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DESIGN AND OPTIMIZATION FRAMEWORK FOR COMPLEX FREE-FORM STRUCTURES JOINTS USING ADDITIVE MANUFACTURING

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Abstract

This research introduces a flexible and iterative framework for the design and optimization of complex nodes of free-form steel structures, integrating topology optimization with additive manufacturing (AM) techniques. The methodology combines CAD modeling, Computer-Aided Engineering (CAE) simulations, topology optimization, and Finite Element Analysis (FEA) to improve structural performance, on-site assembly, and ensure manufacturability for feasible 3D printing designs.
The approach evolves from conceptual design to the development of a fully optimized and manufacturable component, with the main goal of achieving an optimal balance between performance and manufacturing feasibility, always observing the functional requirements.
The initial conceptual design output is refined iteratively not only by algorithms (e.g. topological optimization) but also through manual adjustments, ensuring that the algorithmic solutions are aligned with the conceptual design vision. Then, the workflow includes advanced modeling techniques to handle complex geometries and incorporates innovative features to enhance and simplify on-site assembly, always checking the printability of the solution. Finally, Finite Element Models (FEM) are employed to assess structural performance, refining design to limit stress concentration and optimize material use and final shape.
A critical innovation of this methodology is the integration of snap clips as a solution for enhanced assembly, improving precision alignment, reducing the need for additional support structures and simplifying the assembly process. The framework is applicable across various structural applications, enabling more efficient and adaptable free-form structural joint designs.

Keywords: Additive Manufacturing; Topology Optimization; Complex steel nodes; Enhanced Assembly; Optimization Workflow; Free-form structures.

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1 INTRODUCTION

The advent of Additive Manufacturing (AM) has revolutionized structural engineering [1], particularly in the design of complex joints within free-form structures.

One hallmark of free-form construction is the use of triangular discretization to approximate the intended curvature and shape. In these designs, the node geometry generally remains uniform, with all geometric variations concentrated in the beams (

Figure 1). As a result, each beam requires careful cutting and machining, with strict tolerances to ensure proper fit and alignment. Consequently, on-site assembly can become labor-intensive and prone to errors and inefficiencies.

By leveraging AM, engineers can produce uniquely tailored nodes while largely standardizing the beams. This not only streamlines on-site assembly, since beams can remain uniform, but also ensures that each node's geometry can be optimized for the specific load demands.

Figure 1: Fiumicino Terminal gridshell

Traditional fabrication methods often impose constraints leading to inefficient geometries, material wastage [2], and intricate assembly processes.

In contrast, AM offers unparalleled design freedom, enabling the creation of optimized structures that were previously unattainable.

Consequently, the goal of this research is to explore how additive manufacturing can facilitate the creation of highly customized structural nodes in free-form steel frameworks, supporting improved structural performance, reduced material waste, and simplified assembly through the design of standardized beams and individualized node components.

This study specifically focuses on a peculiar type of free-form structure that is widely used in modern architecture, including landmark projects such as the Fiumicino Terminal in Rome, Singapore Changi Airport, Zlote Tarasy in Warsaw, Fuksas Trade Fair in Milan and Doha Airport's 'The Orchard' dome (

Figure **2**). These structures feature iconic curved facades composed of glass panels supported by a steel framework, forming visually striking and structurally efficient enclosures. The primary structural units within these facades are triangular steel frames with circular connections at their intersections, ensuring stability and uniform load distribution.

These architectural elements rely on steel gridshell systems, where nodes serve as connection points for six converging beams of varying cross-sections. This complexity presents unique challenges in terms of load distribution, manufacturability, and on-site assembly, particularly due to the varying angles and forces acting on each node. The intersection points of these beams require highly customized joints that can efficiently handle stress while maintaining structural continuity and aesthetic integrity.

Figure 2: Gridshell examples: a) 'The Orchard' Doha Airport, b) Singapore Changi Airport, c) Zlote Tarasy Warsaw, d) Fuksas Trade Fair

Central to this advancement is topology optimization (a computational technique that determines the optimal material distribution within a given design space), adhering to specified performance objectives and constraints. By iteratively removing unnecessary material, topology optimization identifies the most efficient load paths, resulting in lightweight yet robust structures. The synergy between topology optimization and AM facilitates the production of components with complex geometries tailored for performance and manufacturability.

Despite these advancements, challenges persist. The raw output from topology optimization often manifests as irregular, mesh-based geometries that are not immediately suitable for manufacturing or integration into existing workflows. Traditional design tools may require labor-intensive manual remodeling to convert these outputs into practical designs, potentially leading to delays and increased costs. Moreover, ensuring that these optimized designs meet structural performance standards and are feasible for AM remains a critical concern.

This paper focuses on two main aspects:

1) The description of a comprehensive design and optimization framework that seamlessly integrates topology optimization with additive manufacturing constraints and structural performance analysis. The methodology encompasses automated post-processing of topology optimization results, advanced modeling techniques for geometry refinement, and the incorporation of innovative assembly features such as snap-fit mechanisms.
2) The possibility of using snap clips to support the assembly process of grid-shell joints.

By addressing both the computational and practical aspects of design, this framework aims to streamline the development of complex free-form structural joints, enhancing both performance and manufacturability.

2 DESIGN OPTIMIZATION WORKFLOW

The proposed framework follows a structured process that ensures each design iteration is both structurally efficient and manufacturable. The workflow includes the following key stages:

1. Node isolation and force extraction
2. Topology optimization and design exploration
3. Manual refinement and stress flow optimization
4. Snap clip integration for enhanced assembly
5. Finite element analysis
6. Low-cost prototyping

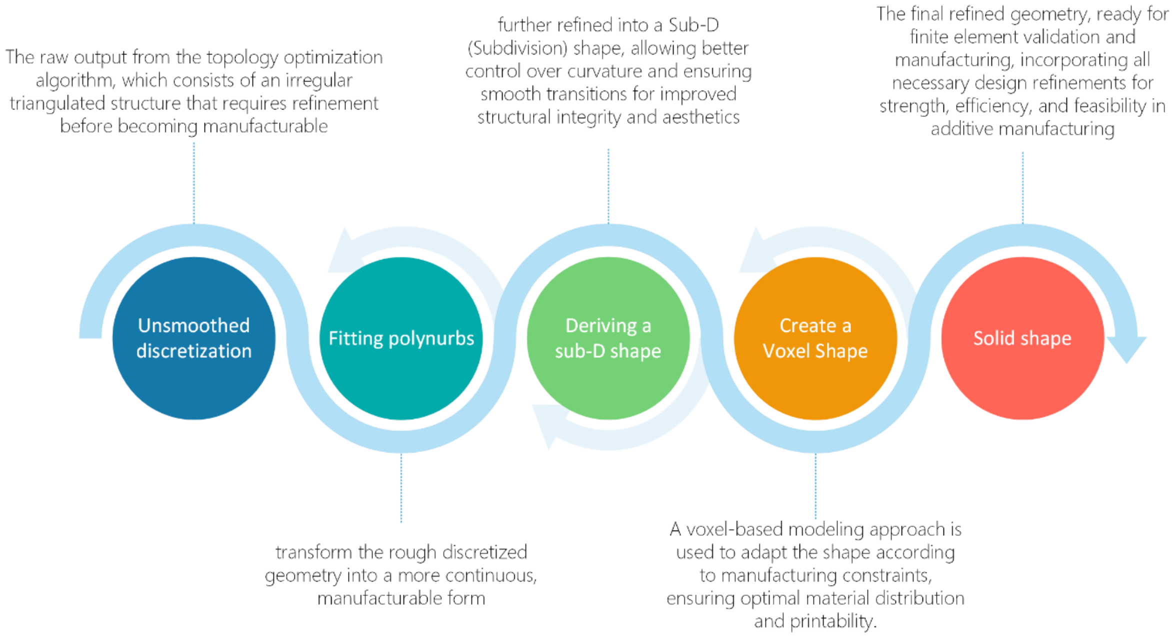

Figure 3: Workflow for topology optimization: From raw discretization to final solid shape.

2.1 Node Isolation and Force Extraction

The process begins with identifying critical nodes within the structure through a comprehensive global analysis (

Figure **4**) using Building Information Modeling (BIM) data and FEM. These critical nodes are selected based on their structural significance and loading conditions. Once identified, nodal force distributions under ultimate limit state (ULS) conditions are extracted to serve as essential load cases for the subsequent optimization steps. To ensure the accuracy of the optimization process, boundary conditions are carefully defined, simulating realistic structural behavior under anticipated loads.

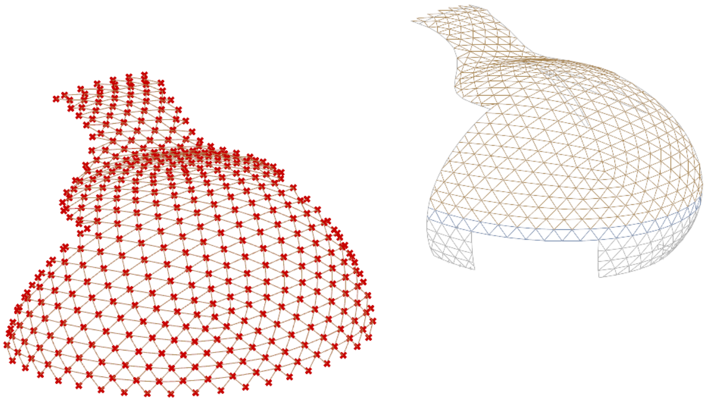

Figure 4: Critical node identification and structural discretization.

2.2 Topology Optimization and Design Exploration

A topology optimization approach, with a particular focus on the Solid Isotropic Material with Penalization (SIMP) method [3] , is employed to develop structurally efficient joint designs [4], [5], [6]. This optimization process integrates key manufacturing constraints, such as maintaining overhang angles within the 45° to 60° range and ensuring that minimum feature sizes are compatible with additive manufacturing capabilities. Various configurations of design and non-design spaces are analyzed to evaluate different stress flow distributions and structural responses. Figure 5 illustrates a possible application of the proposed optimization approach to a structural node derived from the original node geometry of the Fiumicino Terminal (
Figure **1**).

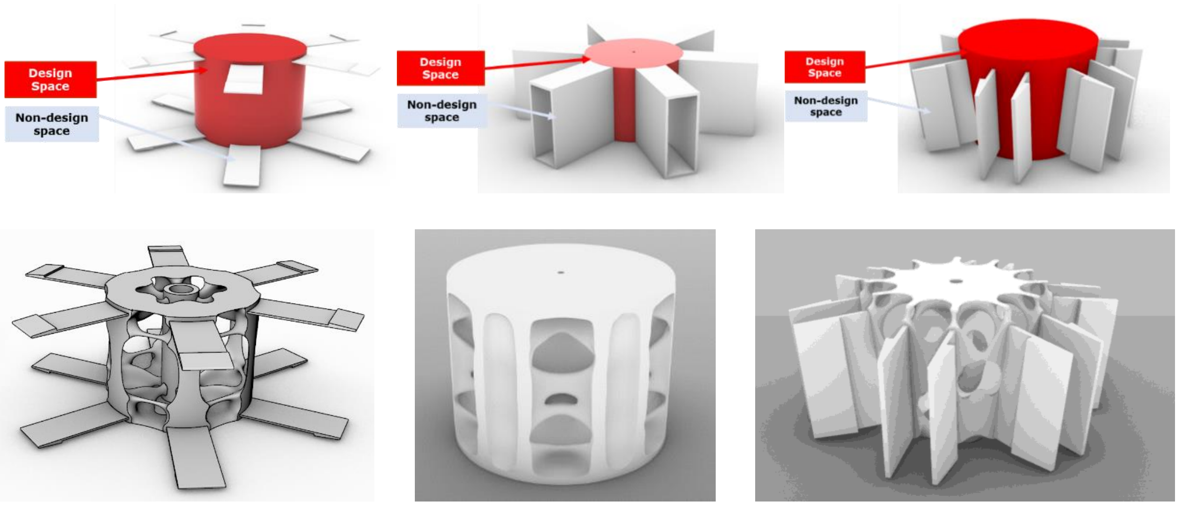

Figure 5: Design and non-design space definition (top) and multiple optimized solutions (bottom)

To ensure manufacturability, specific additive manufacturing constraints are directly incorporated during the topology optimization phase. One of the primary considerations is minimizing the need for support structures by adjusting overhang angles. Additionally, material anisotropy is taken into account to optimize part orientation and ensure that principal load paths align with material properties [7]. These constraints help generate optimized material distributions that are both structurally efficient and feasible for fabrication.

It is essential to emphasize that topology optimization serves as a conceptual design tool, generating an initial material distribution that requires subsequent refinement. This refinement phase ensures both manufacturability and structural feasibility, bridging the gap between algorithmic outputs and practical engineering applications.

2.3 Manual Refinement and Stress Flow Optimization

Following the initial topology optimization, the generated designs undergo manual refinement to align algorithmic outputs with engineering intuition and real-world constraints. This process involves recognizing and controlling stress flow and load paths, ensuring that abstract computational results are translated into feasible structural details. During this phase, additional additive manufacturing constraints are integrated to further refine the component for printability and performance. Dimensional tolerances are enforced to maintain wall thickness and geometric precision, ensuring that the final shape is manufacturable while meeting structural requirements.

To maintain geometric continuity and manufacturability, advanced modeling techniques such as PolyNURBS and voxel modeling are employed, enabling smooth transitions between optimized and manually refined features.

Voxel-based modeling provides a powerful approach to refining topology-optimized structures, particularly when handling complex free-form geometries and additive manufacturing constraints.

The workflow begins with voxelization [8],[9],[10], breaking down the design into structured grids to capture fine details. Next, filtering and smoothing algorithms remove artifacts and improve surface continuity, ensuring manufacturability and structural efficiency.

2.4 Snap Clip Integration for Enhanced Assembly

To streamline the assembly process and minimize the need for traditional machining and bolted connections, a snap clip mechanism [11] has been integrated into the joint design as shown in Figure 6. These clips serve a dual purpose: enhancing precision and speed during construction while reducing reliance on on-site adjustments that typically require looseness during the assembly phase.

The snap-fit system allows structural components to self-align during assembly, ensuring fast and accurate positioning of the beams within the joint. By leveraging the anisotropic properties of additive manufacturing materials, the clip mechanism is designed to offer both structural rigidity and flexibility, enabling a secure fit while accommodating slight variations in manufacturing tolerances.

Unlike conventional bolted connections, which require pre-machined holes, additional fasteners, and torque adjustments, the snap-fit approach reduces dependency on precision machining. This results in:

- Elimination of excess milling and drilling operations in both workshop and on-site conditions.
- Faster assembly with reduced need for secondary fixation methods such as welding or bolting.
- Lower labor costs and simplified logistics, as fewer components need to be transported and installed separately.

Before full-scale implementation, the snap clip system undergoes validation through low-cost prototyping and iterative testing. These tests allow for fine-tuning of the clip geometry, flexibility, and insertion force requirements, ensuring reliable engagement and long-term structural integrity. By integrating AM-enabled snap clips, the assembly process becomes more efficient and less reliant on conventional fastening techniques, ultimately leading to a lighter, more modular, and easily constructible structural system.

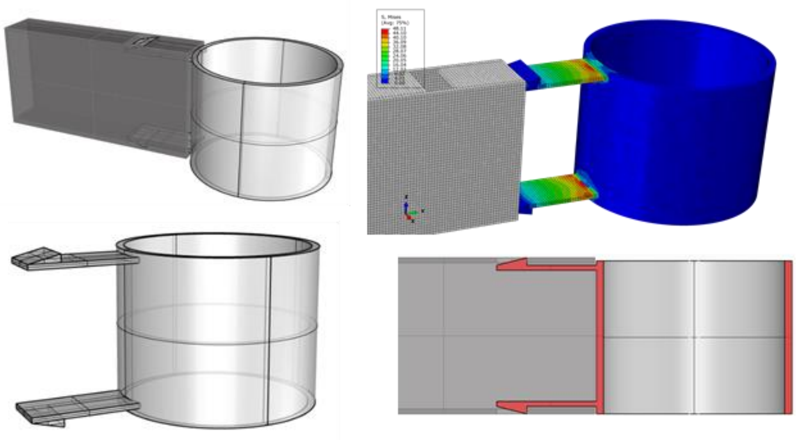

Figure 6 Snap clip integration: Joint design, structural analysis, and assembly mechanism.

2.5 Finite Element Analysis Validation

A detailed FEM validation process is conducted to evaluate the performance of the optimized structural joints. The analysis focuses on stress distribution, deformation behavior, and stiffness improvements, ensuring that the refined designs meet the required safety and performance standards. Critical stress points are identified, leading to further design refinements to mitigate potential weaknesses and redefine the solution re-iterating the process shown in Figure 7. To enhance accuracy, FEM simulations incorporate both isotropic and anisotropic material properties [12], providing a comprehensive understanding of structural behavior under real-world loading conditions. Comparative studies with traditional welded counterparts highlight the advantages of optimized designs in terms of weight reduction and structural efficiency.

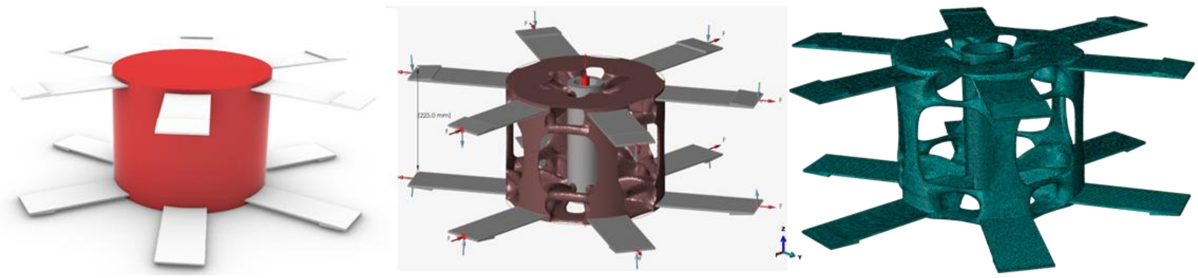

Figure 7: From design space to FE model

2.6 Low-Cost Prototyping

Before transitioning to full-scale production, low-cost prototyping techniques such as Fused Deposition Modeling (FDM) are employed to validate assembly features and geometric accuracy. These physical prototypes allow for iterative refinements, particularly in optimizing snap clip dimensions and wall thickness based on practical testing feedback. Once the design is finalized, the component is prepared for metal 3D printing using advanced techniques such as Wire Arc Additive Manufacturing (WAAM) or Laser Powder Bed Fusion (LPBF), ensuring the highest level of precision and structural performance for real-world applications.

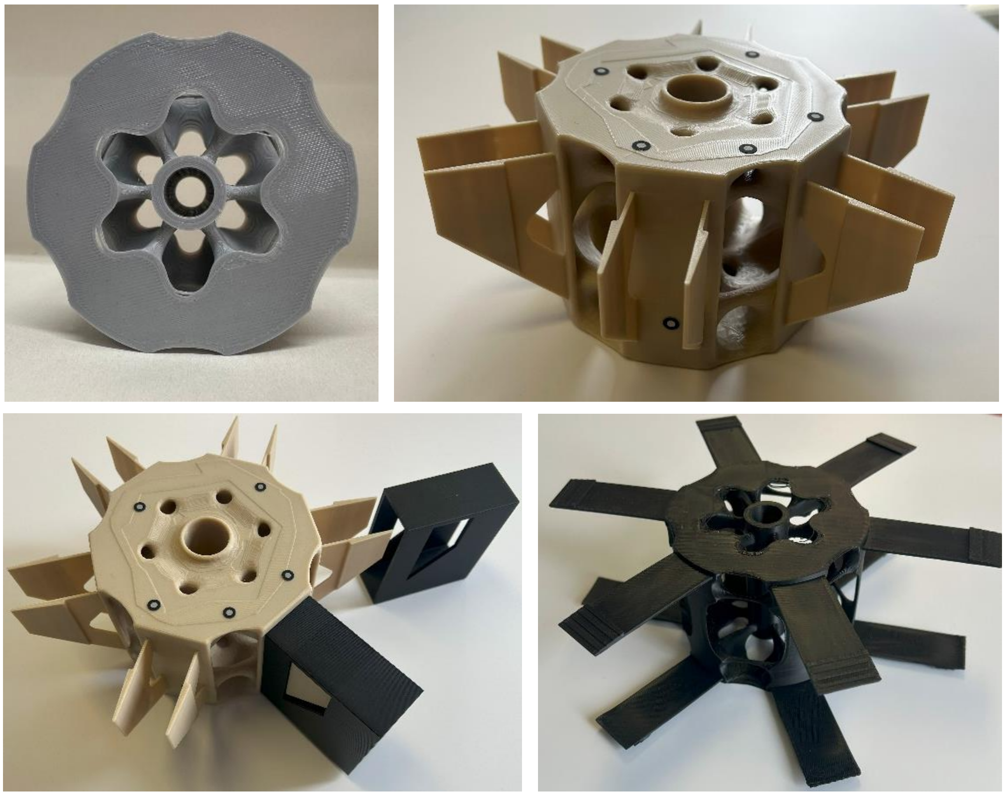

Figure 8: Low-cost prototyping: 3D-printed models used for validation of assembly, geometry, and snap-fit functionality.

Before advancing to full-scale production, low-cost prototyping serves as a critical step in the optimization workflow, facilitating both design refinement and manufacturing feasibility assessment. Techniques such as Fused Deposition Modeling are employed to create rapid and cost-effective physical models, allowing for iterative refinements before committing to metal 3D printing [13] .
As illustrated in

Figure **8**, low-cost prototyping offers multiple benefits that enhance both the design and fabrication processes:

- Detection of Potential Printing Issues: Prototyping helps identify challenges such as overhang stability, support placement, and dimensional accuracy, mitigating risks before transitioning to metal 3D printing.

- Evaluation of Aesthetic Integration: Physical models enable a visual assessment of the joint's geometry, ensuring it aligns with architectural and structural design intent.

- Simulation of Assembly Behavior: By producing scaled models of both nodes and beams, the functionality of snap clips connections can be tested and refined to ensure precise alignment and structural integrity during assembly.

By addressing these critical aspects early in the process, low-cost prototyping significantly reduces costly design iterations, streamlining the transition to full-scale manufacturing. Once validated, the final design is prepared for fabrication using advanced metal 3D printing techniques, such as Laser Powder Bed Fusion (LPBF), ensuring optimal precision, structural efficiency, and real-world applicability.

3 RESULTS AND CRITICAL CONCLUSIONS

The design process does not follow a strictly linear sequence but is iteratively refined at every stage based on the interplay between topology optimization, manual adjustments, structural validation, and manufacturing constraints following the workflow indicated in Figure 3. Each step informs the next, ensuring continuous improvements in efficiency, feasibility, and performance, ultimately leading to a structurally optimized and manufacturable design.

By integrating topology optimization, structural analysis, and additive manufacturing constraints, the proposed framework enables the development of free-form steel joints that achieve:

- Material efficiency, reducing weight while maintaining structural integrity.
- Improved stiffness and stress distribution, optimizing load paths for enhanced performance.
- Simplified on-site assembly, leveraging snap-fit mechanisms to reduce machining operations and minimize reliance on bolted connections.

This methodology strikes a balance between computational design and practical feasibility, offering a robust and adaptable approach for optimizing structural joints. The incorporation of snap-fit features highlights the potential of additive manufacturing in streamlining assembly, reducing fabrication complexity, and enhancing overall efficiency in structural applications.

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