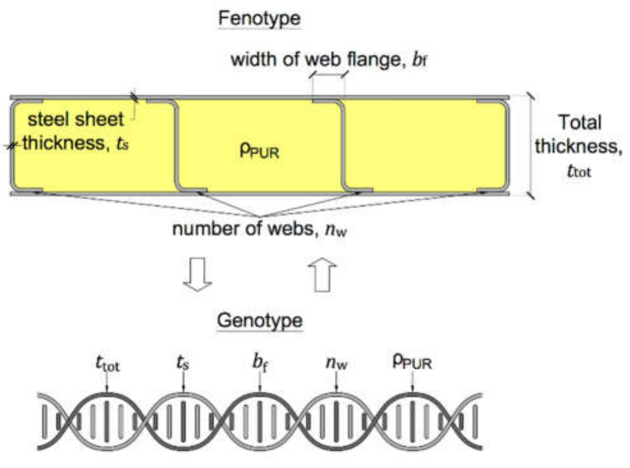


Figure 4. Encoding procedure of the characteristics of the sandwich panel: t_{tot} is the total thickness, t_s is the steel sheet thickness, b_f is the width of the web flange, n_w is the number of webs and ρ_{PUR} is the density of the PUR foam

The design variables of the sandwich panel are of mixed nature: t_{tot}, t_s, and b_f are continuous (real) design variables whereas n_w and ρ_{PUR} are discrete design variables. In the computer implementation of the GA, a mixed-floating-integer data structure is used to accommodate all the variables to search the continuous and discrete design variables simultaneously [26].

The cross-sectional areas of CFS sheets (A_{steel}) and PUR foam (A_{PUR}) are calculated according to the following expressions (in the A_{PUR} the area occupied by the webs is neglected):

$$A_{steel} = 2 \times t_s \times b + n_w \times t_s \times \left(t_{tot} - 2 \times t_s + 2 \times b_f\right) \tag{10}$$

$$A_{PUR} = (t_{tot} - 2 \times t_s) \times b \tag{11}$$

where b is the width of the sandwich panel.

The optimization aims to find the optimal design variables satisfying the constraints and minimizing the objective functions, i.e. weight (wt), cost (cst), and GWP (gwp):

$$wt = A_{steel} \times \rho_{steel} + A_{PUR} \times \rho_{PUR} \tag{12}$$

$$cst = A_{steel} \times CPU_{steel} + CPU_{PUR} \times \rho_{PUR} \tag{13}$$

$$gwp = A_{steel} \times CO_2e_{steel} + A_{PUR} \times CO_2e_{PUR} \tag{14}$$

where ρ_{steel} is the density of the steel, CPU_{steel} and CPU_{PUR} are the unit cost of the steel and PUR foam, and CO_2e_{steel} and CO_2e_{PUR} are the unit equivalent carbon footprints of the steel and PUR foam whose values are given in Table 1.

The objective function is formulated in Equation (15) according to the weighted-based genetic algorithm (WBGA) approach.

$$f(\boldsymbol{x}) = \sum_{i=1}^{3} w_i \times f_i'(\boldsymbol{x}) \tag{15}$$

In Equation (15), $\boldsymbol{x}$ is the design variables vector, w_i is the weight assigned to the *i-th* objective function, and $f_i'(\boldsymbol{x})$ is the normalized value of the objective functions. Indeed, the magnitude of each objective function f_i is different, thus, a min-max normalization is implemented.

The WBGA approach aggregates the objectives, producing a single compromise solution according to the decision-maker [51]. It is a simple extension of the single objective GA and therefore, it is straightforward to implement. Thus, it is considered the most adequate in the scope of the Lightslab R&D Project, which requires optimizing the design in a reasonable time frame. Indeed, future tasks, such as the definition of the experimental campaigns and possible adjustments in the manufacturing process, heavily rely on the outcome of this optimization procedure. The choice of the weights is straightforward for retrieving the lightest, most economical, and least polluting designs, which are the targets of this work. However, if different alternatives are sought, new runs of the optimizer are required, tuning the aggregate function. In this case, the Pareto-based approach has the advantage of providing a set of optimal solutions in a single run. This approach is preferable when the decision-maker has no clear preference of the objective, and the final solution is often a trade-off.

4.1 Objective functions

The weight, cost, and GWP of the sandwich panel are calculated from the nominal dimension and the mass density, unit cost, and carbon footprint of steel, PUR foam, and the adhesive (see Table 1). The unit costs are estimated based on the prices provided by the suppliers of the sandwich panel manufacturer. The unit carbon footprints are assessed with reference to the values found in the literature [27] and the life cycle assessment study (LCA) conducted by different hot-dip galvanized steel manufacturing companies [52]. The LCA studies considered in this work follow the cradle-to-gate approach, i.e. the environmental impact of building materials is evaluated from the extraction of raw materials in the earth to the finished product ready to be shipped from the gate of the factory. Therefore, it does not consider subsequent downstream activities such as transportation, final use, disposal, and recycling. The impact category studied is global warming whose indicator is the GWP for a time horizon of 50 years. Furthermore, given the small amount of adhesive to be used in the panel its contribution to the overall mass and carbon footprint is neglected.

Table 1. Mass density, unit cost, and carbon footprint of the components of the sandwich panel

Material	**Mass density** [kg/m^3]	**Unit cost** [€/kg]	**Unit carbon footprint** [kgCO_2-eq./kg]
Steel	78.5	0.82	2.8
PUR foam	35, 40, 50, 60, 70, 80, 90, 100, 110, 120	1.79	4.14
Adhesive	Neglected	9.54	Neglected

4.2 Constraints and penalty function

As stated before, the optimal solutions must satisfy a series of constraints that can be grouped into two categories. The first one includes the so-called behavioural constraints [53], which are an implicit function of the design variables and they represent the requirements defined in Section 3 (see Table 2),

Table 2. Behavioural constraints of the sandwich panel

Constraint	**Category**	**Terms definition**
$R_{\mathrm{Md,Q}} = \dfrac{R_{\mathrm{Md}} \quad \gamma_{\mathrm{G}} \times G_{\mathrm{k}}}{\gamma_{\mathrm{Q}}} \geq 2.0\ [\mathrm{kN/m^2}]$	ULS	It is derived from Equation (4) substituting Q_k with the value imposed by the EN 1991-1-1 [27]. The resistance of the panel is expressed in terms of live load carrying capacity ($R_{Md,Q}$)
$R_{\mathrm{Vd,Q}} = \dfrac{R_{\mathrm{Vd}} \quad \gamma_{\mathrm{G}} \times G_{\mathrm{k}}}{\gamma_{\mathrm{Q}}} \geq 2.0\ [\mathrm{kN/m^2}]$	ULS	The same comments made for the previous constraint apply in this case. $R_{Vd,Q}$ is the live load carrying capacity of the panel with respect to shear force
$\delta_{\max} \leq 10\ [\mathrm{mm}]$	SLS	It comes from Equation (6) considering L equal to 5 m
$U_{\mathrm{C}} \leq 0.3\ [\mathrm{W/m^2K}]$	Thermal	U_C is the corrected value of the thermal transmittance considering the effect of the thermal bridges
$D_{nT,w} \geq 30\ [\mathrm{dB}]$	Acoustic	$D_{nT,w}$ is the weighted standardized sound pressure level related to in-situ conditions
$L_{nT,w} \leq 100\ [\mathrm{dB}]$	Acoustic	$L_{nT,w}$ is the weighted standardized impact sound pressure level related to in-situ conditions

The behavioural constraints are incorporated in the objective function employing an adaptive penalty function, firstly proposed by Smith and Tate [9] and improved by Smith and Coit [54]. This penalty function involves the estimation of a near-feasible threshold (*NFT*) for each constraint. *NFT* represents the distance from the feasible region of the solution space beyond which the GA is discouraged to search for a solution. Indeed, the inclusion of unfeasible regions at the beginning of the search is useful since the optimal solution often lies at the boundary of the feasible region [55]. The penalized objective function f_p is evaluated using:

$$f_p(\boldsymbol{x},t) = f(\boldsymbol{x}) + \left(F_{feas}(t) \quad F_{all}(t)\right) \times \sum_{i=1}^{6} \frac{d_i}{NFT_i} \tag{16}$$

where t is the number of generations, $F_{all}(t)$ the unpenalized value of the best solution yet found, $F_{feas}(t)$ the value of the best feasible solution yet found, and d_i the distance metric of each constraint. The difference between $F_{all}(t)$ and $F_{feas}(t)$ provides adaptive scaling to the penalty function based on the ongoing results of the search. The term d_i measures the distance of the solution from fulfilling each constraint. An example of its formulation is given in Equation (17) for the ULS constraint on the resistance to bending moment:

$$d_1 = \begin{cases} 2.0 \quad R_{\mathrm{Md,Q}} \text{ if } R_{\mathrm{Md,Q}} < 2.0 \\ 0 \text{ if } R_{\mathrm{Md,Q}} \geq 2.0 \end{cases} \tag{17}$$

The term NFT_i incorporates the dynamic parameter of the penalty function (λ) and it is computed as:

$$NFT_i = \frac{NFT_{0,i}}{\lambda \times t} \tag{18}$$

where $NFT_{0,i}$ is the upper bound of NFT_i, namely its starting value at the beginning of the search. If λ is a positive value NFT_i will decrease monotonically as the search progress, thus, guiding it towards the feasible region. Recommended values of $NFT_{0,i}$ and λ are presented in Section 5.

The second group of constraints is the box conditions on the design variables established according to several reasons: i) t_{tot} can range between 50 and 200 mm which is comparable to those of traditional floor systems; ii) the limit for ρ_{PUR} is established based on the constraints of the sandwich panel manufacturer; iii) the total maximum number of webs n_w (including the outer webs) initially considered is 4 due to both manufacturing constraints and the literature on sandwich panels [56,57] that show that a maximum number of 2 webs in the core is generally sufficient in terms of structural behaviour; iv) and t_s and b_f are within the interval permissible by EN 1993-1-3 [39] for the design of CFS members.

Table 3 presents the variation bounds and steps of the mutation of the design variables considered in this study.

Table 3. Box conditions and steps of the design variable of the sandwich panel

Design variable	Symbol	Unit	Minimum	Maximum	Step
Total thickness	t_{tot}	[mm]	50	200	1
Steel sheet thickness	t_s	[mm]	0.5	2.0	0.1
Width of web flange	b_f	[mm]	20	$50 \times t_s$	1
Number of webs	n_w	[mm]	3	4	1
PUR foam mass density	ρ_{PUR}	[kg/m^3]	35	120	1

4.3 Evolutionary search process

The overall procedure of the GA is illustrated in Figure 5 along with the genetic operators implemented in the code.

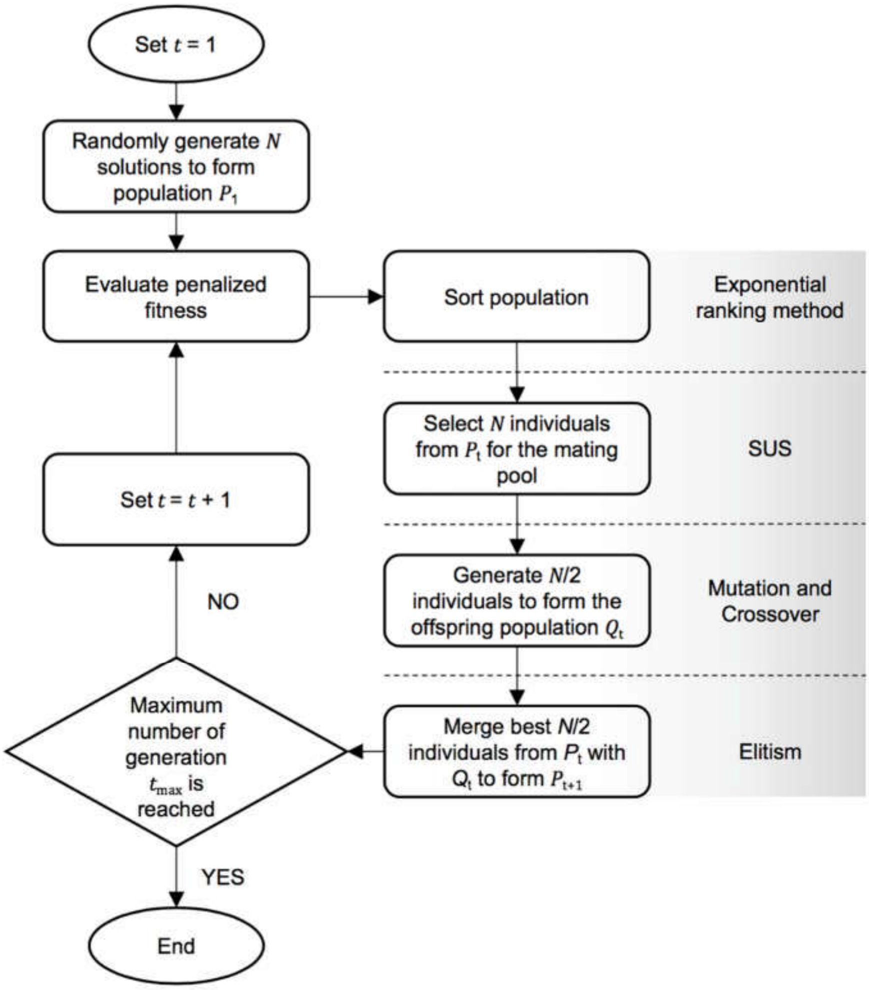


Figure 5. Procedure of the newly developed GA with the main genetic operators involved

A starting population P_1 of N individuals is randomly initialized. To update the population from generation t to t+1 the penalized fitness is evaluated for each solution. The individuals are ranked according to the penalized fitness and their probability to reproduce p is calculated using Equation (19).

$$p = s^{\mathrm{r}} \quad (19)$$

In Equation (19), r is the ranking of the individual and s is the selective pressure parameter, which is the degree to which the better individuals are favoured. In the case of this work a value of 0.7, i.e. 30% of the offspring population inherits the genes of the best solution, is found to be optimal. The use of the exponential method is justified by the fact that it is desirable to keep the selective pressure constant throughout the whole run. This avoids: (i) premature convergence due to the presence of so-called “super individuals” in the starting population and (ii) slowing down the search at the end when the difference between the fitness of the solutions is small [58].

The mating pool, which is the set of N solutions that will generate the offspring population, is selected according to the probability given in Equation (19). The selection is made by the Stochastic Universal Sampling (SUS) method which can be visualized as the result of a spinning roulette with slots proportional to the probability of reproduction of each individual with multiple equally spaced pointers [59]. Once it stops, the number of pointers over each slot corresponds to the number of copies selected for each individual for the mating pool. This method grants the minimum selection error which is caused by the fact that the number of copies is an integer number and must be rounded from the probability of reproduction of the individual which is a real number. The search history of the variables and constraints presented in Section 5.1 shows that the original combination of the penalty function, fitness scaling through the exponential ranking method, and SUS in the GA allowed to i) explore a wide solution space, ii) ensure that the best designs are favoured and iii) maintain the diversity and beneficial information of the unfeasible solutions required to overcome local optima.

The genetic information of the parents in the mating pool is manipulated by crossover and mutation. The child solution inherits part of the genetic code from the parent 1 solution and the rest from parent 2 (see Figure 6). The crossover or recombination accelerates the search bringing into a single individual the features of two parents. Later, a mutation can take place in all the genes of the new-born solution with a rate of 0.8. Mutation reintroduces diversity in the population, and it is essential to overcome the problem of converging to local optima.

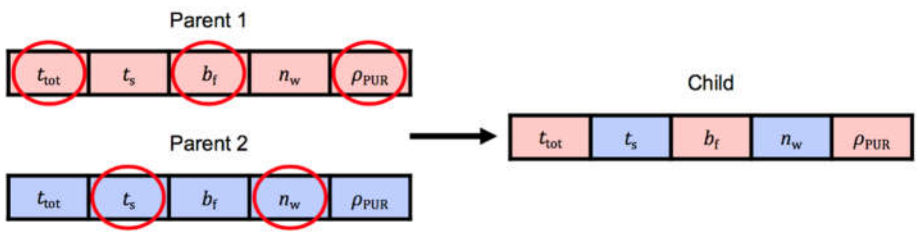


Figure 6. Recombination of the genetic information of the parents into a single individual

Finally, the offspring population Q_{t} made of $N/2$ individuals is combined with the best half of the parent population P_{t} to form the next generation $P_{\mathrm{t+1}}$. This strategy which consists in preserving the best genetic information found yet in the search is known as elitism. GAs implementing this technique have proven to outperform their non-elitist counterpart [60]. The process is repeated until a maximum number of generations t_{max} is reached.

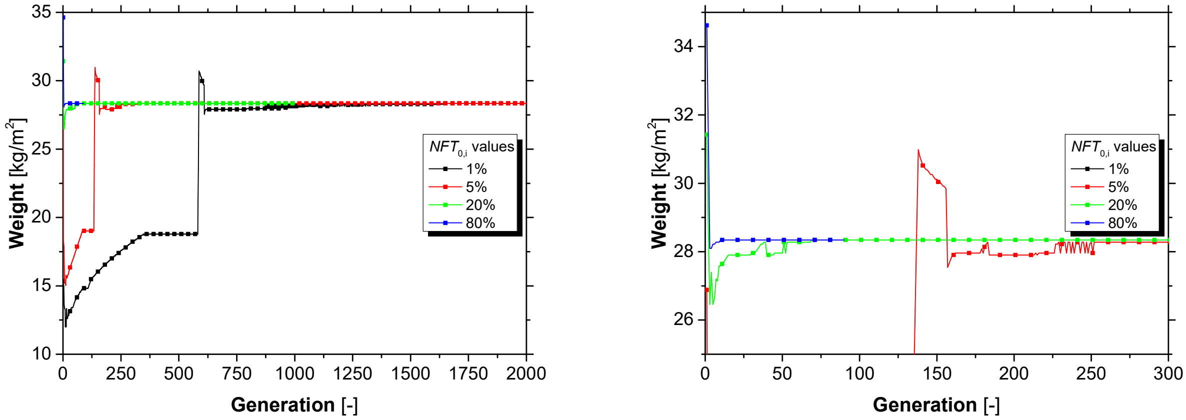
5 Results discussion

The penalty function adopted in the newly developed GA has been successfully applied for the design optimization of sandwich panels. However, it may be applied to any structural element whose design is expressed through analytical formulation. Especially for what concerns the structural design, building codes usually state verification in terms of inequalities between the design resistance and action. This can be readily used to calculate the d_i coefficient of the penalty function given in Equation (16), namely the distance between the required design resistance and its actual value. The penalty function has also proven to be easy to use since the procedure of tuning the parameters showed that they have little influence on the convergence to the optimal solution.

A parametric study conducted on $NFT_{0,i}$ and λ is used to verify the reliability of the results obtained from the GA. The optimal solutions presented in this section are compared in terms of weight with a preliminary known design. The relative difference is less than 5%, thus, the best designs are considered acceptable [61]. A novel method is proposed for the definition of $NFT_{0,i}$ for each constraint that has proven to be effective. Conceptually, $NFT_{0,i}$ is such that at the beginning of the search the GA heavily penalizes only the solutions which comply with less than 5% of the value of the *i-th* constraint. As an example, the calculation of $NFT_{0,i}$ for the SLS constraint is given in Equation (20).

$$NFT_{0,3} = \frac{\delta_{\max}}{5\%} = \frac{10}{0.05} = 200\ [\text{mm}] \tag{20}$$

The weight vector ($\boldsymbol{w}$) which contains the weights assigned to each objective function is firstly set equal to $\boldsymbol{w}$={1,0,0}, i.e. the GA only optimizes the weight of the sandwich panel (see also Equation (15)). The results of multiple search varying $NFT_{0,i}$ are shown in Figures 7(a) and (b).



(a) (b)

Figure 7. Weight of the lightest sandwich panel found by the GA: (a) along different runs varying the value of $NFT_{0,i}$; (b) with a zoom on the first 300 generations

The weight per square meter of the lightest sandwich panel is plotted against the number of generations. It can be observed that with high values of $NFT_{0,i}$ the optimal solution, which weights 28.34 kg/m^2, is approached starting from very light sandwich panels which do not satisfy the constraints. On the other hand, with a low value of $NFT_{0,i}$ the starting solutions are heavier than the optimal one but in fulfilment of the requirements. In general, the higher the $NFT_{0,i}$ the more generations are required to reach convergence. However, computing speed may be relatively important. In a second search, the weight vector is set equal to $\boldsymbol{w}=\{0,1,0\}$, i.e. the GA only optimizes the cost of the sandwich panel. Reducing $NFT_{0,i}$ speeds up the search but also reduces the solution space explored. The result is that for $NFT_{0,i}$ equal to 80% the GA falls into a local optimum failing to reach the most economical solution, whose cost is 35.24 €/m^2, as shown in Figure 8.

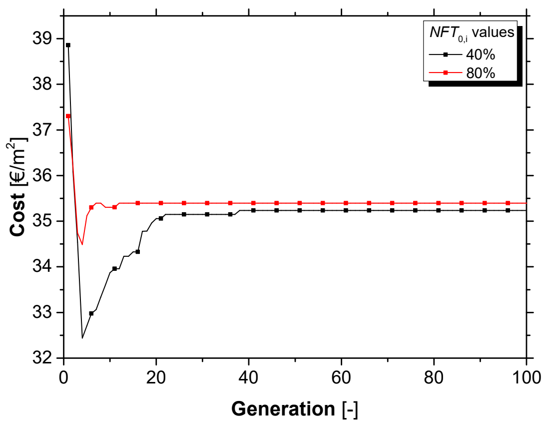


Figure 8. Cost of the most economical sandwich panel along two different runs with different $NFT_{0,i}$

For what concerns the coefficient λ, the results of the parametric study are reported in Figure 9. The coefficient influences the search in a similar way to that of $NFT_{0,i}$. The higher it is the coefficient λ the faster the GA reaches convergence. Nevertheless, the optimal solution is reached in all of the runs.

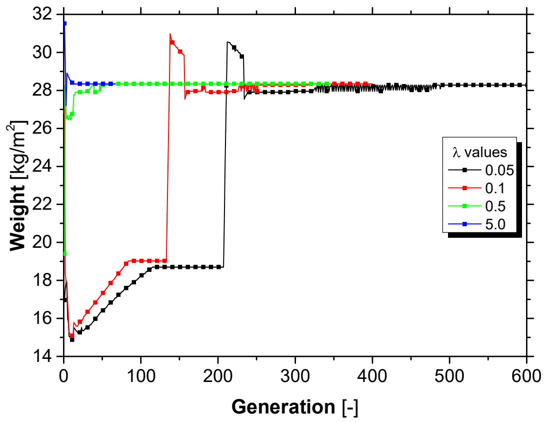


Figure 9. Weight of the lightest sandwich panel found by the GA along different runs varying the value of λ

The results of the tuning runs of the GA suggest that it is preferable to search for a wider solution space at the expense of the computational speed. In this fashion, the starting solutions present extremely low values of the objective function and are subsequently adjusted to satisfy all the constraints. Therefore, in the next simulation $NFT_{0,i}$ and λ are set equal to 5% and 0.1 respectively. Since each iteration of the GA takes up approximately 0.05 s, 20000 iterations are recommended as a stopping criterion for the optimization procedure: in this way, the results of a single run can be retrieved within a period of about 20 minutes.

Table 4 summarizes the parameters of the genetic operators adopted in the search of the optimal solutions presented in the next section.

Table 4. The genetic parameters adopted in the GA

Genetic parameters	**Symbol**	**Default value**
Number of individuals in a population	N	1000
Near-feasible threshold upper bound	NFT_0	5%
Dynamic search parameter	λ	0.1
Selective pressure of exponential ranking method	s	0.7
Type of selection scheme	-	SUS
Type of crossover operator	-	Multi-point crossover
Crossover rate	-	1
Mutation rate	-	0.8
Elitist strategy	-	TRUE
Maximum number of generations	t_{max}	20000

Finally, to compare the performance of the adaptive penalty function adopted in this work with other constraint handling techniques, the GA was properly modified to accommodate a static penalty function commonly found in the literature [19,24] and given by:

$$f_p(\boldsymbol{x}) = f(\boldsymbol{x}) + \sum_{i=1}^{6} d_i \tag{21}$$

Several runs of the modified GA were performed, and their results compared to the solution previously found by the proposed GA. The modified GA retrieved the optimal solution only one out of five runs, i.e. the second run in Figure 10. Furthermore, only small variations can be observed during the early stages of the search. It can be concluded that the proposed adaptive penalty function allows i) to explore a wider solution space, ii) avoid premature convergence, and iii) make the results of the GA less sensitive to the starting population.

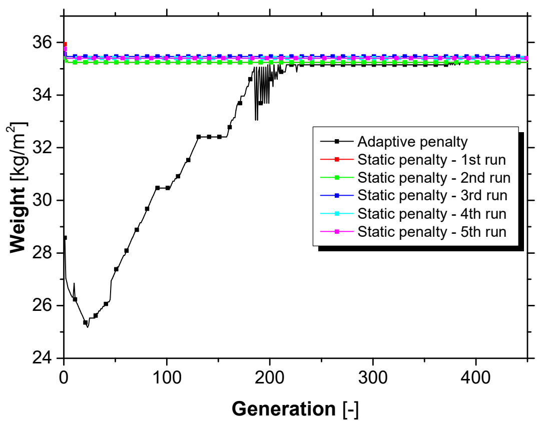
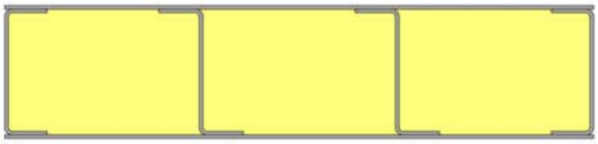


Figure 10. Comparison of the performance of the new GA including the adaptive and static penalty function

5.1 Optimal solutions

The GA is set to search the 3 optimal solutions, namely the lightest (S_1), the most economical (S_2), and the least polluting (S_3). A summary of the characteristics of the optimal solutions is illustrated in Figures 11(a) and (b).



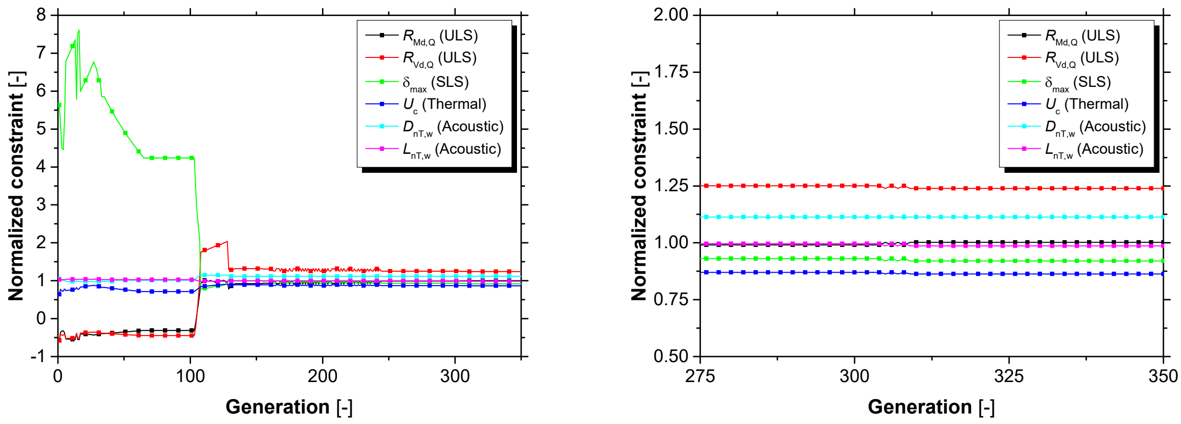
(a)

(b)

Figure 11. Cross-section and characteristics of the optimal solutions: (a) S_1 and S_3 and (b) S_2 solutions

As it emerges from the results in Figure 11 the S_1 solution coincides with the S_3 one which agrees with the optimization study conducted by Garrido et al. [27]. This may be explained by the fact that the carbon footprint is proportional to the weight of the component materials. The steel weight makes up for 80% of the total weight of the sandwich panel, thus the GA minimizes its use. A different scenario may arise if a less conservative approach is adopted and the PUR foam contribution is considered in the calculation of the structural requirements. In such a case, a lighter solution may be obtained increasing the density of the foam to allow for the use of a thinner steel sheet with an improved buckling resistance thanks to the denser core support. However, this evolutionary strategy may not lead to a less polluting solution since the PUR foam has a greater environmental impact than steel according to Table 1.

The normalized value of the constraints during the search of the S_1 and S_3 solutions is shown in Figures 12(a) and (b).



(a) (b)

Figure 12. Search history of the values of the normalized constraints when the GA is searching for the S_1 and S_3: (a) the whole run and (b) the zoom on the last 100 generations. Note: The lines with triangle symbols represent the constraints that must be equal or less than 1, whereas the lines with square symbols represent the constraints that must be equal or greater than 1

The bending moment resistance is the active constraint [62], i.e. the requirements which is ultimately governing the design as it is the last one to be fulfilled during the search. This depends mostly on the total thickness of the panel which is the last design variable converging to its optimal value as shown in Figure 13. The shear resistance and the midspan vertical deflection are relatively less stringent as they are fulfilled earlier in the run. The value of the thermal resistance fluctuates when great variations in the total thickness are observed. This is an expected result as the thermal performance relies on the thickness of the core insulating layer which makes up most of the total thickness. Despite the large range of geometric design variables explored during the search, the sound insulation constraints show little variation. This corroborates the difficulty of improving the acoustic performance of sandwich panels. A 4 dB increase in the sound insulation can only be achieved by doubling the weight of the sandwich panel. The GA identifies in the 4 webs configuration, i.e. the maximum number allowable, a preferable option both for the S_1, S_2, and S_3 solutions. This confirms the findings of previous studies on the flexural behaviour of sandwich panels [56,57]. The webs are fundamental in providing the required bending stiffness to the structural element. It should also be noted that in the lightest solution the flanges of the webs are as wide as possible. This is due to the fact that they provide a constraint for the top face sheet against buckling.

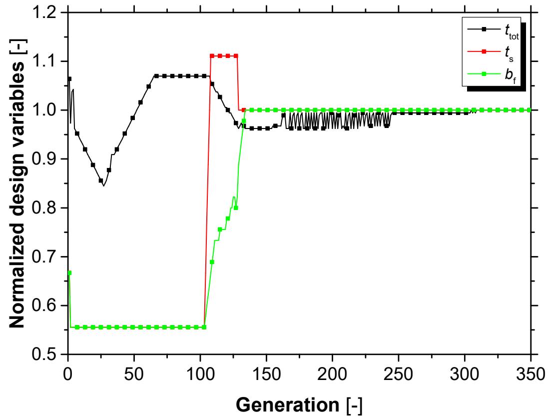


Figure 13. Search history of the normalized design variables when the GA is set to minimize the weight of the sandwich panel

The search history of the S_2 solution is shown in Figures 14 and 15. The constraints and design variables search history show a similar pattern to those of S_1 and S_3 solutions. In comparison to the latter, the S_2 solution presents thicker steel sheets and less wide flanges. This indicated that the price of the adhesive is relevant to the overall cost of the sandwich panel. The GA shows that it is more economical to increase the flexural stiffness of the panel by thickening the steel sheets rather than joining together flanges and top face sheet by means of the adhesive.

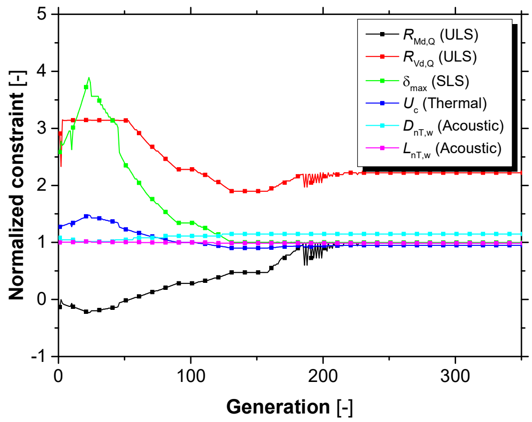


Figure 14. Search history of the values of the normalized constraints when the GA is set to minimize the cost of the sandwich panel. Note: The lines with triangle symbols represent the constraints that must be equal or less than 1, whereas the lines with square symbols represent the constraints that must be equal or greater than 1

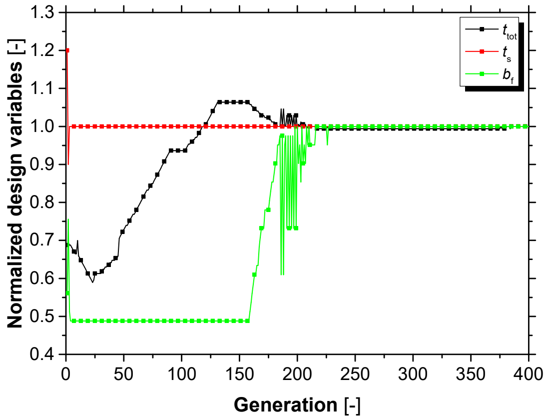
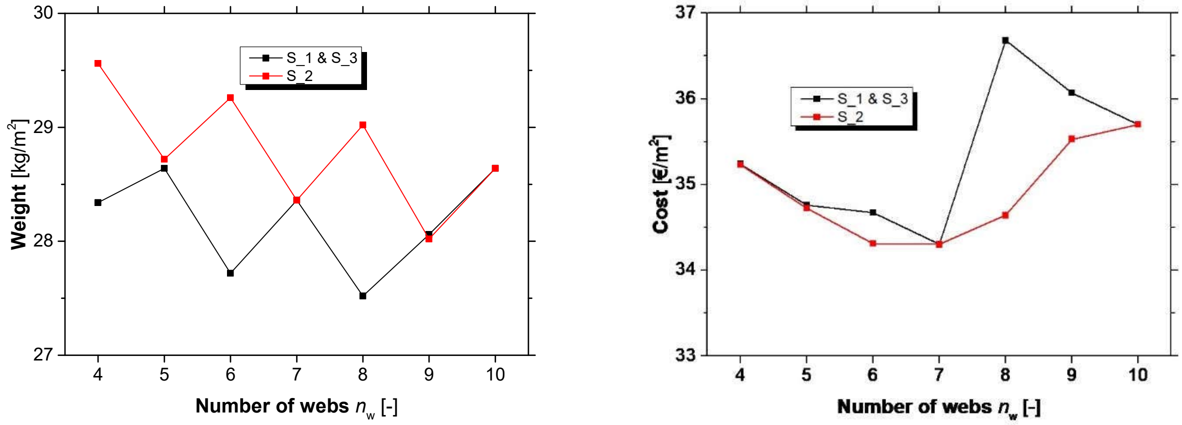


Figure 15. Search history of the normalized design variables when the GA is set to minimize the cost of the sandwich panel

Fluctuations and singularities can be observed in the plot of the design variables and the constraints along with the search of solutions S_1 and S_2 (see Figures 13, 14, and 15). During the search for the optimal solution when a design with a low value of the objective function, not fitting the constraints, ceases to be the best solution, two new designs might appear with very similar values of the penalized objective function. The GA takes some generations to establish the best among the two competing designs which result in the fluctuations and singularities in the graphs above. The GA keeps switching between the two solutions until the closest to meet the constraints emerges as the best one. This may be explained by the fact that both the $NFT_{0,i}$ and λ values are set to be small (the former one in terms of percentage) so that the unfeasible region of the solution space that the GA is encouraged to search is slowly decreasing through the generations. Indeed, in Figures 7(a) and 9 it is possible to observe that fluctuations and singularities tend to disappear when the above-mentioned parameters are set in order to perform a faster search and explore an unfeasible region that is rapidly decreasing.

5.2 Parametric study and offset of the input data

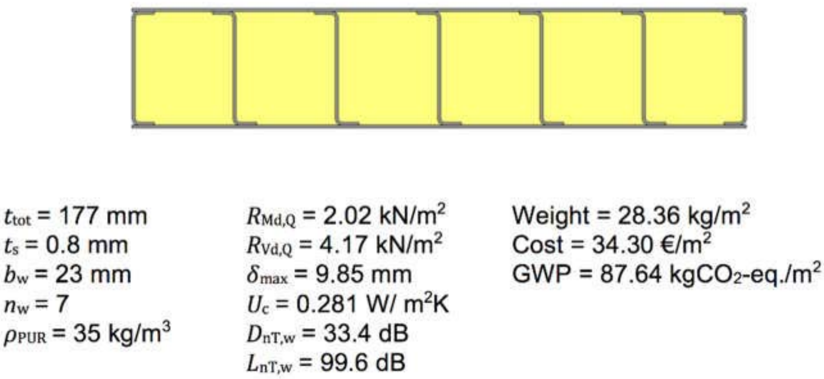
To explore a wider solution space, the values of design variables and requirements are modified keeping the other factors constant. Firstly, the maximum number of webs in the core is progressively increased, disregarding the manufacturing constraints. The population is forced to maintain a constant number of webs during the whole search so that multiple optimal solutions with a different number of webs are retrieved. The result of the parametric study is shown in Figures 16(a) and (b). The S_3 solution with 8 webs is the lightest and least polluting sandwich panel (see Figure 17(a)). However, it is also the most expensive since a large amount of adhesive is required to bond the flanges with the top face sheet. The S_2 solutions with 6 and 7 webs are both economically competitive. Furthermore, the 7 webs architecture (see Figure 17(b)) appears to be a local optimum as the S_1, S_2, and S_3 solutions are identical.



(a) (b)

Figure 16. Characteristics of sandwich panels with an increasing number of webs when the GA is set to minimize different objectives: (a) weight and (b) cost

(a)



(b)

Figure 17. Cross-section and characteristics of the absolute (a) S_1 and S_3 and (b) S_2 solutions

In Figure 18 the live load-carrying capacities, deflection, and thermal transmittance of the S_1, S_2, and S_3 solutions are reported for each number of webs. $R_{Md,Q}$ for optimal solutions with less than 8 webs approaches the limit value, as shown in Figure 18(a), that is the bending moment is the active constraints for these sandwich panels. On the other hand,

$R_{Vd,Q}$ of all the optimal solutions is always largely fulfilled (see Figure 18(b)). The assumption of a constant thickness for the whole section facilitates the effective width calculation but it seems to preclude the possibility of further improvement in the optimization of the webs, which govern the shear resistance of the panel. The vertical deflections increase with increasing number of webs (see Figure 18(c)). This may be explained by the fact that the optimal solutions with a greater number of webs have smaller total and steel sheet thicknesses (see Figures 19(a) and (b)) that result in a lower lever of arm produced by the face sheets and reduced effective area, respectively. Both these phenomena contribute to the decrease of the bending stiffness of the panel. Finally, thermal performances are illustrated in Figure 18(d). The thermal transmittances of the S_1 and S_2 solution with more than 9 and 8 webs, respectively, are slightly above the limit. Thus, for these sandwich panel architectures the governing criterion of the design is not related to the structural performance but to the thermal one.

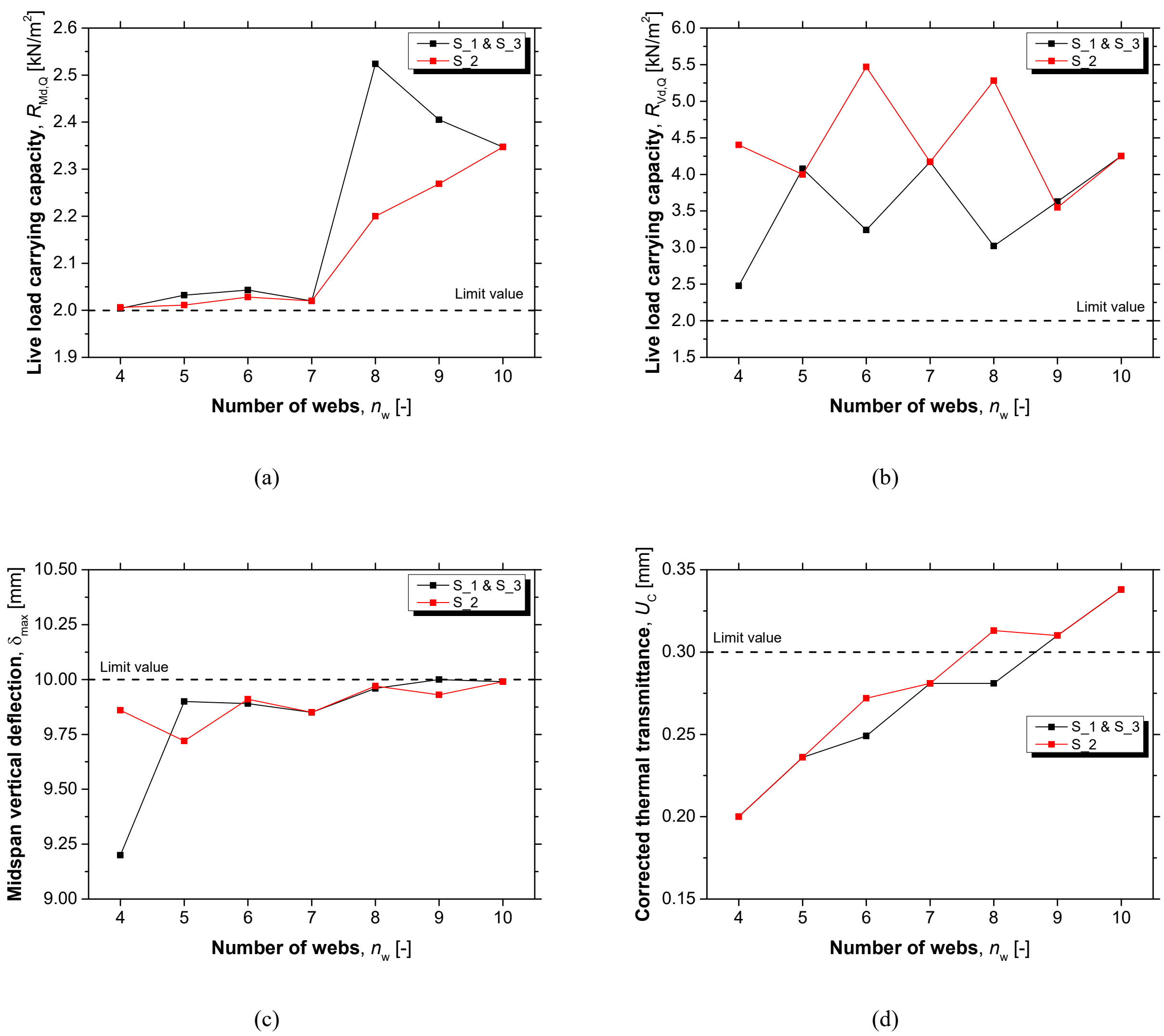


Figure 18. Value of the structural and thermal performances of sandwich panels with an increasing number of webs when the GA is set to minimize different targets: (a) live load-carrying capacity with respect to bending moment, (b) live load-carrying capacity with respect to shear (c) deflection at midspan and (d) thermal transmittance

The design variables for the different layouts are plotted in Figure 19. The GA reduces the cost of the panel mainly by thinning the thickness of the steel sheet and narrowing the width of the web flanges. On the other hand, S_1 and S_3 are obtained by reducing the total thickness as well as the steel sheet thickness.

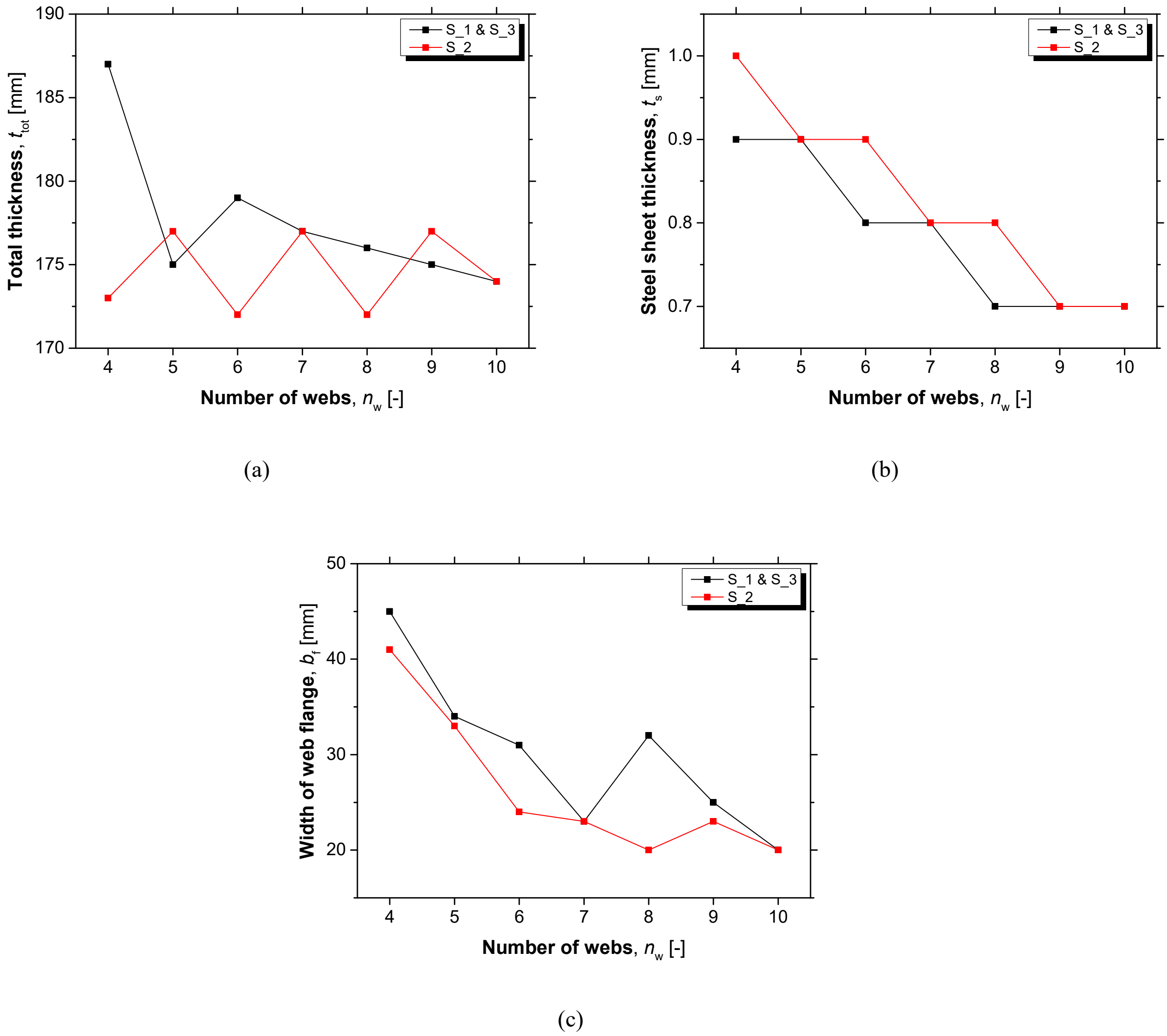


Figure 19. Value of the design variables of sandwich panels with an increasing number of webs when the GA is set to minimize different targets: (a) total thickness, (b) steel sheet thickness, and (c) width of the web flange

In the second stage, the influence of the cost of the adhesive is also investigated offsetting the original price by +10% and -20%. A decrease in the price of the adhesive makes the S_1 and S_3 solution with 4 webs also the most economical solution. An increase in the price provokes instead a narrowing of the flanges in the S_2 solution, thus diminishing the surface area to be bonded. At the same time, the total thickness of the panel is increased to compensate for the loss of the moment of inertia. This suggests that for an adhesive with a unitary cost equal to or less than approximately 8.5 €/kg there is no relevant difference in the overall price for a sandwich panel with an adhesive or mechanical connection between its face sheets and webs.

The full sound insulation requirements are imposed in the GA to verify the possibility of using sandwich panels as separating elements of dwellings in new construction. The highest acoustic insulation is achieved when the GA is set to search for the S_1 and S_3 solution. The sandwich panel fulfils 80% and 65% of the airborne and impact sound insulation requirements respectively. The GA conceive a much heavier sandwich panel compared to the previous one making use of most of the steel mass allowable by the box conditions and the highest density PUR foam (see Figure 20).

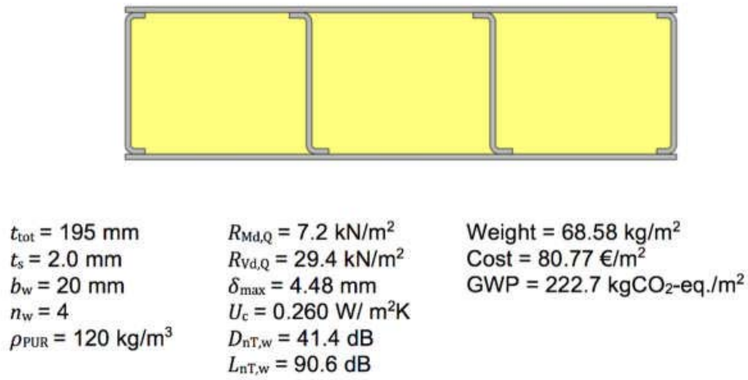


Figure 20. Cross-section and characteristics of the highest acoustic insulating sandwich panel

Finally, based on the obtained solutions and the manufacturing constraints the S_2 with 4 webs is selected as the optimal architecture for the sandwich panel to be produced in the scope of the Lightslab R&D Project. The nominal dimensions were slightly modified to conform to more convenient and traditional sizes of floor and CFS profiles, i.e. the total thickness and the web flange width are set equal to 170 mm and 45 mm respectively.

6 Conclusions

In this paper, a comprehensive approach to the design of steel web core sandwich panel is presented in view of applications in the rehabilitation of degraded floors in existing buildings and modular constructions. A newly developed GA for the optimization of the design with respect to weight, cost, and GWP along with its main genetic operators is proposed. An extensive study on the performance of the adaptive penalty function suggests that the feasibility of the optimal solutions is ensured by a starting population with low objective function values, not in fulfilment of the requirements but not vice versa. Recommended values of the penalty parameters are provided so that the search proceeds in such a fashion. The penalty function can be implemented in a straightforward way for any requirement expressed through a closed-form expression such as the Eurocodes verifications. Furthermore, an effective definition of the $NFT_{0,i}$ parameter as a percentage of the value of the constraint to be met is introduced. In general, the penalty function shows promising features such as ease of tuning the parameters and efficiency.

The relations between the objective functions, the design variables, and the requirements are investigated through the analysis of the search history and parametric studies. The lightest sandwich panels are also the least polluting for how the optimization problem is formulated. The most influential factor which determines the difference between the S_1 (lightest) and S_2 (economical) solutions is the use of the adhesive bonding connection. The least expensive sandwich panels have a reduced width of the web flanges. Thus, an accurate estimate should be carried out when considering the substitution of mechanical metal joints with adhesive ones.

The optimization study has also highlighted general challenges and improvements of sandwich floor panels: i) the biggest drawback in floor system applications is the poor acoustic insulation of lightweight structures; ii) the thickness of the face sheet and the webs should be considered separated to further improve the efficiency of the design; and iii) if face sheet and web material with good thermal insulation are employed, such as FRPs, cross-section with thinner webs and small interspace may lead to highly efficient structures.

In light of the result of the optimization procedure solution S_2 is selected to be produced within the scope of the Lightslab R&D Project. The steel web core sandwich panel covers a span length of 5 m and it is in fulfilment of the structural safety, thermal, and part of the acoustic requirements. However, if one excludes the manufacturing constraint related to the number of webs, which may be overcome by upgrading the production process, optimal solutions present a total thickness ranging between 170 and 190 mm and a steel sheet thickness exclusive of the coatings varying between 0.7 and 1 mm. In particular, the 7 webs architecture present a good compromise between all the objective functions. On the other hand, the 8 webs layout is not advisable both for economical and thermal issues.

Annex A

In this section further details on the calculation procedures used to estimate the structural, thermal, and acoustic performance of the sandwich panel are given.

Effects of local buckling

As regards the structural safety assessment, the effects of local buckling on the plates composing the cross-section are considered using the effective area A_{eff} (see also Figure 2):

$$\rho = \frac{A_c}{A_{eff}} = \frac{\lambda_p \quad 0.055 \times (3 + \psi)}{{\lambda_p}^2} \tag{A.1}$$

In Equation (A.1) ρ is the reduction factor, A_c is the gross sectional area, λ_p is the plate's slenderness and ψ is the stress ratio. The latter may assume different values depending on whether the plate is subjected to a uniform or non-uniform compressive stress. The plate slenderness, λ_p, is obtained from:

$$\lambda_p = \frac{b_p/t_s}{28.4 \times k_\sigma \times \varepsilon} \tag{A.2}$$

where b_p is the width of the single plate element (see Figure 2), k_σ is the buckling factor and ε is the square root of the ratio between 235 and f_y. The buckling factor depends on the stress ratio ψ and the boundary conditions of the plate, i.e. whether only one or both of its longitudinal edges are stiffened by the presence of webs or flanges.

Ultimate resistance

The resisting bending moment, R_{Md}, and shear force, R_{Vd}, are then calculated using Equation (A.3) and (A.4) based on the simply supported beam structural model.

$$R_{\mathrm{Md}} = \frac{8 \times M_{\mathrm{Rd}}}{L^2} \tag{A.3}$$

$$R_{\mathrm{Vd}} = \frac{2 \times V_{\mathrm{Rd}}}{L} \tag{A.4}$$

Thermal requirements

For what concerns the thermal requirements, the presence of insulating and finishing layers of general residential floors is considered in the estimation of the insulation properties of the panel as shown in Figure A.1. It is worth noticing that these layers are included in the structural calculation as additional dead load in the amount of 1.5 kN/m^2.

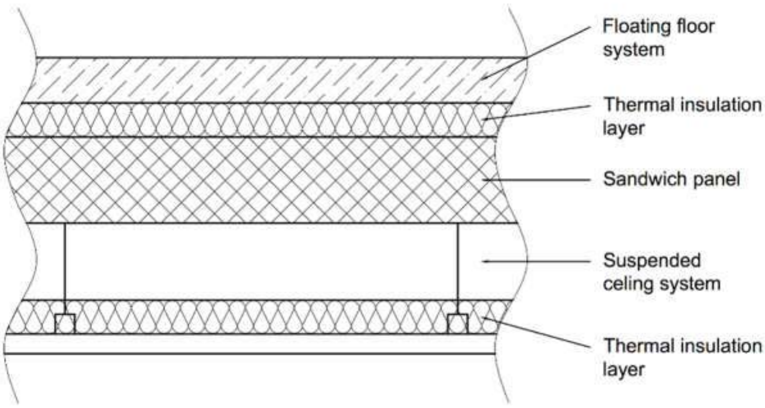


Figure A.1. Constructive detail of the sandwich panel floor with suspended ceiling and floating systems and thermal insulation layers

The corrected thermal transmittance, U_c, is obtained from

$$U_{\mathrm{c}} = U + \Delta U_{\mathrm{f}} \tag{A.5}$$

where ΔU_f is the correction factor for mechanical fasteners, i.e. the metal webs of the panel, which is given by

$$\Delta U_{\mathrm{f}} = \alpha \times \frac{\lambda_{\mathrm{f}} \times A_{\mathrm{f}} \times n_{\mathrm{w}}}{\mathrm{w}} \times \left(\frac{R_1}{R_{\mathrm{T,h}}}\right)^2 \tag{A.6}$$

In this expression the coefficient α depends on the length of the fastener, λ_f is the conductivity of steel, A_f is the cross-sectional area of one web, R_1 is the thermal resistance of the core insulating layer, and $R_{T,h}$ is the thermal resistance of the whole floor system without the webs.

Acoustic requirements

Finally, the acoustic insulation of the sandwich panel with respect to airborne and impact sound is estimated in accordance with Equation (A.7) and (A.8).

$$R = \quad 10\log(\tau) \tag{A.7}$$

$$L_{\mathrm{n}} = 125 \quad 30\log(m') + 10\log(T_{\mathrm{s}}) + 10\log(\sigma) + 10\log(f) \tag{A.8}$$

where m' is the mass per unit area of the panel, T_s is the structural reverberation time, σ is the radiation factor, and f is the frequency. The correspondent single number quantities, R_w and $L_{n,w}$, are obtained through a procedure illustrated in Figure A.2. A reference curve is translated until the difference with the estimated curve is less than 32 dB. The value of the shifted reference curve at 500 Hz is the single number quantity sought.

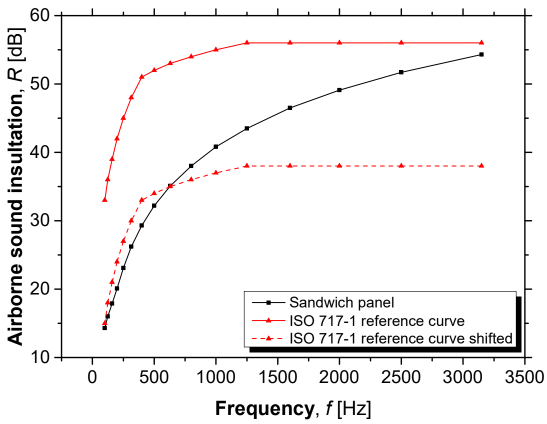


Figure A.2. Airborne sound insulation, R, of the sandwich panel and the ISO 717-1 (2013) reference curve with which the single number quantity, R_w, is obtained

The relative in-situ values, $D_{nT,w}$ and $L_{nT,w}$, accounting for different transmission channels other than direct transmission through the panel are then obtained from:

$$D_{\mathrm{nT,w}} = R_{\mathrm{w}} + 10\log\left(0.32 \times \frac{V}{S_{\mathrm{s}}}\right) \tag{A.9}$$

$$L_{\mathrm{nT,w}} = L_{\mathrm{n,w}} \quad 10\log(0.32 \times V) \tag{A.10}$$

where V is the volume of the receiving room and S_s is the surface of the sandwich floor panels separating the emitting and receiving rooms.

Declaration of conflicting interests

The author(s) declared that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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