Holistic Design Explorations of Building Envelopes Supported by Machine Learning

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Abstract
The design of building envelopes requires a negotiation between qualitative and quantitative aspects belonging to different disciplines, such as architecture, structural design, and building physics. In contrast to hierarchical linear approaches in which various design aspects are considered and conceived sequentially, holistic frameworks allow such aspects to be taken into consideration simultaneously. However, these multi-disciplinary approaches often lead to the formulation of complex high-dimensional design spaces of solutions that are generally not easy to handle manually. Computational optimisation techniques may offer a solution to this problem; however, they mainly focus on quantitative aspects, not always guaranteeing the flexibility and interactive responsiveness designers need in the early design stage. The use of intuitive geometry-based generative tools, in combination with machine learning algorithms, is a way to overcome the issues that arise when dealing with multi-dimensional design spaces without necessarily replacing the designer with the machine. The presented research follows a human-centred design framework in which the machine assists the human designer in generating, evaluating, and clustering large sets of design options. Through a case study, this paper suggests ways of making use of interactive tools that do not overlook the performance criteria or personal preferences of the designer while preserving the simplicity and flexibility needed in the early design stage.

Keywords
holistic design approach, building envelopes, graphic statics, conceptual structural design, machine learning, simplicity and performance

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1 INTRODUCTION

1.1 BUILDING ENVELOPES AND THE ILL-DEFINED NATURE OF DESIGN

The building envelope is the main interface between the outdoors and the interior spaces of a building. The design of building envelopes is an excellent example of a multi-disciplinary process in which both qualitative and quantitative aspects must be addressed simultaneously. Conflicting parameters belonging to diverse fields – such as architecture, structural design, and building physics – strongly influence the performance and the outcome of the design, thus making the building envelope a dominant system among all the subsystems in a building (Lang, 2013). Because of the number of aspects involved, it is crucial to operate in a holistic way in order to have effective coordination between these aspects throughout the entire design process, and especially in the conceptual phase. Designers have to find suitable trade-offs based on a cognitively complex process of synthesis between objective and subjective evaluations. Digital tools offer adequate support to designers in dealing with such a complexity. However, their implementation within the design process is not always straightforward. Indeed, computers typically require a precise numerical formulation and univocal objectives (Harding & Olsen, 2018), elements that are both generally in conflict with the ill-defined nature of the design process itself (Rittel & Webber, 1973).

1.2 HOLISTIC DESIGN OF BUILDING ENVELOPES

When dealing with the design of building envelopes, designers have the opportunity to explore different levels of integration between disciplines (Rush, 1986) and investigate the influence of each aspect, starting from the early design stage. Definition of the architectural space, load-bearing capacity, and mitigation of external climate conditions are all aspects that can become an integral part of the building envelope. Despite the lack of a univocal definition (Rush, 1986), the term *holistic* – or *integrated* – *design* refers here to an approach based on mutual relationships between the different aspects involved in the design process.

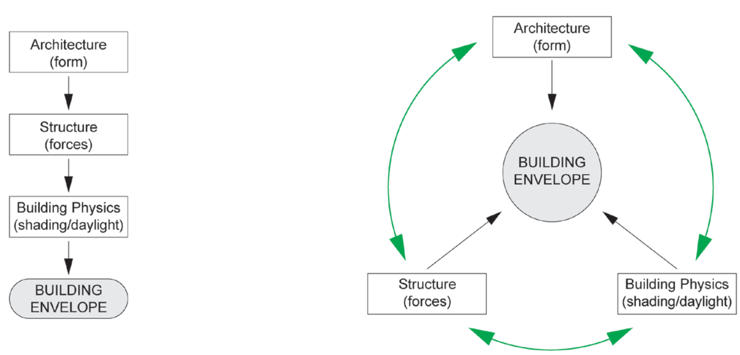

FIG. 1 Schematic workflow of a possible sequential linear approach (left) and a holistic approach (right) for the design of building envelopes

The present research is based on the assumption that the lack of such relationships often leads to a linear design process (Fig. 1, left) where the outcome is conceived just as a sum of the different parts (Saint, 2007), and which frequently entails the non-optimal use of material resources (Nervi, 1965). Conversely, the ability to operate through holistic approaches (Fig. 1, right) would foster an interdisciplinary discourse that, in addition to widening the range of possible design options, ultimately allows for more conscious use of the available resources in the final built constructions. This paper aims to investigate the latter strategy, regarding geometry as the mediator between architectural qualities, structural and sun-shading performance of the building envelope. Specifically, the research focuses on the interplay between the form of the building envelope, the inner forces within its load-bearing structure, and its performance in terms of solar protection and daylight modulation.

1.3 DIGITAL DESIGN FRAMEWORKS IN ARCHITECTURE AND ENGINEERING

A design framework can be generally characterised as a process that is composed of different individual operations (Brown, Jusiega, Mueller, 2020). Fig. 2 schematically shows three characteristic frameworks that represent an adaptation of the work of Oxman (2006) and Wortmann (2018). The main features of these three different frameworks will be briefly described in the following paragraph.

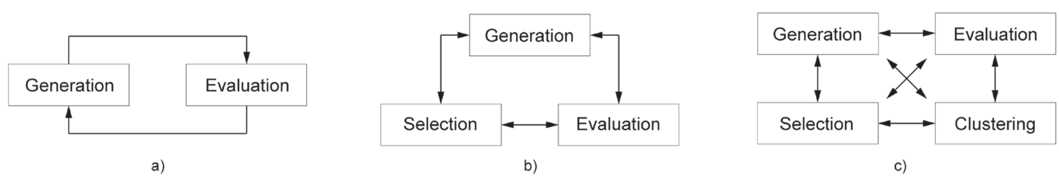

FIG. 2 Three design frameworks, with their different operations and relationships highlighted

One typical design approach is to first *generate* design options and then *evaluate* them with respect to a set of criteria. Designers can repeat this sequence, meaning that they can generate new options according to the results of the evaluation in a trial-and-error fashion (Fig. 2a). Thanks to the introduction of digital parametric tools, designers can now automatically generate a vast number of alternative options with minimal computational effort. However, this generation is often not directly guided by any performance criteria. Hence, such a problem-oriented approach is often time-consuming and not very efficient when dealing with multi-dimensional design spaces that involve a high number of design parameters. One possible way to address this challenge is to make use of optimisation techniques such as multi-objective optimisation (MOO). These techniques allow the *evaluation* step in searching for the best performing options to be simplified. More precisely, in the case of multi-objective optimisation, they support guided explorations of the design space, providing sub-optimal options (Brown & Mueller, 2017; Turrin, Von Buelow, & Stouffs, 2011; Yang Ren, Turrin, Sariyildiz, & Sun, 2018), from which the designer has to make a *selection* (Fig. 2b). Although very powerful in solving well-defined problems, optimisation techniques do not always offer the flexibility and the responsiveness necessary in early, ill-defined design stages. In this context, the major challenge is that all design objectives must be explicitly formulated before they are even known (Harding & Olsen, 2018), thus making the inclusion of qualitative aspects rather complex to achieve. The introduction of an intermediate *clustering* step enables the systematic integration of such qualitative considerations (Fig. 2c). For example, clustering algorithms based on machine learning can provide additional support by automatically organising large sets of diverse design options according to similarities pertaining to specific criteria (Wortmann & Schroepfer, 2019).

In combination with filtering functions, these algorithms offer the possibility to manage vast, multi-dimensional design options and eventually allow designers to negotiate quantitative and qualitative aspects according to personal preferences (Harding & Olsen, 2018; Fuhrimann, Moosavi, Ohlbrock, & D'Acunto, 2018; Saldana Ochoa, Ohlbrock, D'Acunto, & Moosavi, 2020). Following this approach, the designer is prevented from being overwhelmed (Brown & Mueller, 2017) by examining all the options individually and at the same time is not forced to focus exclusively on quantitative aspects. In line with the approach of Saldana Ochoa et al. (2020), the present research also implements a design process that includes *generation*, *evaluation*, *clustering*, and *selection* steps with the scope of considering both quantitative performance criteria and qualitative preferences of the designer while preserving the simplicity and flexibility needed in the early design stage.

1.4 OBJECTIVES AND CONTENT OF THE PAPER

This research aims to support an effective design workflow for the multi-disciplinary design of building envelopes, with a particular focus on the conceptual design phase. Thanks to its holistic nature, the proposed approach fosters new design possibilities and opens up new perspectives for the conscious use of the available resources. Following a geometry-based approach in which the form of the building envelope is simultaneously informed by aspects related to architecture, structure, and solar control, a set of user-defined performance criteria are taken into consideration without necessarily overlooking the qualitative aspects involved in the design.

The paper is structured as follows. Section 2 outlines the methods that form the basis of the research, introducing the applied geometry-based approach, the digital tools involved, and the metrics considered. Section 3 illustrates the advantages of the proposed framework through a case study in which several non-standard design options for a load-bearing façade are investigated and discussed. Finally, Section 4 outlines the conclusions and presents an outlook on future work.

2 METHODOLOGY

2.1 GEOMETRY-BASED DESIGN APPROACH

Geometry plays a crucial role in the generation of architectural space. This dependency from geometry persists in other fields, thus making geometry a common ground where aspects belonging to diverse fields meet. For example, in structural design, geometry plays a key role in defining the overall behaviour of a structure. Equilibrium-based methods such as graphic statics (Culmann, 1866; Maxwell, 1864; Cremona, 1872) and their contemporary digital implementations have proved to be powerful tools for the generation of structures (Van Mele, Rippmann, Lachauer, & Block, 2012; Rippmann, Lachauer, & Block, 2012; Beghini, Carrion, Beghini, Mazurek, & Baker, 2014; D'Acunto et al., 2019; Konstantatou, D'Acunto, & McRobie, 2019; Ohlbrock & D'Acunto, 2020). Unlike analytical methods, which are generally implemented through quantitative numerical approaches, geometry-based methods provide significant support since the conceptual stages of the design, when a visual understanding of forces is essential in order to generate creative design options (Schwartz, 2012; Kotnik & D'Acunto, 2013). Geometry has a relevant role also in the phase of evaluation of given design options. Digital tools for structural and energy analysis can now provide very accurate calculations on high resolution models. However, this often comes at the price of long computation time, and it requires a consistent effort for the creation of the models. Since such accuracy usually is not needed in the early stage of the design, material-independent geometry-based approaches represent a suitable simplification for conceptual design tasks and are therefore the base for the present research. Detailed models that take into account material properties can be then included in the design process at a later stage.

2.2 TOOLS, PARAMETERS AND METRICS USED IN THE DESIGN PROCESS

Fig. 3 gives an overview of the various tools that are part of the proposed design framework for the conceptual design of building envelopes. Drawing from the approach presented by Saldana Ochoa et al. (2020), the proposed framework consists of four main steps: *generation*, *evaluation*, *clustering*, and *selection*. The whole framework is developed using the CAD platform Rhinoceros (www.rhino3d.com, accessed 20/11/2020) and the Grasshopper visual scripting environment (www.grasshopper3d.com, accessed 20/11/2020).

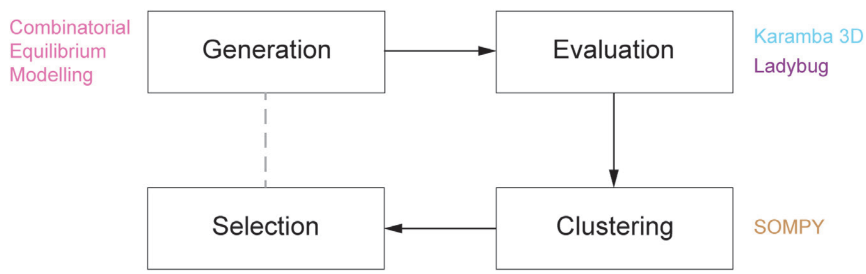

FIG. 3 Different tools integrated into the proposed framework for the conceptual design of building envelopes

The *generation* of design options is addressed through the Combinatorial Equilibrium Modelling (CEM) (Ohlbrock & D'Acunto, 2020). The CEM is a digital form-finding tool grounded in vector-based 3d graphic statics (D'Acunto et al., 2019), and it is used in this work to quickly generate a broad set of form diagrams in static equilibrium as pin-jointed frameworks that represent the structures of load-bearing building envelopes. Within the CEM, the edges of the form diagrams are subdivided into two distinct categories: the *trail edges* that connect each node with a (topologically) direct load transfer to the closest support; the *deviation edges* that connect nodes on different trail edges. Moreover, the user can directly assign a set of metric values to the edges, and specifically the *trail lengths* – i.e. the lengths of the trail edges – and the *deviation force magnitudes* – i.e. the force magnitudes of the deviation edges (Ohlbrock & D'Acunto, 2020). After the definition of the topology of the structure and the dominant load case, which in this case are kept constant, the CEM is able to generate different form diagrams as alternative *design options*. This step is performed considering various user-defined combinations of tension and compression forces in the edges of the form diagrams and metric values assignments for the *trail lengths* and the *deviation force magnitudes*.

Interpreting the form diagrams generated via the CEM as framed structures, various additional performance metrics are then assessed (*evaluation)* for each design option. The Finite Element Analysis (FEA) tool Karamba3D (Preisinger, 2013) is used to evaluate the linear-elastic response of the framed structures under lateral loads in terms of axial and bending deformation energies. The evaluation of environmental criteria such as solar radiation and daylight availability is performed using Ladybug Tools (Roudsari, Pak, & Smith, 2013).

Table 1 shows all the parameters and metrics that are used to describe each design option (form diagram and related framed structure). Note that Load Case 1 [LC1] refers to the vertical loads considered in the generation of the form diagram and Load Case 2 [LC2] to additional unitary horizontal forces taken into account in the FEA. For each generated design option, its geometric characteristics and related performance values, evaluated using the parameters and metrics of Table 1, are recorded into an indexed multi-dimensional vector $D_k = \{d_{k,1},..., d_{k,n}\}$. The latter is stored in a dataset, which constitutes a numerical description of the *design space*.

TABLE 1 List of parameters and metrics used to characterize each design option

SOURCE	PARAMETER/METRIC	LABEL	DESCRIPTION	UNITS
CEM	node position	posXY	position of the nodes (x_i, y_i) in the form diagram	[m]
	edge (trail/deviation) length	edgeLen	length of trail and deviation edges in the form diagram	[m]
	edge (trail/deviation) magnitude	edgeMag	magnitude of axial forces within trail and deviation edges in the form diagram	[kN]
	edge load path [LC1]	edgeLP	product of the length l_i of each edge of the form diagram by the axial force f_i acting in it	[kNm]
	total load path [LC1]	totLP	sum of the products of the length l_i of each edge of the form diagram by the absolute value of the axial force f_i acting in it	[kNm]
	max/min force [LC1]	forMax, forMin	maximum and minimum axial forces within the edges in the form diagram	[kN]
Karamba3D	total mass	totMass	total mass of the structural members of the framed structure	[kg]
	axial deformation energy [LC2]	defAxial	sum of the products of axial forces of the framed structure by the corresponding displacements parallel to their direction	[Nm]
	bending deformation energy [LC2]	defBend	sum of the products of bending forces of the framed structure by the corresponding displacements parallel to their direction	[Nm]
Ladybug	solar radiation reduction	SRR	reduction in percentage of the total amount of solar radiation on a test point without shading elements (SR_i) and with shading elements (SR_f)	[%]
	daylight factor	DF	ratio between the illuminance at an indoor test point (E) and the illuminance at an outdoor test point (E_0)	[%]

Hard quantitative filtering criteria can be then implemented to eliminate the relatively worst-performing sub-set of the design space. After this filtering process, Self-Organizing Maps (Kohonen, 1982) are used for *clustering* the design space. Self-Organising Maps (SOMs) can be regarded as a specific class of unsupervised artificial neural network, which allows for data dimensionality reduction without the loss of non-linear associations between the data (Harding, 2016). Based on user-defined clustering criteria, the SOM algorithm maps the data from a high-dimensional space onto a lower-dimensional one, without losing the topological features of the high-dimensional space. That is, the design options are clustered in the low-dimensional space based on the distance of their corresponding data points in the high-dimensional space. In this way, it is possible to conveniently represent a multi-dimensional design space onto a 2D map, in which each node N_j (x_{j1}, x_{j2}) of the map has an associated multi-dimensional vector $W_j = \{w_{j,1},..., w_{j,n}\}$ or Best Matching Unit (BMU). In fact, each node of the map contains a cluster of design options that are similar with respect to the defined clustering criteria. The SOM thus provides the designer with a quick overview of the design space. The algorithm used in this work is implemented within the Python environment using SOMPY (Moosavi, 2014).

Eventually, in the *selection* step of the design process, the designer can easily navigate within the SOM and select the preferred design options considering both quantitative and qualitative criteria. If necessary, design options can be filtered out according to quantitative criteria in order to reduce the size of the design space further.

3 CASE STUDY

This section outlines an application of the proposed framework for the design of load-bearing and shading façades based on the *FAU Building* designed in 1964 by the Italian architect Enrico Tedeschi (1910-1978) for the campus of the Architecture Faculty of Mendoza, Argentina (Fig. 4).

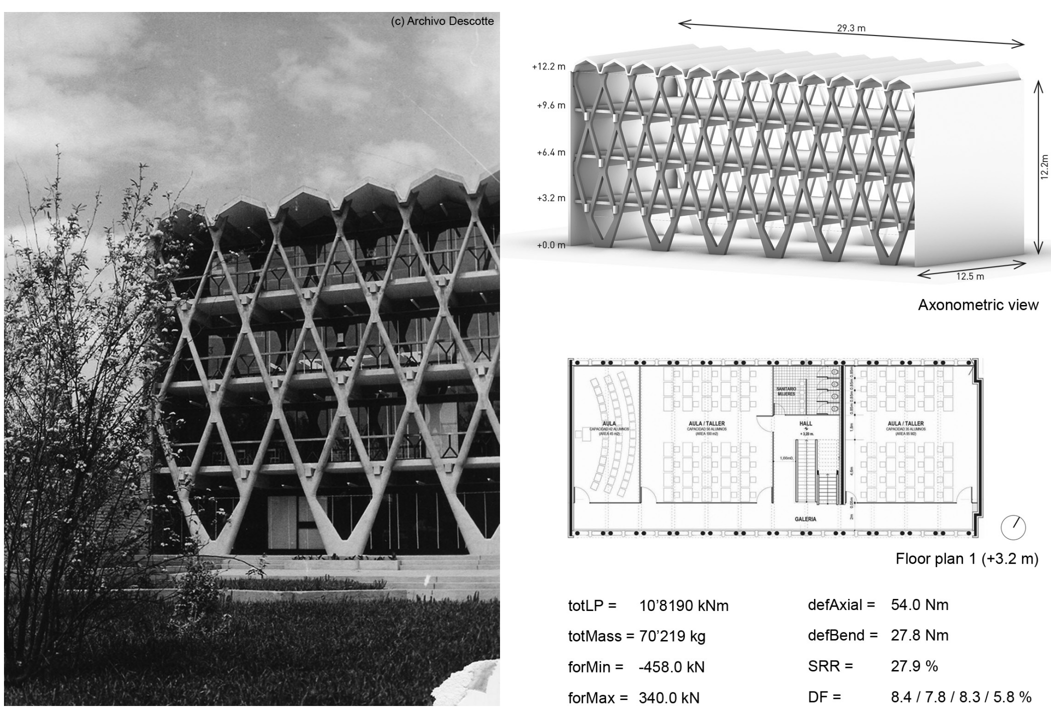

FIG. 4 FAU Building (1964), arch. Enrico Tedeschi, Mendoza (Argentina)

This building was chosen as a case study as its façades are not only load-bearing, but they also provide solar protection to the glazed surfaces and create a unique architectural motif for the building. It is, therefore, a relevant example of a holistic design approach, in which aspects related to architecture, structure, and solar control are considered at the same time. The façades on the long side of the FAU Building are planar diagrids made of reinforced concrete elements with a hollow circular cross-section that support a series of post-tensioned concrete beams spanning 12.5 metres across the façades (Codina, 2013). Thanks to these reticular façades, the architect could achieve column-free spaces and solve the question of horizontal stability at the same time, a peculiar feature considering the high seismicity of the zone. A critical aspect of the design was the control of natural lighting. In this case, the objective of the architect was to obtain diffuse lateral lighting, avoiding glare and overheating issues due to direct solar radiation on the glazed surfaces.

3.1 GENERATION AND EVALUATION OF THE DESIGN OPTIONS

Taking the FAU Building as a reference, various alternative design options for its façade were explored following the proposed design framework, based on the same design objectives that led to the realisation of the FAU Building.

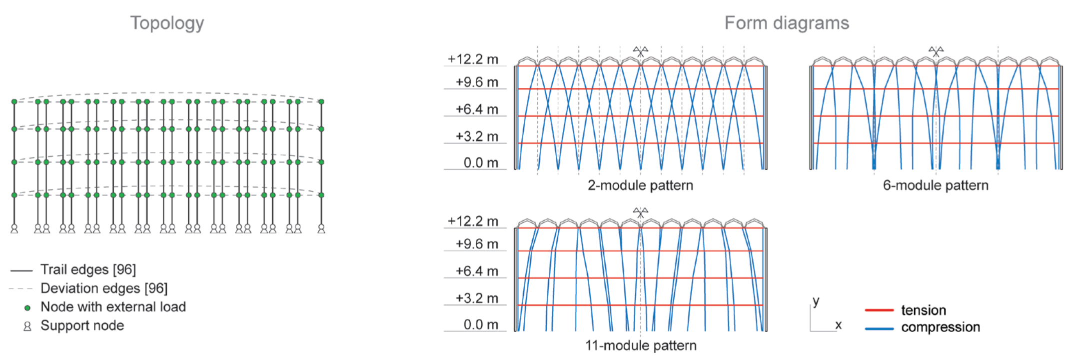

FIG. 5 Generation of various form diagrams (right) via the CEM. The topology (left), the floor heights and the load-case are kept constant, and only the distribution of deviation force magnitudes (devMag) is varied

Fig. 5 (left) shows the topology of the structure that was used as a base for the entire generative process via the CEM. The topology consists of 120 vertices, which are connected through 96 trail edges and 96 deviation edges. The 96 values of the deviation force magnitudes (*devMag*) were randomly generated following linear, parabolic, and sinusoidal distributions. These distinct force distributions were then applied to groups of two, six, or eleven neighbouring edges, keeping the central axis of the form diagram as an axis of symmetry. The values of the trail lengths (*trailLen*) were controlled by the given floor heights and the necessity to ensure that all the nodes of the form diagram belonging to the same floor were horizontally aligned. External forces [LC1] were applied to the nodes of the form diagram according to their corresponding tributary area and assuming a 10 kN/m^2 distributed load on the floor slabs (5 kN/m^2 dead load + 5 kN/m^2 live load). Fig. 5 (right) shows three exemplary form diagrams that resulted from this generative set-up in which only the 96 deviation force magnitudes (*devMag*) were automatically varied (Fig. 6a).

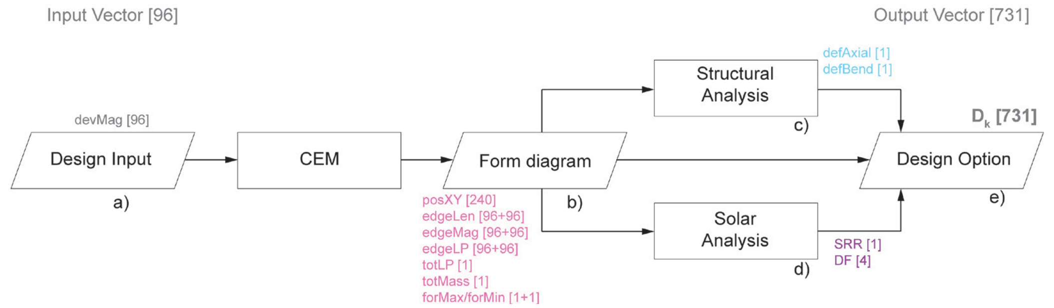

FIG. 6 Flowchart of the generation and evaluation steps showing the parameters involved, their labels (Table 1) and the number of items for each parameter (in square brackets)

Each of the form diagrams was subsequently interpreted as a framed structure and then analysed in relation to structural (Fig. 6b, c) and sun-shading performance (Fig. 6d) using the CEM, Karamba, and Ladybug. These analyses were carried out in order to evaluate the quantitative metrics introduced in Table 1. In particular, the total mass *totMass* of each design option was calculated considering hollow circular cross-sections in reinforced concrete (C20/25) for the façade elements, dimensioned according to the axial forces they had to withstand. The evaluation of the axial and bending deformation energies – *defAxial* and *defBend*, respectively – was performed with respect to a load case [LC2] where unitary horizontal forces were applied to the framed structure in addition to the vertical forces of load case 1 [LC1]. The solar radiation reduction *SRR* was calculated on a vertical test grid corresponding to the glazed surface of the façade, with a resolution of 0.5 x 0.5 m and an analysis period of one year. Four daylight factors *DF(0-3)* were evaluated considering four horizontal test grids, with a resolution of 1.0 m by 1.0 m, located at the four floors, at a height of 0.9 m above the floor planes. Each generated design option (form diagram and corresponding framed structure) and its performance was then numerically described using a 731-dimensional indexed vector $D_k = \{d_{k,1}, ..., d_{k,731}\}$ (96 input and 635 output) (Fig. 6e). Using a 10-core 2.5 GHz CPU, the generation and evaluation of each design option required 15 seconds, on average. By taking advantage of parallel computing, it was possible to generate and evaluate 20'144 design options in about 20 hours.

3.2 QUANTITATIVE FILTERING AND CLUSTERING OF THE DESIGN OPTIONS

In order to describe the peculiarities of the design options synthetically, the higher-order statistics (mean, variance, skewness, kurtosis) (Farid, 2002) of the following parameters were additionally calculated: position of the nodes *posXY*, edge length *edgeLen*, edge force magnitude *edgeMag*, edge load path *edgeLP*. Before proceeding with the clustering of the generated design options, hard filters were introduced to eliminate those design options that did not meet specific performance levels. The filtering criteria and their sequence of application can be defined by the user based on the task at hand. Within the analysed case study, the following filters were applied: total load path *totLP* (90^{th} percentile, 18'129 options kept), maximum edge force *forMax* (90^{th} percentile, 15'944 options kept), minimum edge force *forMin* (90^{th} percentile, 14'349 options kept), and solar radiation reduction *SRR* (90^{th} percentile, 12'758 options kept). That is, from the initial set of 20'144 design options, 12'758 were kept after the filtering process.

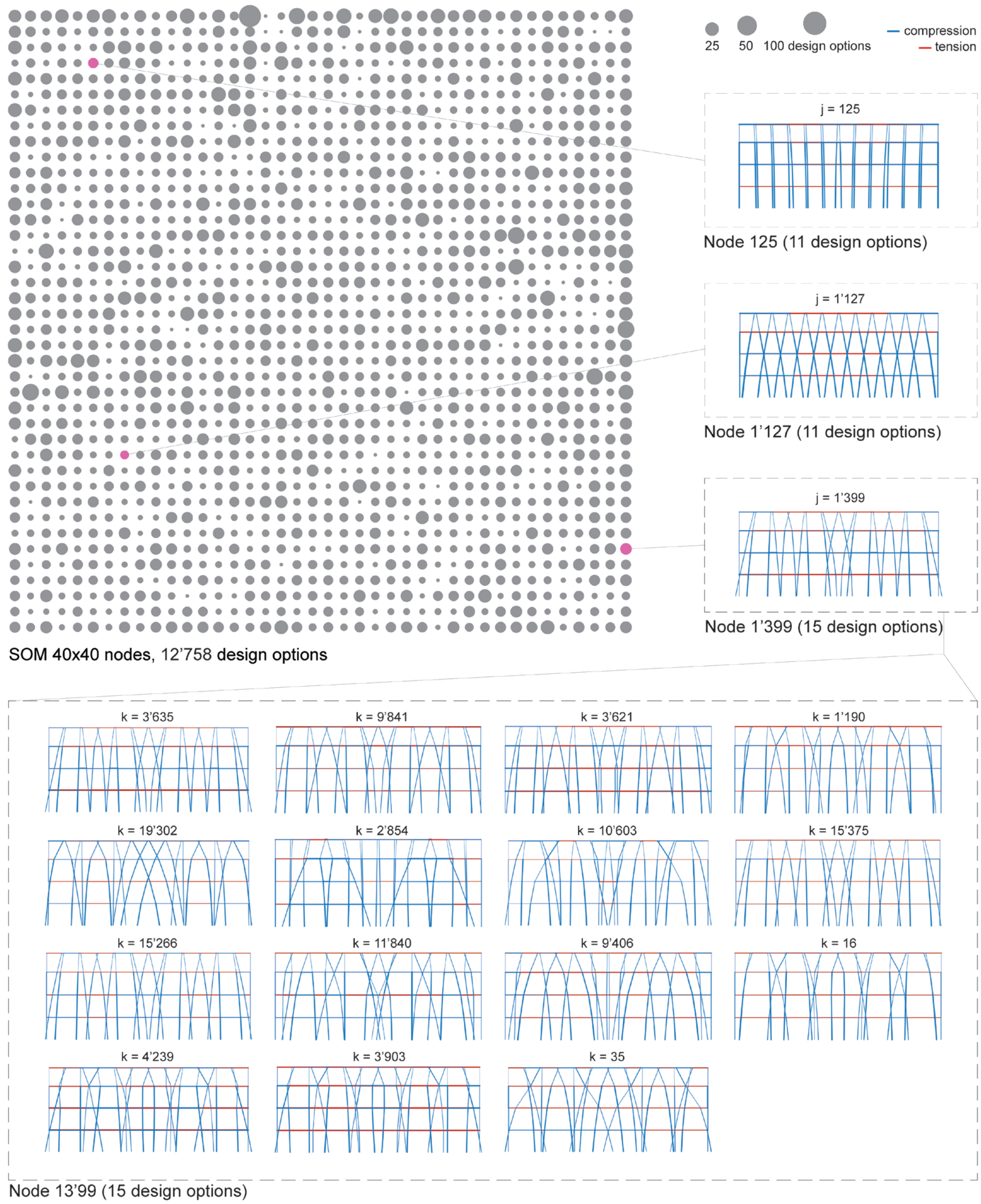

FIG. 7 Using the SOM algorithm, the generated and filtered design options (12'758) are clustered onto a 40x40 map (top left). Each node Nj of the map (grey circle) contains several design options, the size of the circle being proportional to the number of design options contained in that node. Representative design options for three nodes of the grid (N125, N1127, N1399) are shown (top right). The designer can easily navigate within the design space and select any of the nodes to explore further the entire set of design options contained therein. For example, N1399 (bottom) includes 15 similar design options, each one identified with its corresponding index k and the associated 731-dimensional vector Dk.

After the filtering process, the remaining design options were clustered onto a 40 x 40 map using the SOM algorithm (Fig. 7). The clustering was performed taking into account the following parameters: total mass *totMass*, maximum edge force *forMax*, minimum edge force *forMin*, axial deformation energy *defAxial*, bending energy *defBend*, solar radiation reduction *SRR*, and higher order statistics of edge load path *edgeLP*, position of nodes *posXY,* and daylight factors per floor *DF*.

3.3 SELECTION OF THE FINAL PREFERRED OPTIONS

Thanks to the SOM, the designer can navigate a complex multi-dimensional design space, having a clear overview of the relationship between the different design options with respect to qualitative and quantitative criteria. If necessary, the designer can also re-iterate the process investigating a different clustering strategy, introducing new filters for the quantitative evaluation, or generating a new pool of design options informed by the outcome of the first iteration. Within the analysed case study, additional filters were applied to the SOM (Fig. 7) to narrow down the design space further and proceed with the selection of three final design options. Considering the distribution maps of Fig. 8, in the first case, only those design options whose total mass *totMass* was less than the 5th percentile and the mean value of daylight factor *DF_mean* was greater than the 90th percentile were considered. These filters accounted for 14 nodes in the SOM (Fig. 9). Out of this subset, node N_{61} (j = 61), containing 20 design options, was chosen. Among these design options, the one with index k = 16'562 was eventually selected as *Option A*.

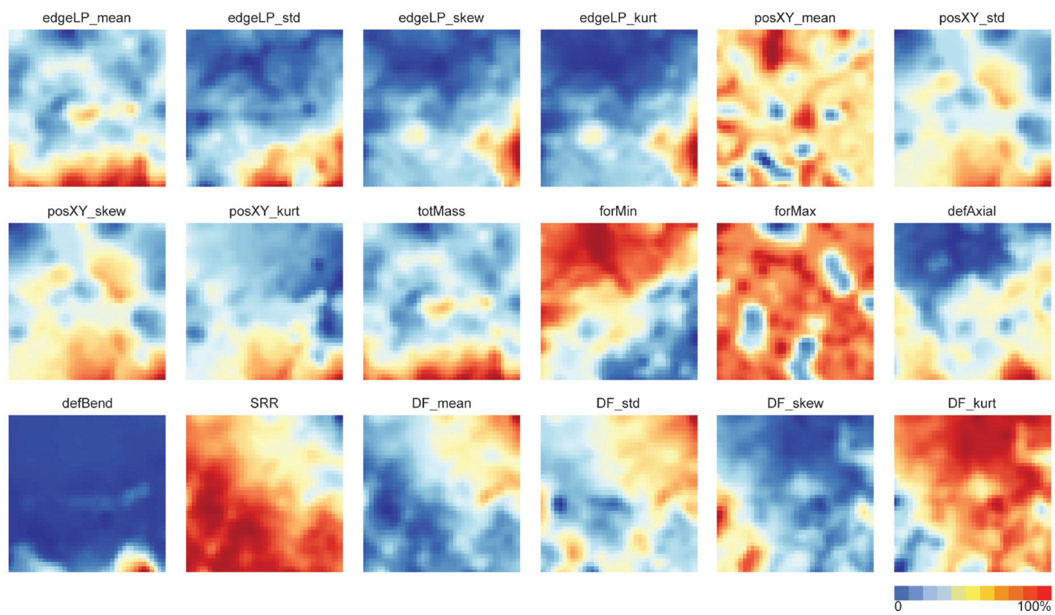

FIG. 8 Distribution maps of the 18 parameters used for the SOM. Values are normalised in the range 0-100%.

Following a similar procedure, *Option B* (j = 969; k = 19'117) was selected among the design options with a standard deviation value of daylight factor *DF_std* lower than the 10th percentile and maximum force magnitude *forMax* lower than the 5th percentile. Finally, *Option C* (j = 1'213; k = 1'041) was selected among the design options with a solar radiation reduction *SRR* higher than the 95th percentile and a standard deviation value of the position of the nodes *posXY* higher than the 70th percentile.

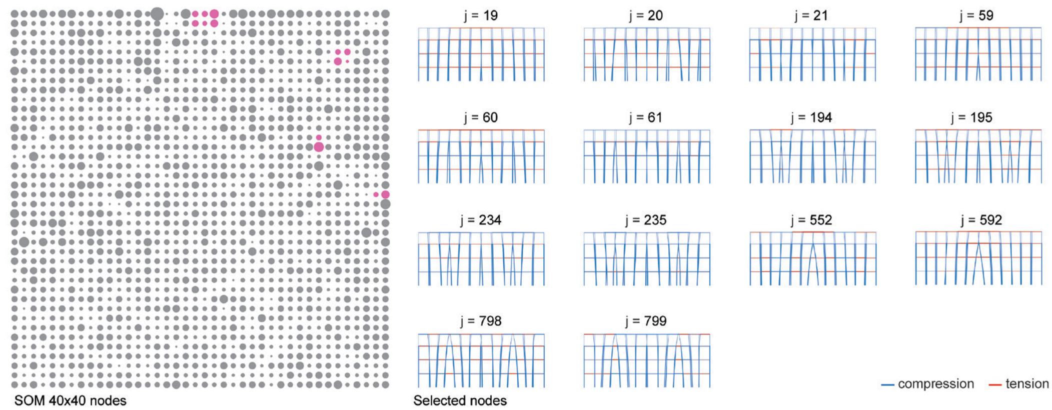

FIG. 9 Selection procedure for Option A (j = 61; k = 16'562). Representative design options (right) for the 14 nodes retained from the 40 x 40 SOM (left) after the application of hard filters on the total mass totMass (5th percentile) and the mean value of daylight factor DF_mean (90th percentile).

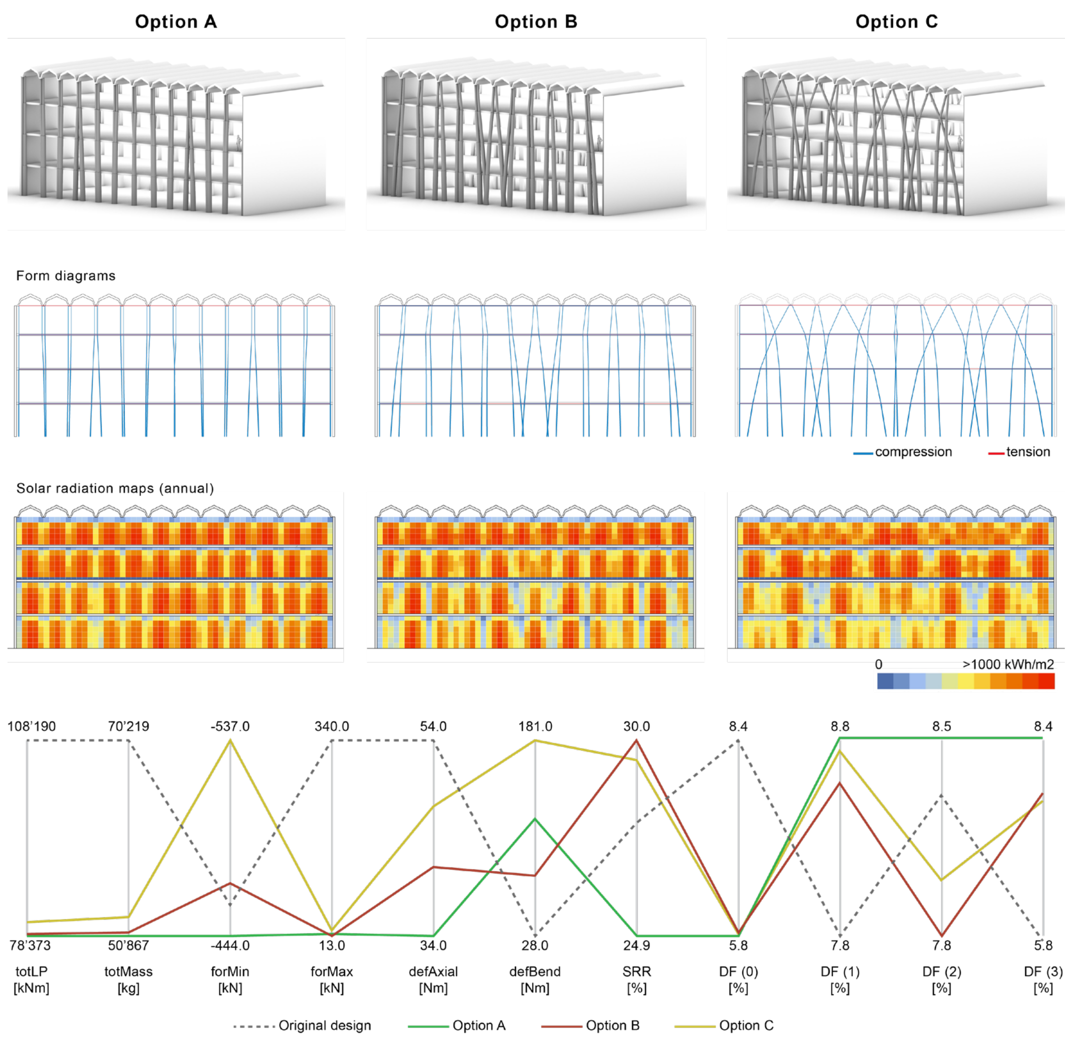

FIG. 10 Axonometric views, structural diagrams, and solar radiation maps for 3 options extracted from the dataset

3.4 DISCUSSION

The parallel coordinates plot in Fig. 10 shows the structural and sun-shading performance metrics of the three selected design options in comparison to the original design of the FAU Building by Enrico Tedeschi. Although illustrating very diverse geometries and patterns, all the selected design options are characterised by similar values for the total load path *totLP* and its correlated total mass *totMass* (Fig. 10), which are lower than those of the original design. These differences can be mainly explained with the high maximum axial forces *forMax* that is needed to redirect the accumulated vertical forces at the height of the first floor in the original design. Since the original design defines an overall triangulated structure, the bending deformation energy *defBend* is smaller than the one calculated for the selected design options, which strongly rely on the bending capacity for resisting lateral loads. Among the selected design options, *Option B* and *Option C* show a better performance for the solar radiation reduction *SRR* in comparison to *Option A* and the original design. As expected, when it comes to the daylight factor on different floors, the opposite can be observed.

The presented design exploration considered the FAU building as a reference case study. Several global and local geometric parameters used for the generation of the façades were intentionally made compliant with the original design. Indeed, introducing additional geometric parameters such as, for example, three-dimensionality of the façade geometries, variable overhang of the floor slabs and roof, and adjustable cross-section geometries of the façade elements, could potentially widen the design space and possibly lead to the generation of entirely new design options. For instance, the cross-sections of the façade elements could be materialised into different shapes, thus introducing further local variations among the design options. Fig. 11 shows a possible application of such a principle, taking *Option C* as a reference. The geometry of the façades in *Option C1* and *Option C2* are based on the form diagram of *Option C,* but their edges are materialised into façade elements with rectangular cross-sections instead of the circular hollow cross-sections of the original design. While neglecting local instability problems, the façade elements of *Option C1* and *Option C2* are dimensioned to withstand the same axial forces of *Option C* – i.e. same cross-section areas. As a result, these three options have the same values for total load path *totLP*, total mass *totMass,* and maximum and minimum internal forces *forMax/forMin*. In particular, the façade elements in *Option C1* are thin walls perpendicular to the plane of the façade. While its width is kept constant, its thickness is adjusted proportionally to the axial force it has to resist. The cross-section of the façade elements in *Option C2* follows a similar rule, although in this case, the elements are parallel to the plane of the façade. The parallel coordinates plot in Fig. 11 shows that varying these local parameters has an impact not only on the visual appearance of the design options but also on their sun-shading performances in terms of solar radiation reduction *SRR* and daylight factor *DF*. This parallel coordinates plot further visualises the relationships between the different considered metrics and informs the negotiation process that is, in any case, necessary in multi-disciplinary design.

4 CONCLUSIONS AND FUTURE WORK

Despite allowing full control over the design process, manual design explorations often show severe limitations due to the restricted evaluation capabilities of the designer when dealing with vast, multi-dimensional design spaces. With the aim to couple the advantages of traditional interactive manual explorations with the power of contemporary computational approaches, this paper presented a holistic framework for the conceptual design of building envelopes that integrates aspects related to architecture, structural design, and building physics.

The proposed framework relies on a geometry-based tool (Combinatorial Equilibrium Modelling - CEM) for the generation of design options as structures in static equilibrium, tools for the evaluation of the structural (Karamba3d) and solar (Ladybug) performances of these options, and machine learning (Self-Organising Map - SOM) for clustering the design space. These tools facilitate the designer in the selection process, which is informed by sets of quantitative performance criteria and takes into consideration the designer's subjective preferences at the same time. The machine eventually becomes a precious support through which the designer can easily generate, evaluate, cluster, and finally select one or more suitable design options.

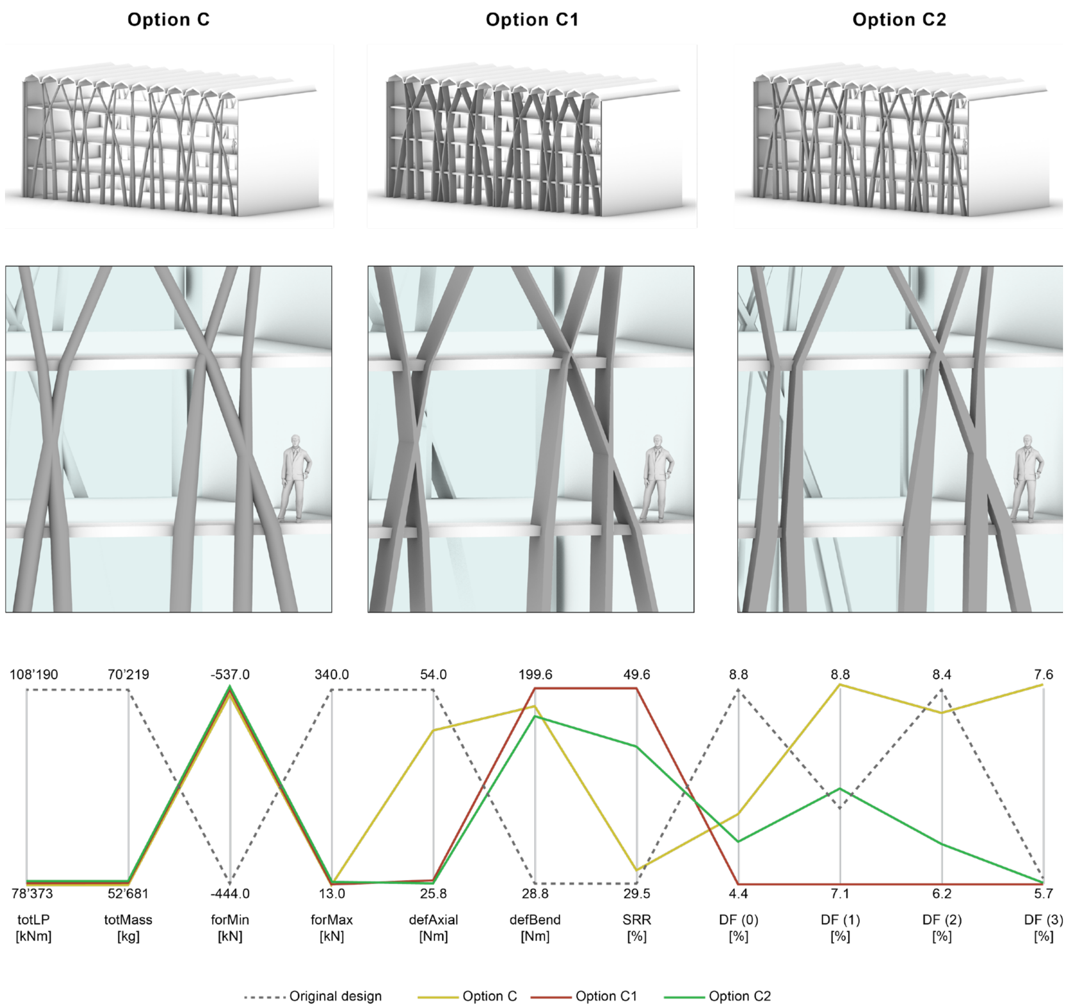

FIG. 11 Three different materialisations of the same form diagram. While keeping constant values for the cross-section areas, rectangular cross-sections with different proportions (Option C1 and C2) are compared to the circular hollow sections of Option C.

The illustrated case study demonstrated the application of the proposed design framework to the design of alternative solutions for an existing building façade. This example was developed by running the different steps of the proposed design process in a sequence. Future work will explore the opportunity of using the set of design options selected by the designer to inform the re-generation of new design options, potentially through supervised machine learning algorithms for classification (Saldana Ochoa et al., 2020). Besides, in the proposed generative step carried out using the CEM, the topology of the structure was kept constant. A computational implementation that is topologically flexible would allow the number of possible design options to be significantly enhanced, thus fostering the diversity and openness needed in the early design stage without overlooking performance criteria or personal preferences of the designer. Future developments of this research will thus investigate possibilities to compare and cluster design options with different topologies. Moreover, further applications and extensions of the design framework to different case studies and building typologies will be investigated as well as the combination with other relevant design aspects.

When dealing with building energy simulations, long computation times may represent a significant limitation for workflows that benefit from the interactivity in the early design phase. In the presented case study, this issue was solved by reducing the number of aspects evaluated and by keeping the overall resolution of the simulation on a moderate level. A possible approach to reduce computation time could be the implementation of surrogate modelling, which has already been applied to building energy simulation in the early design stage in several research projects (Ritter, Schubert, Geyer, Borrmann, & Petzold,., 2014; Wortmann, Costa, Nannicini, & Schroepfer, 2015). Alternatively, geometry-based solar design tools (Olgyay & Olgyay, 1957; Lechner, 2014) – similarly to graphic statics in the field of structural design – could represent a possible alternative research direction. Interpreting sun rays as vectors that interact with the building envelope, simplified solar radiation and daylight availability studies could be embedded into a fully geometrical generative tool that possibly allows for real-time design explorations. The designer would mostly interact with a limited number of parameters, such as the angle and intensity of sun rays and the geometry of the building itself. Indeed, being able to integrate environmental parameters as early as the generative phase of the design process would greatly enhance the variability of the design space.

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