A Generative Design Method for Cultural Heritage Applications: Design of Supporting Structures for Artefacts

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Abstract. This paper presents a Generative Design Method (GDM) for highly customised Cultural Heritage applications concerning the exhibition and conservation of pottery. As a fundamental requirement, archaeological finds must be preserved in their structural integrity. Additionally, when present, the exposition supports must be aesthetically pleasant meaning that they must be non-invasive in the field of view of the observer. Furthermore, each artefact presents a unique geometry, hence its supporting structure must be designed accordingly. The proposed GDM considers these requirements, adopting a synergy of CAD, CAE, and optimisation tools. It is developed through two phases. The first phase, P_1, concerns with the structural integrity of the fragment. In this phase, a Parametric Modelling approach is chosen for its ease of use both in the Finite Element Analysis evaluations of artefacts and in the design and optimisations of feasible supporting structures. The output of the phase P_1 is the optimised configuration of the functional elements of the support ('C_i') which are the interface region between the support itself and the fragment of pottery. They represent the input of the second phase, P_2, that aims to generate lightweight concepts for the complete supporting structure considering the optimal 'C_i' configuration. During this phase, an aesthetics criterion (related to the minimisation of the support's visibility) is also considered to achieve non-invasive supporting structures. Doing so, the GDM provides informed decisions in the early stages of the design activities with a simulation driven approach oriented to manufacturing. In this way, users are able to focus on design requirements since the concept's variants are generated by means of an optimised configuration of standardised components ('C_i') and obstacle geometries.

Keywords: Generative Design, Parametric Modelling, Parametric Optimisation, Cultural Heritage
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1 INTRODUCTION

In the field of Cultural Heritage (CH), CAD and CAE have provided great improvements in the transportation, restoration and conservation of ancient artefacts. For example, [15] provides a method for design automation of the packaging for artefacts and, in [16], a survey is provided considering other methods (lattice structures) along with the latest digital techniques to support the CH field. In [1], it has been proven that it is possible to apply FEM with good approximation to ancient bronze statue and, in [4], [6] and [7], FEA has been applied to support the restoration of an ancient bronze statue to explore different positions of statue's fragments. Also, in [2], Topology Optimisation (TO) has been used to design the inner frame of a statue. Regarding pottery, a lot of work has been done in the automatic alignment of fragments [11]. However, nothing has been found in the literature about the creative design and the generative design of supporting structures for the exposition in museums of ancient pottery. This is probably because these structures are mostly designed by architects according to the exhibition needs and manufactured by artisans. Hence, it represents a time-consuming procedure since it requires to manually acquire the geometry of the pottery and to decide the anchor points for the assembly. Moreover, this choice is not supported by any stress analysis, so it exposes the fragment to possible stress concentrations which may lead to a failure of the artefact. Therefore, a Generative Design Method (GDM) to aid the design process for highly customised components in Cultural Heritage is proposed. In particular, the developed GDM focuses on the conceptual design of supporting structures for fragments of pottery for both exhibition and conservation.

The GDM is simulation-driven and manufacturing-oriented in order to provide an effective tool to ensure informed decisions in the early stage of designers and archeologists activity [5]. Indeed, Finite Element Analysis (FEA) and Generative Design (GD) are selected to account for structural performances and manufacturing methods, in addition to limitations connected to orientation and visibility issues in exposition. According to this, GD is used to derive lightweight and manufacturable conceptual structures of the fragment's support for the desired orientation of the artefact. In fact, Generative Design is an iterative algorithmic design methodology which introduces a certain level of automation in the design process [12, 14, 18]. GD gives the designer the possibility to focus on the requirements and on the process parameters of the design, instead of on the design itself. [12] states that the generative power of a GD algorithm relies on its capability to generate a topology of artefacts by varying the input parameters of the problem statement. [14] reports a classification of GD methods, including Parametric Modelling, Genetic Algorithms and Topology Optimisation as enabling tools. The proposed GDM integrates all of them: the choice to use a Parametric Modelling GD approach has been inspired by the practical Generative Design Method developed by Krish [13], and by the applications of the Natural Optimisation Algorithm (NOA) to different engineering problems [17]. Indeed, during the conceptual design phase, a minimum imposition on the designer's workflow is provided using standard components, and different combinations of the parameters can be analysed via a Genetic Algorithm (GA) through FEA seeking for the best solution.

The adoption of a CAD-CAE pipeline, based on Parametric Modelling and interfaced with a GA, allows to build a GDM suitable to explore optimised shapes that are not constrained by already known solutions, and, in addition, suitable geometrical constraints, related to the non-occlusion of the field of view, are defined. Moreover, FEA allows early-design evaluations in terms of structural integrity, and it also supports the selection of the best configuration through the GA.

In addition, Generative Design powered by Topology Optimisation has allowed to derive lightweight and additively manufacturable conceptual structures of the fragment's support. Regarding this aspect, [3, 18] compare traditional density-based TO algorithms with respect to GD algorithms based on the TO Level-Set-Method and which also includes manufacturing methods. [18] argues that GD may be better at the conceptual phase since it does not require to consider a fully defined design space (which may lead to a local optimum [3]) as it occurs in traditional topology optimisation, but only geometries to be connected (avoiding obstacles) in organic and lightweight shapes. Moreover, as stated in [3], the design workflows are different since TO requires a manual loop of design and FEA validation of the TO geometry. In addition, GD outputs multiple solutions for each study since it can include different combinations of obstacles, loads and constraints, materials, manufacturing methods, design objectives and constraints (see subsection 2.2.1).

The developed GDM has been set up using a simplified fragment for the development of the procedure and then, it has been applied to a real-shaped artefact to assess its robustness and weaknesses to the increase in the shape complexity. The GDM workflow is divided into two main phases: Phase 1 (P_1), that is the Parametric Modelling and optimisation of the interface regions (namely 'C_i' components) between the artefact and its support; Phase 2 (P_2), that is based on the generation of a variety of supporting structures within the Generative Design environment of Autodesk Fusion 360.

The research goal is to provide a GDM able to speed up the traditional design workflow for the exposition and the preservation of the structural integrity of ancient artefacts. Moreover, the GDM gives the possibility to evaluate trade-offs between supports' concepts based on both aesthetics and structural performances, also providing the least effort on the designers to use a CAD environment in the conceptual design phase. Section 2 presents the GDM workflow by using a simplified case study, then a more complex test is presented in Section 3, to highlight the most general results. Finally, Section 4 points out the achieved conclusions and discusses future works.

2 WORKFLOW OF THE GENERATIVE DESIGN METHOD

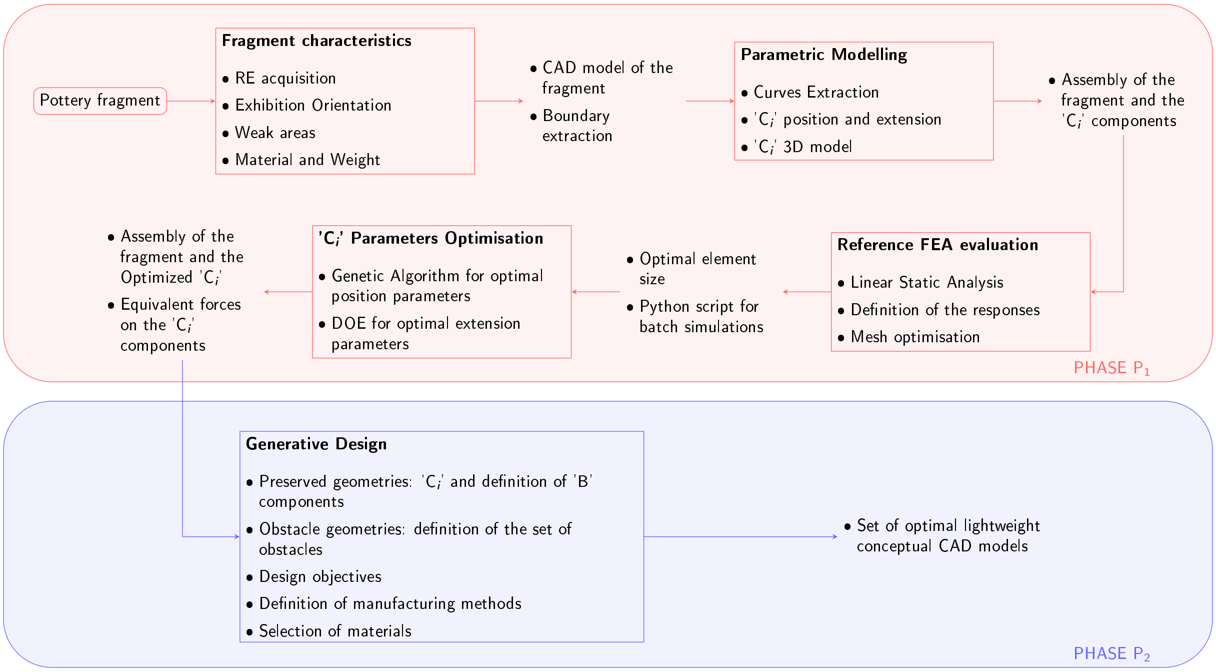


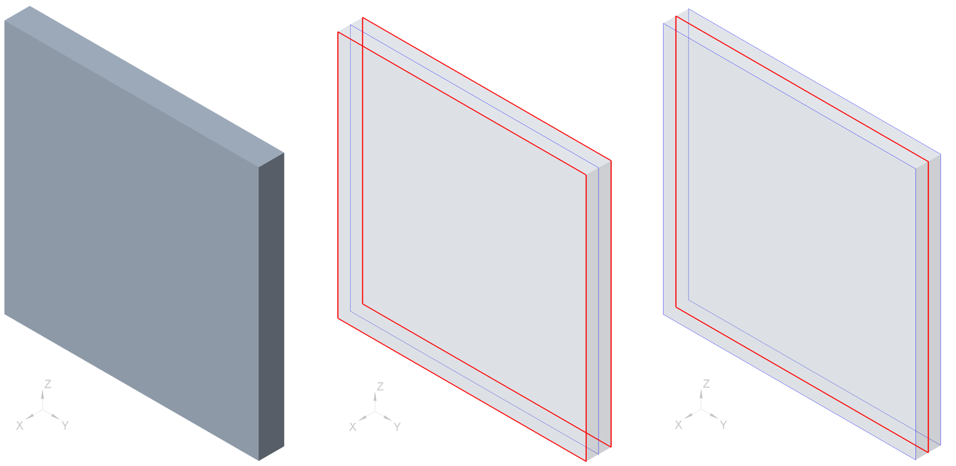
Figure 1: Workflow of the GDM.

The developed GDM (Figure 1) consists of two main phases: the first phase (P_1) aims to design and optimise the C-shaped interface regions ('C_i') between the support and the fragment of pottery while the second phase (P_2) aims to design the overall support given by the results of the phase P_1.

Phase P_1 starts with the preliminary operations to be done in order to achieve the CAD model of the pottery fragment and its relevant curves for the following Parametric Modelling step of the C-shaped elements necessary to connect it to the support. In the most general case, the fragment model is assumed to be provided by Reverse Engineering, as commonly made for sake of documentation in archeological excavations, restoration, or in museum exhibition set-up [9]. The extraction of the boundary curves, along with the thickness distribution and the center of mass coordinates are the basic input to develop the definition of the support interfaces in the Parametric Modelling step. It is devoted to automating the placement of the support interfaces in the respect of the fragment's stability, stress, and displacement reduction. The automation is necessary to explore the optimal set and space positioning of the support interfaces 'C_i'. Doing so, it is possible to automatically achieve, in batch, an assembly composed by the fragment and the 'C_i' elements. According to this, the FEA Evaluation step provides the first guess FEA modelling of the problem, as parametrically built in the Parametric Modelling step, ready to be used in the next Parameters Optimisation step.

By interlacing PTC Creo Parametric 8 and Altair SimLab through a Python script that excerpts the FEA output in terms of stress and displacement, the structural Parameters Optimisation is then provided. It is done in Altair Hyperstudy where a single-objective Genetic Algorithm and a Design of Experiment (in this case a full-factorial DOE) are performed in order to achieve the optimised configuration of position and extension parameters for the C-shaped 'C_i' elements defined in the Parametric Modelling step. Furthermore, the SPC forces, acting on each C-shaped element, are extracted to replace the fragment with an equivalent load in the next generative phase P_2. In this phase, conceptual CAD model's variants of the support are obtained through Generative Design connecting the 'C_i' components with the 'B' components (elements of the support that enables its fixturing by screws on the exhibition basement or wall) to evaluate the influence of different obstacle geometries, materials, manufacturing methods, design objectives and constraints.

To better highlight the theoretical and practical issues related to the GDM workflow, its set-up is explained in the next subsections, with the help of a simplified fragment, a squared piece of pottery, made of clay, 100x100 mm, with a thickness of 10 mm, Figure 2(a).



(a) Fragment. (b) fragment's mean boundary curve (red). (c) fragment's external boundary curves (red).

Figure 2: Simplified fragment and its boundary curves.

2.1 GDM: PHASE 1 (P_1)

The phase P_1 consists of preliminary operations (starting with the acquisition of the CAD model of the artefact), and of the Parametric Modelling and optimisation through GAs and Design of Experiments (DOE) of the interface regions between the artefact and its support to be developed.

The objective of phase P_1 is to provide the optimal positions and extensions of the interface regions, between support and artefact, in order to minimise the mean value of the displacement of the artefact and constrain the maximum stress (von Mises) on the artefact below a critical value during the exposition. These requirements are to be achieved imposing an input orientation of the piece and the distance from the mounting table that are commonly given by archaeologists, CH experts and exposition needs.

2.1.1 Preliminary Operations and Parametric Modelling

Preliminary Operations start from the definition of the basic input of the problem: fragment CAD modelling, derived by Reverse Engineering acquisition, and its pre-processing in order to obtain a parametric model of the C-shaped elements 'C_i'. The 'C_i' set represents the interfaces between the fragment model and the supporting structure.

Figures 2(b)-2(c) show the boundary curves of the simplified fragment associated with the parametric model. These are the mean surface boundary edge (Figure 2(b)) and the outer and the inner layer edges (Figure 2(c)) and represent the position locus where the C-shaped ('C_i') components are located.

The materials for both the fragment (clay) and the 'C_i' components (ABS) are assumed homogeneous and isotropic with the mechanical properties listed in Table 1. Furthermore, no localised criticalities are considered, thus a global fragment's stress limitation is imposed.

Element	Material	Density $\left(\frac{kg}{m^3}\right)$	Elastic Modulus E (GPa)	Poisson's ratio
Fragment	Clay	1550	35	0.16
C_i interfaces	ABS	1060	2.24	0.38

Table 1: Material properties.

The origin of the reference system is placed in the center of mass of the fragment and the orientation angle is set, according to the exposition needs, considering the plane fragment oriented in the space with normals to the wider facets in direction $\left(\frac{\sqrt{2}}{2}; 0; \frac{\sqrt{2}}{2}\right)$ (45 degrees of rotation around the y-axis with respect to the basement).

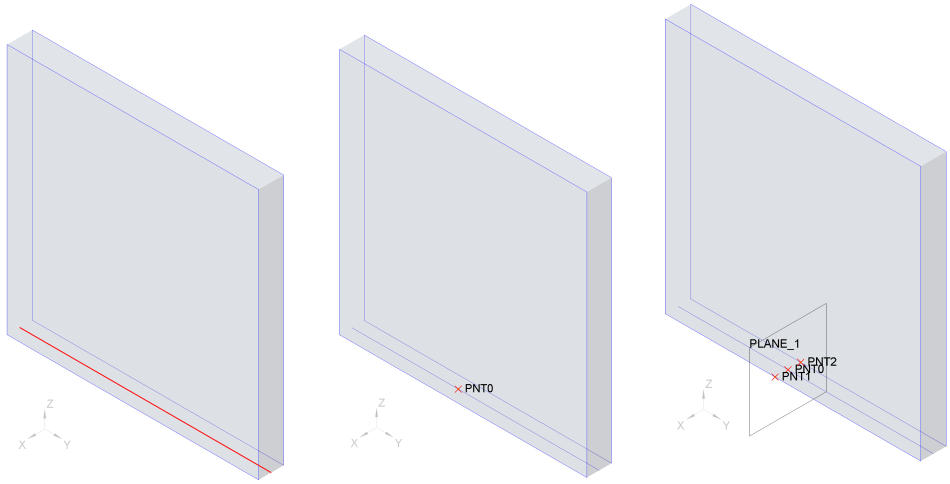
At the end of the preliminary operations, a first hypothesis on the number of the 'C_i' components (interface regions) is made. For this simplified case study, it is assumed that three regions of interface (i=1,2,3) are sufficient to sustain the structure and avoid accidental falls of the artefact (one along the bottom edge and the other two on each lateral one). Related to this, the GDM checks for the stability by analysing the position of the center of mass with respect to the positions of the 'C_i' components.

Once assumed a number N (N $\geq$ 3 to ensure stability) of interface regions between the support's structure and the fragment, the procedure to design each of the standard 'C_i' (i=1, ..., N) components is defined according to the following seven steps:

PM - Step 1: The central boundary curve is trimmed by two endpoints to get a sub-curve 'c_i' (Figure 3(a)) where the i-th 'C_i' component is placed (in this case the end points are the edges of the fragment).

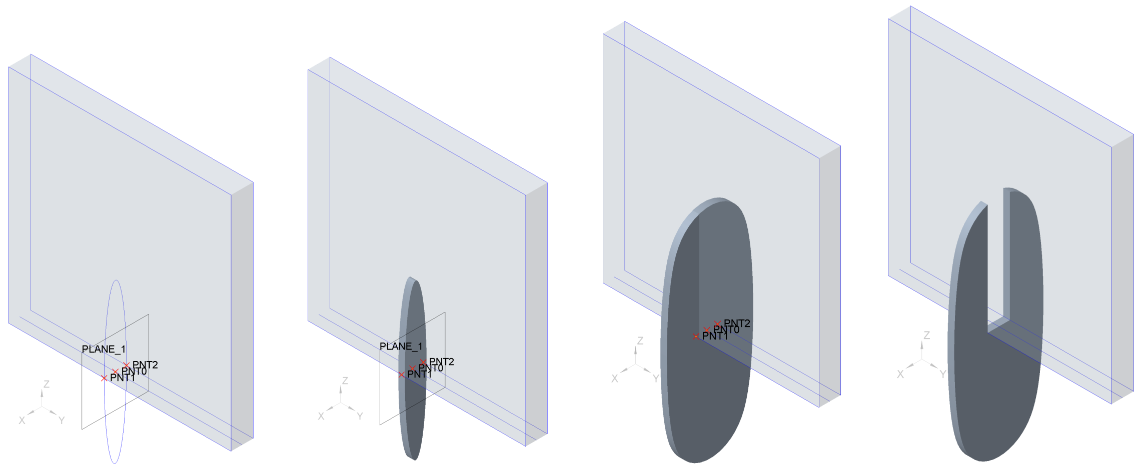
PM - Step 2: The point PNT0 (Figure 3(b)) is assigned to the 'c_i' curve and its relative position on the 'c_i' curve is controlled by a parameter of position 'POS_i' ranging in the interval [0;1] with respect to one of the two extreme points of the 'c_i' curve. According to this modelling step, the 'C_i' component is free to move along the 'c_i' curve.

PM - Step 3: The plane PLANE_1 passing through PNT0 and normal to the curvilinear abscissa of the 'c_i' curve is defined. Two other points PNT1, PNT2 are identified by the intersection of this plane with the external boundary curves of the fragment (Figure 3(c)).



(a) 'c_i' curve (red). (b) Point PNT0 assigned to the 'c_i' curve. (c) Plane PLANE_1 and points PNT1, PNT2.

Figure 3: PM - Steps 1, 2 and 3.



(a) Ellipse defined through PNT1 and PNT2. (b) Symmetric extrusion. (c) Offset. (d) Boolean cut.

Figure 4: PM - Steps 4 and 5.

PM - Step 4: An ellipse is defined on the plane PLANE_1 by the points PNT1 and PNT2 (Figure 4(a)). The 2-D ellipse is extruded symmetrically, and the finite extension is controlled by the parameter 'EST_i'

(Figure 4(b)). Then, an offset of the lateral side of the solid is performed to include part of the transversal section of the fragment (Figure 4(c)).

PM - Step 5: The 'C_i' component is imported in the assembly with the fragment and the other 'C_k' components. A boolean operation of intersection is performed using the fragment as a tool for defining the shape of the hollow to ensure the fragment to fit into the support (Figure 4(d)).

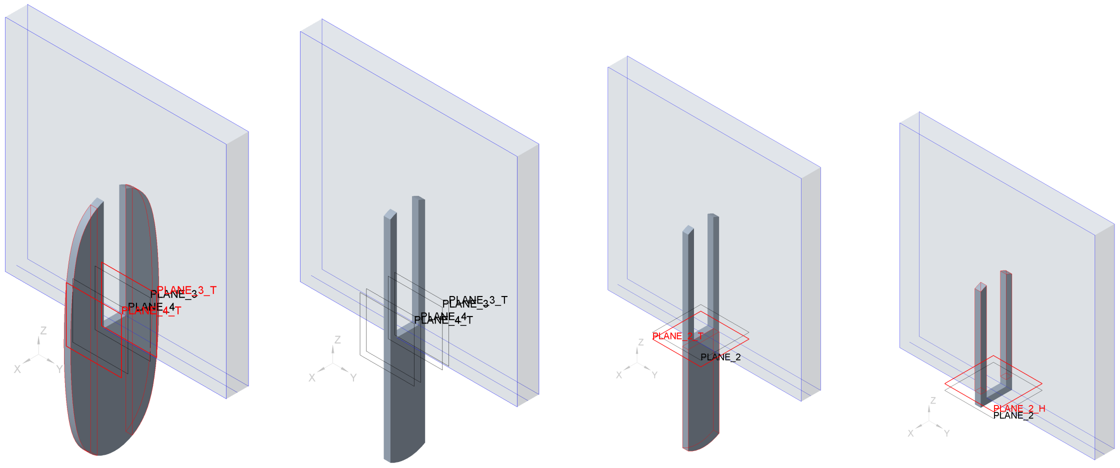


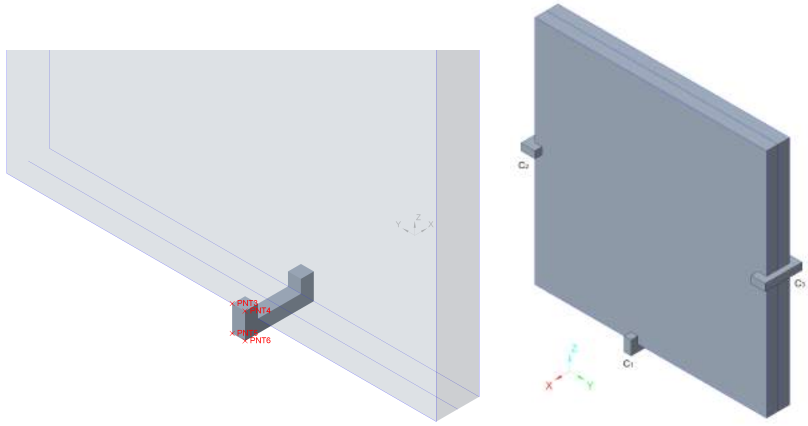
Figure 5: PM - Step 6.

PM - Step 6: At this point, for each of the 3 new facets resulting from the Boolean intersection, 3 out of the 4 vertices are selected, and a plane is defined (PLANE_2, PLANE_3, PLANE_4) passing through them with normal oriented towards the fragment. For each plane (PLANE_i, with i from 2 to 4) is defined another plane (PLANE_2_T, PLANE_3_T, PLANE_4_T) with an offset controlled by the parameter 'T_i' which accounts for the thickness of the 'C_i' component in the negative direction pointed out by the normal of each PLANE_i. Lastly, another plane PLANE_2_H is defined with an offset controlled by the parameter 'H_i' in the positive direction of the PLANE_2's normal (Figure 5). Usually, 'H_i' differs from 'T_i' since the first accounts for the stability of the fragment.

PM - Step 7: The vertices of the face that are constrained in the FEA must be marked as datum points (PNT3-PNT6) (Figure 6(a)).

The final 'C_i' component is reported in Figure 6(a) and the assembly with the fragment and all the 'C_i' components (obtained through the repetition of the procedure for each) is reported in Figure 6(b).

As already mentioned, the Parametric Modelling phase does not deal with the modelling of the complete structure of the support, but only on the elements of it which are in contact with the artefact. This is because the FEA constraints related to criticalities and displacement are imposed on the fragment, hence it is possible to consider only the interface regions, namely the 'C_i' components, between the support and the fragment. In doing so, the computational effort of performing a high number of simulations ($10^2 \div 10^3$) is reduced while finding the optimal positioning of the interface regions. The approximation introduced concerns the rigidity of the support structure, which in this case is higher than the one found at the end of the procedure. Once the PTC Creo Parametric CAD model of the assembly is ready, it can be imported in its original format into the software Altair SimLab to build the Python script for the Finite Element Analysis for the different combination of parameters.



(a) Final 'C_i' component and datum points for FEA.

(b) Final assembly of the fragment and the 'C_i' components.

Figure 6: Datum points and final assembly of the fragment and the 'C_i' Components.

2.1.2 FEA Evaluations

The advantage of this methodology in the field of CH relies in the usage of FEA to aid and speed the design activities giving the possibility to consider the structural performance of each combination of the 'C_i' parameters and thus preserve the fragment's integrity. Since each combination of parameters builds up a different CAD model of the assembly of the fragment and the 'C_i' components, the optimisation procedure (see Subsection 2.1.3) requires a simulation for each one of them. Therefore, the objective of the FEA phase is to assess the structural performance for a reference configuration of parameters within the software Altair SimLab (Optistruct Solver) and the output is a template script which can be used in the following Optimisation phase.

The template script is written in Python and is combined with the proprietary function of Altair SimLab to carry out the simulations in batch. Thanks to this, the repeatability of the evaluations over the different combinations of the 'C_i' parameters is ensured. The most relevant feature of the script is the possibility to work directly over the original CAD model and thus have access to the model's parameters defined in PTC Creo Parametric. Moreover, the script works well for different fragments, because the different shapes of the various artefacts are taken into account by adapting the mesh parameters (element sizes, etc.) and controls (local refinements).

Since the Optimisation phase requires the evaluation of $10^2 \div 10^3$ CAD models (according to the number of 'C_i' components), it is necessary to reduce the computational cost of the FEA evaluations. According to this, a linear static analysis is selected despite the presence of contacts, also because this procedure is intended to aid in the conceptual phase. Moreover, for the same reason, it is fundamental to minimise the number of nodes which ensure the convergence of the mesh model.

To set up the script and thus the structural analysis and validation of the mesh parameters, it is necessary to consider a reference configuration for the 'C_i' position 'POS_i' and extension 'EST_i' parameters which are the only ones considered for the optimisation. Hence, the script automatically imports the CAD assembly along with the parameters and datum points and sets up the linear static analysis. To reduce the number of nodes, first order 2-D triangular elements and first order 3-D 4-sided elements are chosen. Moreover, an additional improvement is reported in the test case at Section 3, where the script automatically builds spherical mesh controls to locally refine the mesh of the artefact in the region of interfaces between itself and the support meaning the 'C_i' components. Therefore, the script assigns the material properties to each element of the assembly distinguishing between the artefact and the 'C_i' components and it establishes a STICK contact condition between them. Subsequently, Gravity and constraints are assigned. Gravity is in the direction (0;0;-1) since the assembly has been previously oriented while constraints are assigned on the faces which have been marked by the vertex points (Figure 6(b)) discussed in Subsection 2.1.1. Finally, the script runs the analysis in batch through the solver Optistruct and extracts the responses. These are the maximum stress (von Mises) and the maximum and mean displacement of the fragment.

The script is ready-to-use for different artefacts and the user has only to fine-tune the mesh parameters in order to ensure the convergence of the FEA. Consequently, few tests are mandatory to identify the values for the mesh parameters which ensure on the one hand the accuracy of the finite element model, and, on the other hand, the reduction of the computational cost of the simulations.

2.1.3 Parameters Optimisation

The objective of this phase is to provide the optimal configuration of 'C_i' position 'POS_i' and extension 'EST-i' parameters which minimise both the average displacement of the fragment and the extension of the 'C_i' components, and constraint the maximum stress on the fragment below a critical value according to the specifications (criticalities) of the artefact to be supported (Table 2). Minimising the average displacement of the fragment means looking for a more stable configuration while the stress constraint regards the structural integrity of the fragment and its surface fragility. Moreover, the 'C_i' components must have a minimum extension so that they do not obstruct the view to the fragment (aesthetics criteria). Hence, the parameters to be investigated are the positions 'POS_i' and extensions 'EST_i' of the 'C_i' components with respect to the constraints previously defined.

Due to hardware limitations, the problem is decoupled in the following way: A Single-Objective Genetic Algorithm (GA) optimises the position 'POS_i' parameters keeping fixed a reference value for the 'EST_i' parameters (for this preliminary test, 'EST_i'=3mm) and subsequently a Full Factorial Design of Experiment (DOE) identifies the minimum extension of the 'C_i' components that keeps the stress below the previously defined critical value and accounts for the minimum thickness required for the additive manufacturing process. Moreover, the parameters are discretised to reduce the number of possible configurations with a step size of 0,05 in the range [0;1] for the parameters of position 'POS_i'.

Objective / Constraint	Goal
Average Displacement	Minimize
Maximum stress (von Mises)	≤ 100 kPa
Extrusion 'EST_i'	Minimize

Table 2: Goals of the Parameters Optimisation.

To carry out the GA, Altair Hyperstudy provides suggested values for the parameters of the algorithm (minimum and maximum numbers of iterations, population size, mutation rate, elitist policy, etc.) based on the number of variables to be optimised. The users may decide to modify them according to their needs. For this preliminary test, the GA is performed over three variables, and according to the Altair Documentation, a population of 70 individuals would have been necessary while, due to hardware limitations, the number is decreased to 50. The GA performed 1106 simulations and it took roughly 48 hours. The optimal solution is found at the 16th iteration of the algorithm (Figure 7) but due to the symmetric nature of the fragment, the solution found at the 6th iteration (that presents limited differences with respect to the 16th) is chosen (Table 3).

POS_1	POS_2	POS_3	Max. Displ. (mm)	Ave. Displ. (mm)	Max. Stress (kPa)	It.	Sol. index
0.50	0.70	0.70	1.2489e-04	1.174e-04	88.735	6	256
0.50	0.65	0.70	1.2847e-04	1.172e-04	94.788	16	675

Table 3: Optimal solution of the position parameters.

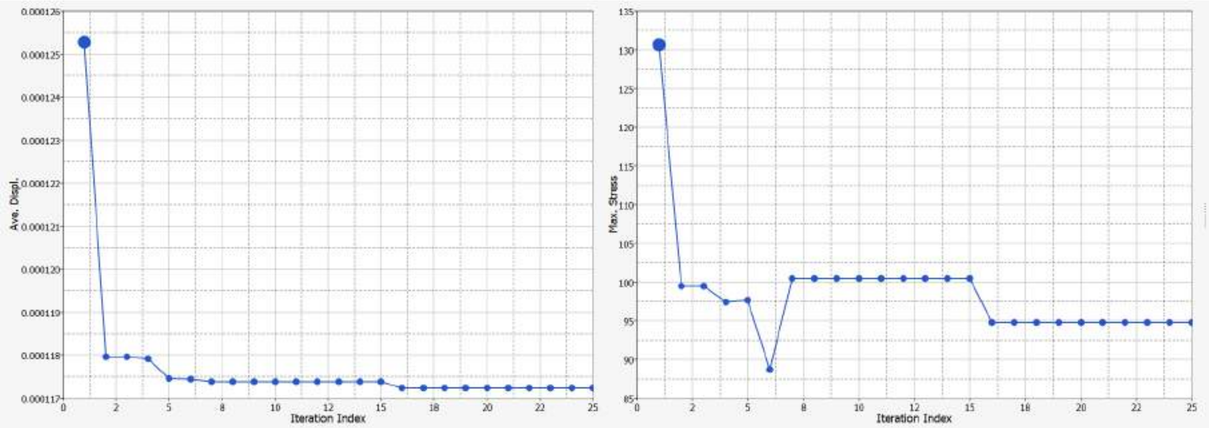


Figure 7: GA optimal solution per iteration.

Subsequently, the Full Factorial DOE for the extension parameters 'EST_i' is performed with the optimal value for the position parameters. In this case, the DOE considers 4 levels in the range [3÷6 mm] for each variable, thus 64 experiments are conducted (Figure 8). As expected, both the average displacement and the maximum stress decrease as the extensions increase. Based on these results, the minimum extension is chosen since it is under the maximum allowed stress.

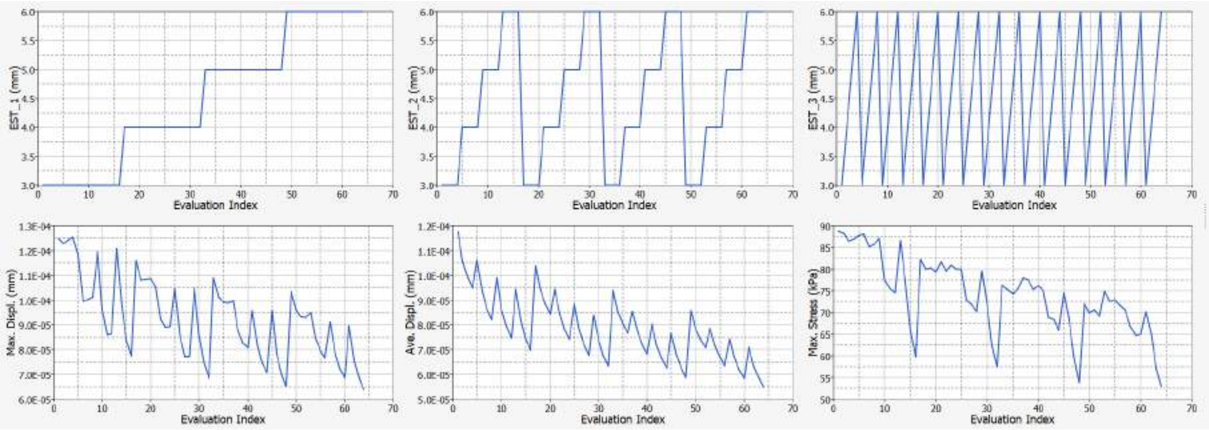


Figure 8: Full Factorial DOE runs, stress and displacement results.

For the optimised configuration, the SPC forces are extracted and used for the GDM phase P_2 as input forces for the Generative Design engine in Fusion 360.

2.2 GDM: PHASE 2 (P_2)

The phase P_2 involves a Generative Design Software to design topologies of supporting structures for the artefact according to the optimised configuration of 'C_i' components, 'B' components, different combinations of obstacle geometries, materials, manufacturing methods and design objectives. Moreover, it is possible to provide some guidelines to speed up the setup for the generative design process.

2.2.1 Generative Design

The Generative Design phase is conducted in accordance with the framework outlined in literature, especially the one reported in [8]. By this point of view, the optimised configuration of the previous phase P_1 is imported in Autodesk Fusion 360. Since the structure requires a functional region to secure the support on the exhibition basement/wall with screws or other fixturing methods, three hollow cylinders (Figure 9) are designed for this aim (namely 'B' components). The 'B' components are designed directly within the GD environment of Fusion 360, and along with the 'C_i' components, these are marked as preserved geometries (green bodies in Figure 9) for the GD algorithm. Preserved geometries are, generally, disconnected solid volumes which must be connected by the algorithm. The software builds up the structure iteratively, connecting these regions according to loads and boundary constraints, and according to each configuration of the so-called obstacle geometries, selected materials, manufacturing methods, optimisation objectives and constraints. Obstacles geometries (red bodies in Figure 10) are solid volumes within which the algorithm is not allowed to add material to connect the preserved geometries. Obstacle geometries are designed for two purposes:

1. Ensure the mounting of the screws (cylindrical obstacle connectors above the 'B' components) to secure the support to the basement, which is designed as a thin plate.
2. Drive the generative design engine to not add material that may cause interference with the artefact or discharge its fruition. Indeed, the artefact is set as one of the obstacle geometries and its weight is replaced by equivalent loads acting on the 'C_i' components. Thanks to the definition of the proper obstacle geometries, the aesthetics requirement of minimising the impact of the support structure on the observer's view is achieved. As a measure of this requirement, the projected area occupied by the support in the reference orientation is chosen. Thus, a lower-is-better solution may drive the selection process of the concepts.

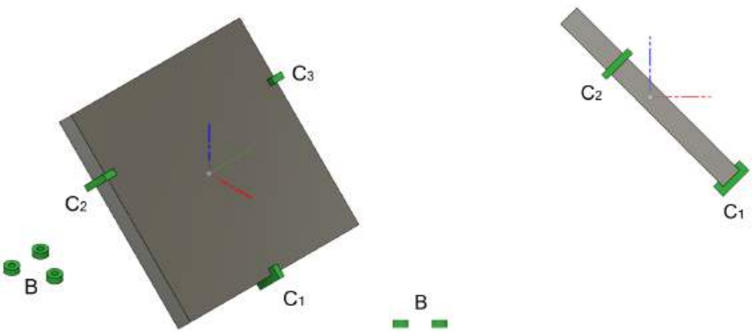
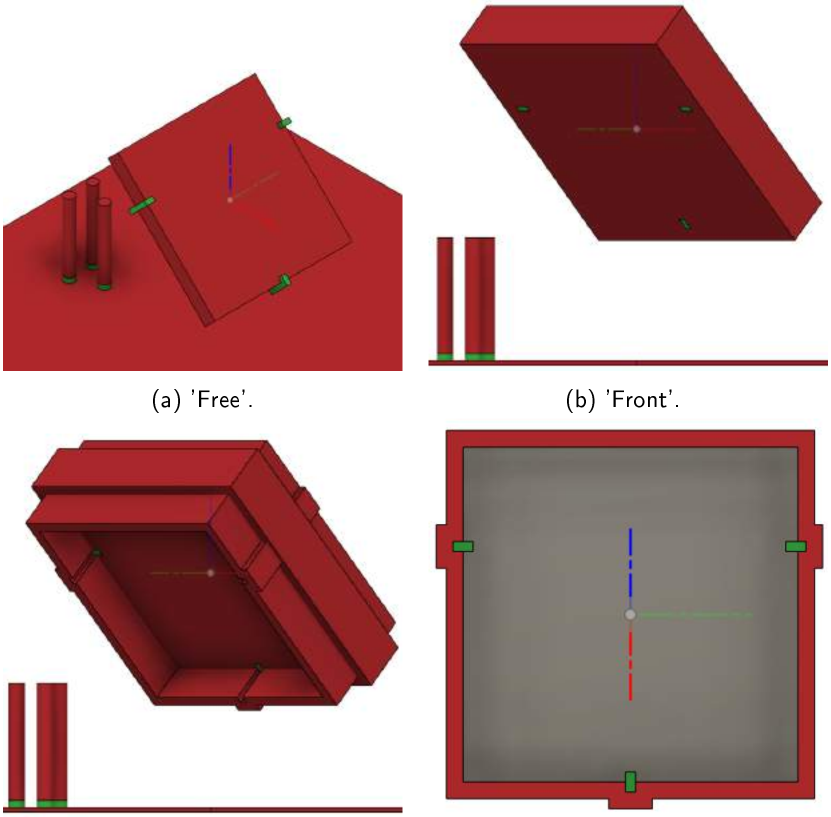


Figure 9: 'B' components, preserved geometries (green), orientation and position.



(a) 'Free'.

(b) 'Front'.

(c) 'Full'.

(d) 'Full' in reference view orientation.

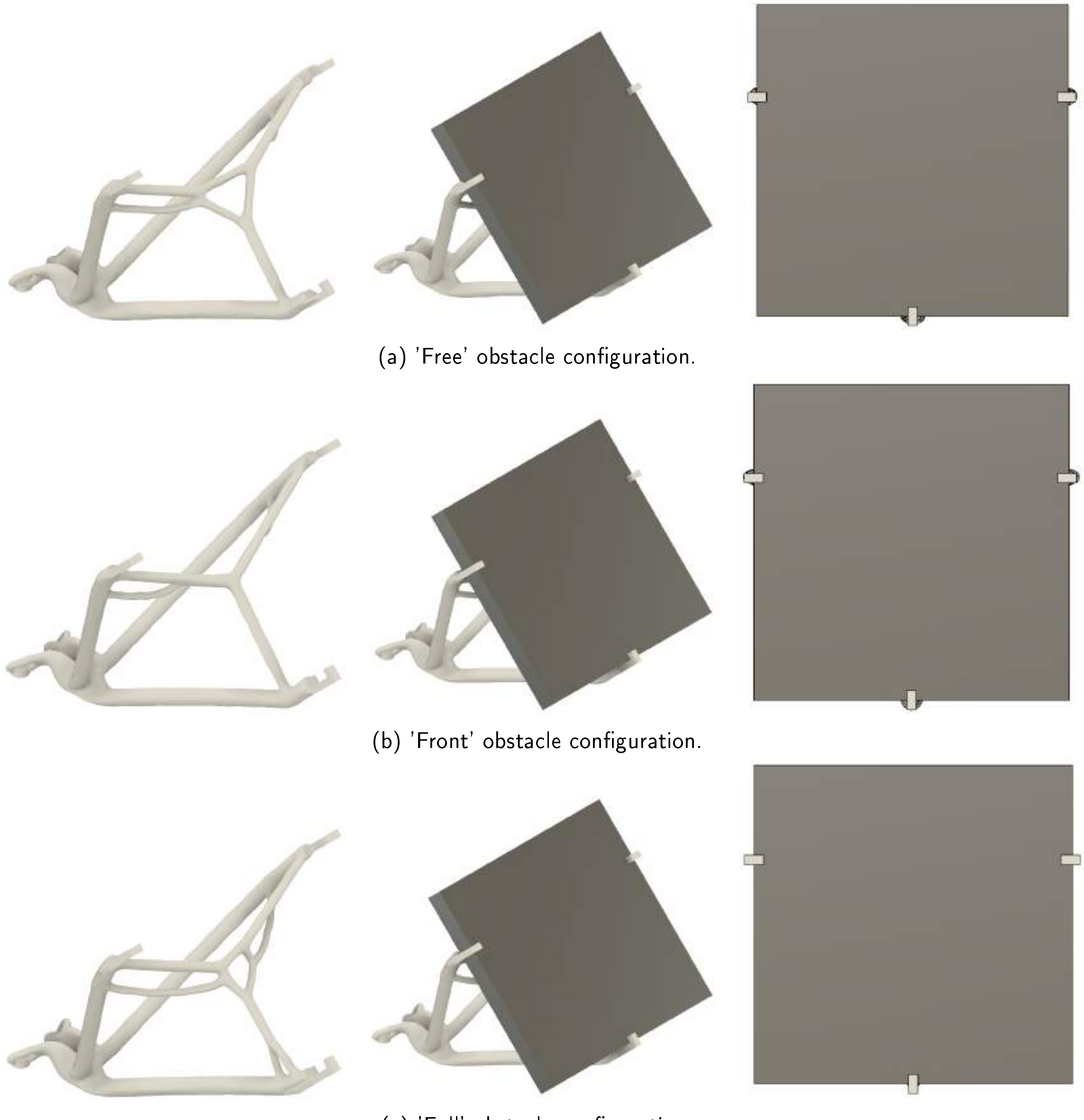
Figure 10: Obstacle geometries (red).

For these reasons, different obstacle geometries are considered in order to drive the results to be aesthetically non-invasive. The configurations of obstacles are named 'Free' (Figure 10(a)), 'Front' (Figure 10(b)) and 'Full' (Figure 10(c)): 'Free' considers only the basic obstacles which are: the mounting basement, the artefact itself and the regions above the 'B' components in order to ensure the assembly of the support with the basement. 'Front' adds an obstacle in front and sides of the artefact to ensure that the fragment's view is not impeded by the structure. 'Full' also considers the non-invasiveness of the support, meaning that it is hidden behind the artefact at least in the reference orientation (Figure 10(d)).

Material	Density $\left(\frac{kg}{m^3}\right)$	Elastic Modulus E (GPa)	Poisson's ratio
ABS	1060	2.24	0.38
AlSi10Mg	2670	71	0.33
AISI 304	8000	195	0.29

Table 4: Selected materials for the support.

Different materials (polymers and/or metals) may be assigned to the support structure and different manufacturing methods may be considered. For this preliminary-test component, the selected materials are ABS, stainless steel and aluminium (Table 4). For what concerns the manufacturing methods, since the support is intended to be produced through AM technologies, non-restricted and AM manufacturing methods in all directions are selected.



(a) 'Free' obstacle configuration.

(b) 'Front' obstacle configuration.

(c) 'Full' obstacle configuration.

Figure 11: Support's generated concepts.

Regarding the design objectives and constraints of the generative design process, a proper workflow is depicted: a first run seeking for the minimisation of the mass of the component providing a safety factor. Therefore, a fine-tune of the mass parameter constraint with the objective to maximise the stiffness of the component to achieve both lightweight, structural performance, and manufacturability.

All the concepts are visualised within the Explore environment of Fusion 360 where trade-offs in terms of weight and maximum stress and/or displacement are made also in terms of the different materials and manufacturing methods. Currently, the authors' efforts are focused on the research of indexes for the evaluation and the comparison of the obtained solutions, as it is done, for example in [10]. By comparing three concepts (Figure 11), one for each different configuration of obstacle geometries, and the visible parts of the supporting structures from the observer's point of view, it is clear that the 'Full' configuration is the one to be used in every pottery fragment of this kind. Hence, as a future development, it would be possible to automate the design modelling of the obstacle geometries related to this aesthetics criteria.

Table 5 reports a comparison of the structural performances of the three concepts (Figure 11). All of them are made in ABS and the selected manufacturing method is additive in 'z+' direction for all of them.

	'Free'	'Front'	'Full'
Mass (kg)	0.021	0.018	0.018
Max. Stress (MPa)	0.127	0.127	0.131
Max. Displacement (mm)	0.009	0.009	0.007
Material	ABS		
Manufacturing	Additive 'z+'		

Table 5: Comparison of structural performances for the concepts related to the different configurations of obstacle geometries.

The following section presents the application of the GDM to a more complex artefact geometry which accounts for the presence of the rim (non-uniform thickness distribution along the mean boundary curve) where additional possible improvements for the entire procedure emerged.

3 TEST CASE

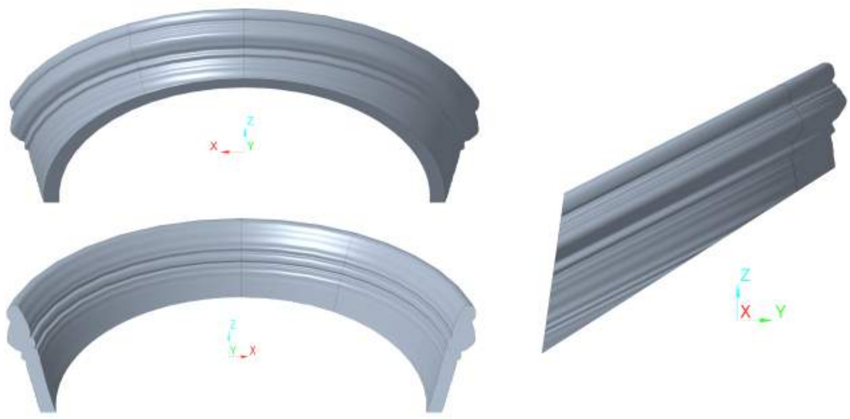


Figure 12: Test case artefact's CAD model.

The GDM is applied successfully to the design of a supporting structure for a more complex artefact's geometry, the top portion of a vase (Figure 12). With respect to the preliminary method, here two slight differences are introduced: the parameters of position 'POS_i' are limited in the range (0;1) excluding the extremes since, close to them, the Parametric Modelling algorithm could lead to non-feasible features of the 'C_i' components due to the complex shape of the edges. Furthermore, in the FEA script, spherical mesh control regions to locally refine the mesh of the fragment near the 'C_i' components automatically adapt to the change in the position 'POS_i' and extension 'EST_i' parameters.

For this test-case, the given orientation (30° with respect to the basement) of the fragment is set once the CAD model has been acquired through RE so that the gravity is accordingly set in the negative z-axis direction.

Here are reported the main steps of the phase P_1 of the GDM: the boundary curves are extracted; the number of interface regions between the support and the fragment is set to N=3; the 'C_i' components are designed and placed as in Figure 13. The script for the FEA evaluation subphase has been already developed in the preliminary test case, and since it is written to adapt to different artefacts, the user has only to change the materials and validate the mesh parameters.

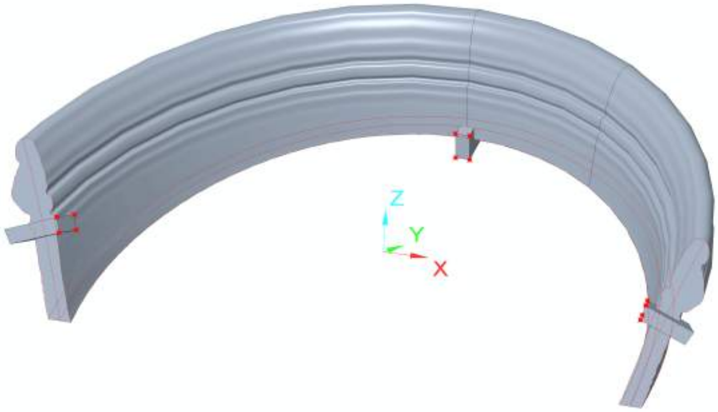


Figure 13: Assembly of the artefact and the 'C_i' components.

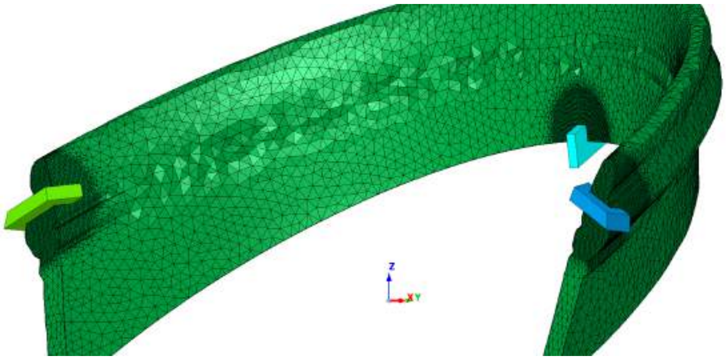


Figure 14: Artefact's mesh model.

For the sake of simplicity, the materials are those reported in Table 1. In Figure 14, the mesh model of the assembly is reported. In doing so, the number of nodes is decreased, outside the regions of interface, while the accuracy of the FEM is preserved, and it automatically adapts the mesh controls to the changes of the CAD parameters (it has to be noted that the fundamental role in FEA is played by the 'C_i' zones, so the inner mesh could be acceptably less accurate).

The Optimisation phase is conducted firstly for the position 'POS_i' parameters (Table 6) and after for the 'EST_i' parameters (Table 7). The GA has taken roughly 10 hours to complete with a population of 50 individuals for iteration and has run 324 simulations (Figure 15).

POS_1	POS_2	POS_3	Max. Displ. (mm)	Ave. Displ. (mm)	Max. Stress (MPa)	It.	Sol. index
0.50	0.80	0.80	4.5939e-04	2.5004e-04	0.3642	12	193

Table 6: Optimal solution of the position parameters.

EST_1 (mm)	EST_2 (mm)	EST_3 (mm)	Max. Displ. (mm)	Ave. Displ. (mm)	Max. Stress (MPa)
5	5	5	6.0574e-04	3.4598e-04	0.5321

Table 7: Optimal solution of the extension parameters.

The full factorial DOE for the 'EST_i' parameters is conducted over 3 levels in the discrete interval [5÷10 mm], and since the problem is symmetric, 'EST_2' and 'EST_3' are set equal. The combination which minimises the extension, 'EST_i'=5 mm for each i, is chosen since it satisfies the maximum stress constraint set to 1 MPa as can be seen in Figure 16 for index 1.

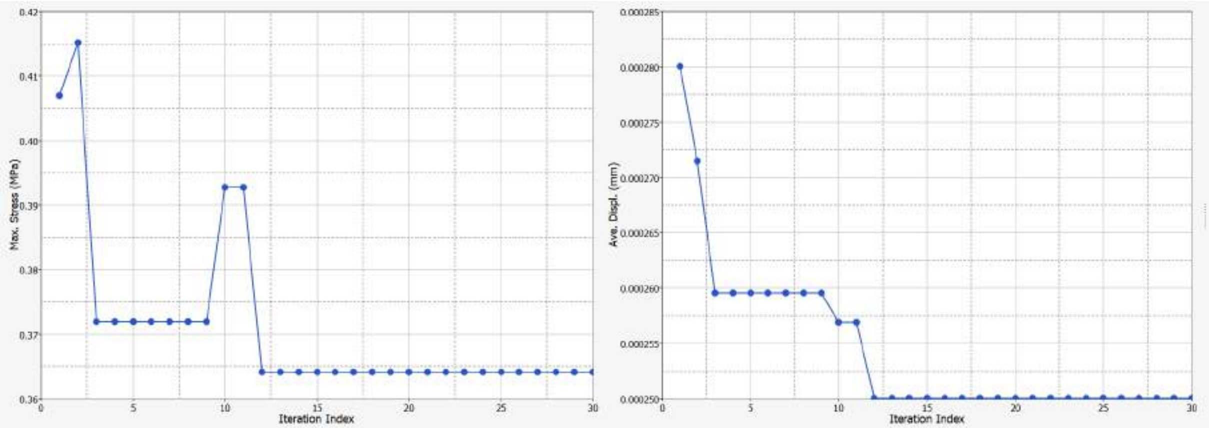


Figure 15: GA optimal solution per iteration.

Once the SPC forces are extracted, it is possible to move to the phase P_2 within the GD environment of Fusion 360. Thanks to the results of the preliminary case study, it is possible to speed up the design activities of the 'B' components and the obstacle geometries, the selection of the design objectives and constraints. In fact, the B components are chosen to guarantee a connection with a vertical wall. The selected materials are the same reported in Table 1. The obstacle geometries, both in the vase fragment and in the development test-case, are chosen by ensuring all the functional performances and preserving the observer's vision ('Full'

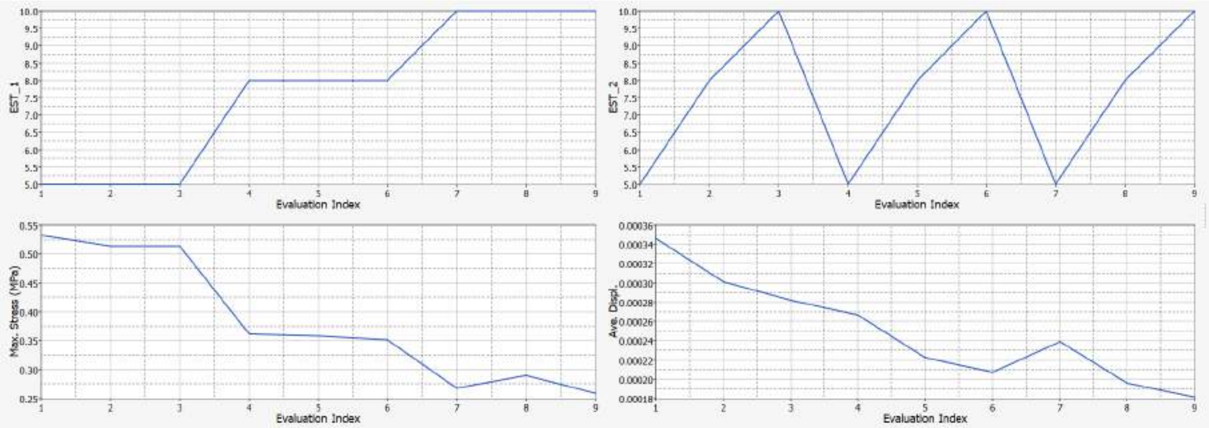


Figure 16: Full Factorial DOE runs and stress and average displacement results.

configuration). One of the obtained possible geometries is reported in Figure 17. It is considered to be additively manufactured, in ABS, along 'z+' direction.

Figure 17: A support's conceptual design variant for the test case.

4 CONCLUSIONS AND FUTURE WORKS

This work outlines a general procedure to aid designers and archaeologists in the conceptual design phase for the design of both lightweight and aesthetically pleasant (non-invasive) supporting structures for highly customised application as those used for the exhibition and storage of Cultural Heritage's artefacts are. This kind of procedure gives the possibility to explore new solutions, and it could be increasingly automatised, in several subphases, resulting in a possible speed up of the process.

In Section 2, the GDM is described to firstly optimise the contact areas between the support and the retrieval in order to guarantee its integrity, and secondly, to generate the complete structure following the requirements of maximising the stiffness according to the amount of material which satisfies the manufacturing process. Thanks to this approach, it is possible to provide better informed decisions in the early stages of the design activity for a task that is usually accomplished by the craftsmen without a massive aid of CAD and CAE software. Doing so, the generative design approach allows to satisfy both aesthetics and structural performances. The first one is here measured in terms of area occupied by the support in the field of view of the observer; and the second ones are evaluated in terms of lightweight design and maximum stress of the fragment for a given orientation and position in space. Finally, in Section 3, the GDM is applied successfully to an artefact that reproduces a sector of an ancient vase. In all the reported cases, the procedure converged to reliable and manufacturable solutions.

Future developments will concern the extension of the GDM to different artefacts and the possibility to adopt AI to automatically identify categories and choose design strategies also including localised criticalities and more realistic material behaviours. Moreover, hardware performances could be improved allowing the GDM to implement Multi-Objective Genetic Algorithms to find pareto-optima for both the displacement and volume criteria of the parameters' optimisation step. Furthermore, the optimal number of 'C_i' components will be also suggested by the algorithm and not only chosen by the designer, who oversees the validation of the mesh parameters, and the selection of the Genetic Algorithm parameters.

Concerning other fundamental design objectives for the phase P_2, also the frequency optimisation and buckling analyses will be included in the procedure since they are key factors for proper safe storage and exposition conditions. Sensitivity analyses concerning the definition of obstacles and preserved geometries ('B' components) will be carried out to understand their influence on the generative design process. Finally, the generated concepts will be exploited in a comparison establishing indexes which accounts for structural performances, aesthetics, and manufacturing.

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