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Hybrid Robot 3d-Printed 50 M Long Steel Bridge Realisation - Ai-Ml Assisted Generative Ga/Ea Design Workflows and Optimizations

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Abstract

AI-assisted Generative Design (GD) with genetic (GA) and evolutionary algorithm (EA) methods, digital twin modeling, and topology optimisations (TO) have undergone tremendous developments in recent years due to their essential applications in many fields of industrial and product design, medicine, synthetic biology, infrastructures, automotive technology, aviation, architecture, engineering and construction industries. The paper discusses an awarded realization project of an AI-assisted generative competition design with evolutionary topological optimisation and cloud computation workflows for a fabricated Steel Bridge. The structural analysis and fitness-tested geometry generation are for a 50 m robot 3d stainless steel bridge mixed with low-cost carbon steel components for special EN-Code permitting in Germany. The bridge must be assembled next year in June 2023. The paper questions the sustainability and production characteristics of a 3d-printed bridge versus a lighter hybrid version of prefabricated steel tube geometries and organically robot 3d-printed steel nodes and posts. It will critically describe and compare the performance-based optimisation workflows of this bio-inspired computed 3d Hybrid Wire and Arc Additive Manufacturing (WAAM) steel pedestrian and bicycle bridge. In the future, we aim to make AI-ML-assisted generative design and topology optimisation workflows more efficient in generating outcomes that demonstrate a balance between the designer's artistic (subjective) preferences and the structure's technical (objective) code-permitting requirements. In summary, the paper will critically compare the GD techniques with the GA and EA algorithm workflows with topological optimisations that use natural mechanisms that emulate the behaviors of living systems.

Keywords: Artificial Intelligence, Generative Design, Evolutionary Algorithm, Additive Manufacturing, Topological Optimization

1. Introduction:

1.a. Bridge Competition Criteria and Ecological Site Design Context

The four-hectare location for the awarded bridge is over a river that flows into the Rhine. The place is still a largely inaccessible postindustrial site to the public, with sealed-off brownfield areas. The site's owner, a German Postindustrial Cooperative in the Ruhr Valley, intends to reshape the estuary and river "Kleine Emscher" along with its large-scale water pumping stations from the coal mining areas below into the Rhine. The large-scale public park project is titled "The Green Window to the Rhine". We developed a drone-assisted digital twin with cloud points to create the ecological context geometry for the perfect length of the competition bridge. Numerous soil, World War 2 bombs lidar investigations and cataloging of the existing flora and fauna with environmental impact analyses have been conducted for two years by several engineering and landscape architecture colleagues. The new bridge micro piles are topographically adapted to the landscape of the estuary. These considerations have the advantage that the prefabricated bridge modules can be transported and assembled using smaller machines and a helicopter from barges for assembly. The new bridge design will transform the industrial area with this experimentally naturally organic bridge design paradigm. The competition was briefed at the end of 2020 and completed in the Spring 2021. The Author's design team in Miami-Berlin won the competition and received the commission in the winter of 2021. Due to the complex permitting requirements, the bridge design has been reiterated from December 2021 to November 2022.. All the park construction is planned so that ecological priority zones are not disturbed. (Fig. 1).

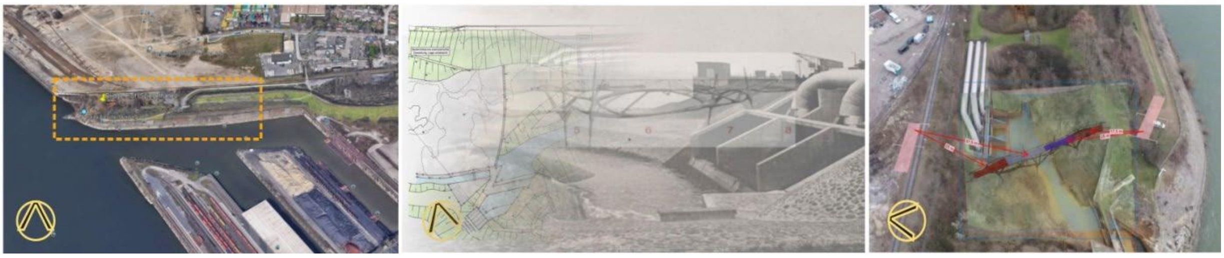

Figure 1: Site view of the park (left), digital twin for the bridge (middle), and bridge assembly location. Source: © Thomas Spiegelhalter.

2.Topology Optimization and Generative Design - an Exploratory Study

Topology Optimization (TO) has been around for 20 years but is not a Generative Design. TO generally begins with one complete human-bias-designed CAD model concept with loads and constraints applied based on the project requirements. TO returns only one optimized concept for evaluation based on the human-designed model. There is no automated ideation. Lastly, it returns to the user an optimized human-designed mesh-model result that must be rebuilt in a CAD system intended for downstream use (Wang, Guo, 2003). Whereas generative design started around 2018. It is an AI-assisted cloud-simulation-driven design methodology that uses algorithms to generate high-performance geometry based on user-defined engineering requirements. The Generative Bridge design begins with hold-out areas, preserved areas, loads, and constraints based on the project requirements. Artificial Intelligence, not humans, determined the topological cloud design outcomes created for further evaluation. Furthermore, the set-up of the performance parameters and material components can be automated, or it can even be text prompted with Graph Neural Networks (CNN) on data described by graphs in a non-Euclidean design space (Bian et al., 2022). Several generative designs (GD) tools are commercially available in design and engineering, including Altair's OptiStruct, Dassault Systemes CATIA V6, SolidWorks, Bentley, Autodesk's Revit-Dynamo Studio, InventorPro, Fusion360, Nastran, Netfabb Shape Generator, Grasshopper-Rhino, and Siemens NX SolidEdge-Frustum. But only Autodesk GD's run wholly integrated with the AIassisted cloud storage; the other brands still run with limitations only locally as standalone versions. The core of all these tools runs as a mathematical method that optimizes a layout of material distribution within a given design domain. Typically, the objective can be described as the flexibility of an object under a load and the total volume and fabrication techniques (Allaire, et al., 2002).

2. Types of algorithms for the generative bridge design

The evolutionary algorithm (EA) to achieve a more natural growth-looking design and the genetic algorithm (GA) have been tested and compared for the generative bridge design iterations. An EA is an algorithm that uses mechanisms inspired by nature and solves problems through processes that emulate the behaviors of living organisms. EA is a component of both evolutionary computing and bio-inspired computing. The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that are based on natural selection, the process that drives biological evolution.

The GA repeatedly modifies a population of individual solutions automatically in hundreds of cloudcomputed FEA iterations and ideations. Cautiously speaking, AI-assisted generative design is the next frontier in design and engineering product development because it flips the paradigm of creating and evaluating a design candidate's performance using non-human AI-assisted scenario experiments with rapid integrated manufacturing and material results, costs and assembly strategy comparisons (Spiegelhalter, 2014).

Furthermore, the GA is a prevalent example of a meta-heuristic search algorithm, which can explore a black box parametric model to find the highest-performing designs based on multiple objectives (Wang, Guo, 2003).

3. GD Automation to autonomously assess Geometry Constraints and Costs

GD is used in the initial design phase to autonomously generate hundreds of designs based on performance-based parameter inputs, materials and manufacturing types to reduce the weight and manufacturing costs. The integrated decision process also stimulates aesthetics by modeling editable CAD cloud results to emphasize organic growth patterns and lightweight construction (Andia, Spiegelhalter, 2014). These workflows are especially relevant in aerospace or automotive applications, where each weight reduction saves fuel and costs. In the forthcoming sections, we will elaborate further on the fabrication techniques of standard components and 3D printing such as Wire Arc Additive Manufacturing (WAAM) or Laser Powder Printing.

4. AI-ML-assisted Generative Bridge Design Iterations, Topological Optimization, Modifications and Validation Workflows

For this experimental bridge design, Autodesk's Robot Structural Analysis, InventorPro, Netfabb, Nastran, CFD Ultimate, ANSYS and the Fusion360 cloud computing subscriptions along with SIEMENS NX and the standalone version of RFEM Dlubal 3D finite element analysis software were used (Fig. 2,3,4,5, and 6). The AI-ML assisted Autodesk cloudprocessed design experiments with GA's and EA's include also multiple validated manufacturing requirements with cost analysis scenarios (e-priory technology) and are seen as an alternative to better performing, more lightweight outcomes than traditional designs. The synchronized cloud-based collaboration with other designers, engineers and manufacturers is a significant shift in design automation speed. Each experimental GD workflow consists of several criteria input steps depending on the objectives' complexity in setting up the GD Work Space for AI-ML-assisted cloud computing. For this, a couple of essential steps for the iterations in the GD cloud are required:

4.1. Iterations No. 1 and 2: The Baseline Model with different approaches

5.1.1 The first iteration was a typical cartesian 80 m by 2,50 m arched steel bridge design with Autodesk Robotic Structure Analysis FEM 2022 and Dynamo-Python scripts as a traditional design procedure. (Fig. 2.)

5.1.2 The second iteration used the same baseline geometry with the typically scaled preserved geometry sets of constraints, obstacles, boundary conditions etc. It was, this time, exported into Autodesk InventorPro, Nastran, Dynamo, and the Fusion360 AI-assisted cloud to run non-cartesian generative GA and EA design experiments. The setup included running the GD cloud studies several times with hundreds of outcomes and options. The second bridge design showed an organic growth-looking 80 m-spanned arched bridge topology (Fig.3). The geometry was based on the starting shape geometry and the main structure above the preserved geometry of the bridge circulation deck.

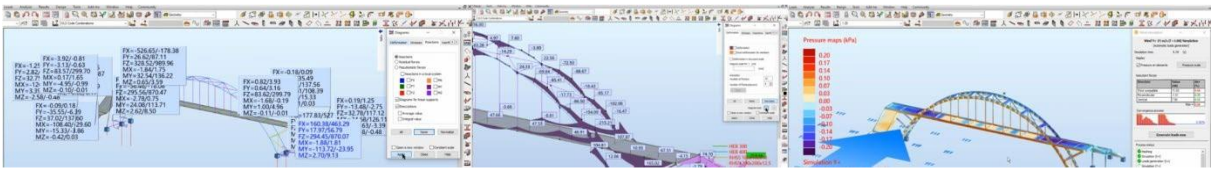

Figure 2: Autodesk Robot Structural Analysis as a Euclidean standard design solution. Source:© Thomas Spiegelhalter.

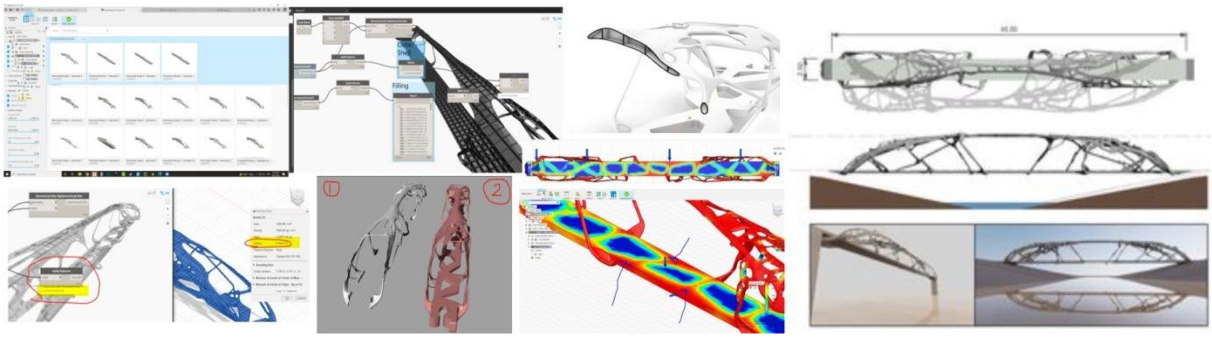

Figure 3: Autodesk InventorPro/Fusion360 Generative Design with organic experimental GA/EA workflows and Dynamo Scripting to topologically optimize the weight and material choices for fabrication. Source:© Thomas Spiegelhalter.

5.2. Iteration No. 3: The winning Competition Model Assessment and Update

The third bridge design and competition-winning solution focused on a different parametric input to distribute loads of the main 50 m long structure under the preserved geometry of the bridge and pedestrian and bicycle deck through seven micro piles over the river estuary. In this third iteration, the GD space, objectives, scales and boundaries were set up based on a more EU-German code-specific detailed input for loads and materials (Fig. 4).

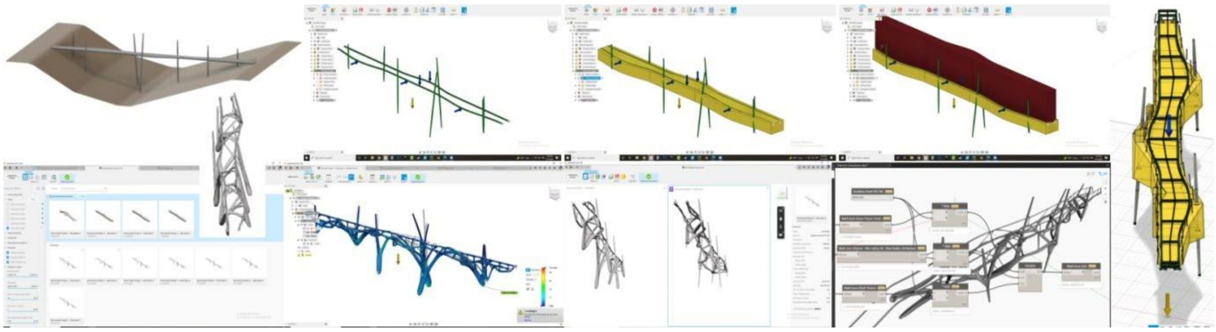

Figure 4: Autodesk InventorPro/Fusion360 Generative Design space, constraints, obstacles, offsets, with genetic and evolutionary Algorithms (GA/EA) and Dynamo Scripting. Source:Source:© Thomas Spiegelhalter.

5.2.1. Design Space, Preserved and Obstacle Geometry, Offsets, and Starting Shape

This time the preserved geometry with boundaries (the keep in's) stayed in the final modeling space of the starting shape (such as nodes and connection points between tubes and pylons) under the preserved geometry, and the scaled obstacle geometry with the constraints (the keep-outs, clearances). The concrete abutments and micropile foundations were separately computed with other FEA software to calibrate and merge the results into the shared cloud Masterfile (Fig. 4).

5.2.2. Structural Design Constraints, Loads, Attributes and Objectives

The next step included coding all the relevant structural design conditions and load types based on Eurocode 3 (EN 1993/EC 3) for the FEA analysis and optimisations. The GD-model settings include the following:

- **Self-weight:** The own weight of the upper structure covering is made of recycled material and calculated with 0.5 kN/m2. The GD process with GAs and EAs is based on all structural boundary conditions and all load specifications that will automatically optimize iteratively in the cloud. With that, the self-weight of the structure was not known during the first iteration. The self-weight was automatically calculated from the generated geometry data of the model (either with organic non-centred or centered tube geometries, wall thicknesses, node strengths, etc.). The weight of the steel was considered as 78.5 kN/m3.

- **Vertical payloads:** The live bridge load is 5.0 kN/m2. The bridge iterations are divided into four sections: first by seven and then later by three pylons. The live load's parameters are applied in sections as non-permanently acting loads. With that concept, it was possible to superimpose flexibly on all iterative static verifications for all design points in Inventor ProNastran and the Dlubal software workflows.

-**Horizontal payloads:** Parallel to the vertical payloads, 10% of them are in the transverse direction of the bridge, each with the most unfavorable sign for the dimensioning.

-**Structural Buckling** is about determining the buckling modes of the digital model. The Results include Buckling Modes and their corresponding Load Multipliers.

-**Nonlinear Stress** determines the static stresses and deformation throughout the model caused by structural loads and boundary conditions.

-**Dynamic Loads** such as:

-**Modal Frequency** was chosen for vertical and longitudinal vibrations:
1.25 Hz ≤ fi ≤ 2.3 Hz, and lateral vibrations: 0.5 Hz ≤ fi ≤ 1.2 Hz.
-**Quasi-static Event Simulation to** determine the static stresses and deformation in a single part or multi-body assemblies of the bridge where nonlinear material behavior is required. -**Dynamic Event Simulation** to determine how the design responds to rapidly changing timedependent loads and constraints, including large deformations and initial velocities.
-**Wind load** with the transverse direction when wind loads impact the structure of a 2.0 m high-traffic band scheduled. The impact applies to each tube and every node.
-**Water load.** The worst-case inundation scenario is when the entire bridge structure is flooded with a water flow rate of 3.0 m/s. Also, the buoyancy forces for all immersed components, especially the hollow tubes, will top because of the sizable displaced volume of liquid and the tubes' dead weight, leading to total lifting forces on the bridge.
-**Impact Loads:** In the event of a flood, impacts of objects on the bridge's structural integrity are expected with a mass of 200 kg, like a 50 by 200 cm tree trunk.
-**Thermal Stress loads** were not considered as they determine excessive heat loads and thermal boundary conditions under steady-state temperature conditions (Fig. 5).

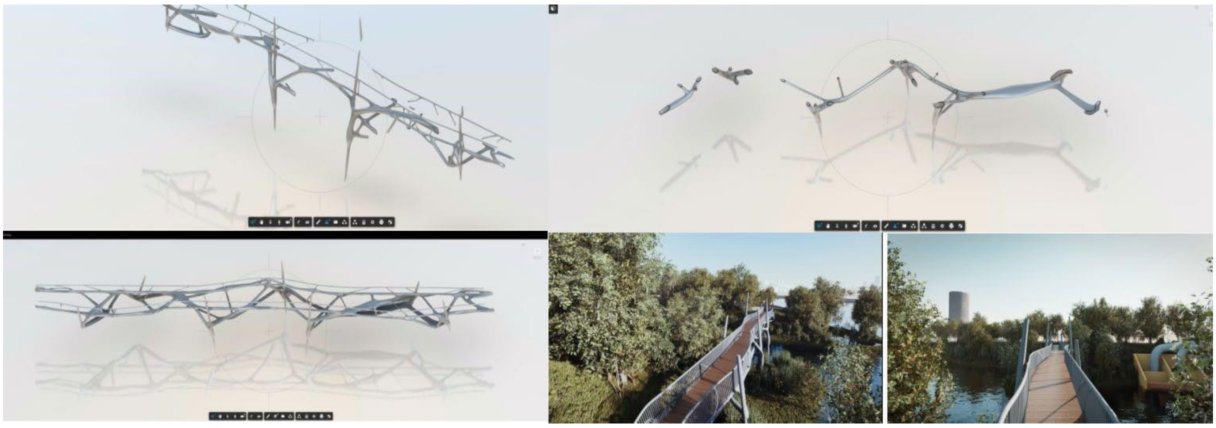

Figure 5. Autodesk InventorPro/Fusion360 Generative Design and Topological Optimizations (TO) with genetic and evolutionary Algorithms (GA/EA), SIEMENS NX, Dynamo Studio. Renderings in Revit.Source:© Thomas Spiegelhalter.

4.2. Iterations No. 3 to 8: Real-World Model Efficiency Comparisons

Four more iterations focused on the most prominent competition challenges: keeping production costs and site assembly within the contracted limits, including foundations. The other challenge represented the additive manufacturing costs and limited time to deliver the bridge modules to the industrial site for punctual assembly. One of the first intentions was that the entire competition-winning organic and aesthetically lightweight looking 50 m design had been entirely 3d printed in stainless steel (SS 308LSi). Printing the whole structure would have consumed ~11.630 hours of 3d WAAM printing or ~2080 hours of printing with six Kuka Robots. Plus, it would have needed 3488 kg consumable wires, an x-amount of protective gas tanks, and 58.147 kWh electricity for around 1,4 Mio. Euro before tax (including shipping), excluding the design and planning, permit mockup testing and other licensing fees. Furthermore, the tied green park planning schedule of many other integrated collective construction processes within months makes it impossible to wait over a year to print a steel bridge. The original wish to solely robot 3d-print the world's largest steel bridge diminished quickly towards a more cost-efficient design. The solution evolved to strive for a hybrid design of a balanced mix of prefabricated steel tubes and 3d-print nodes and posts for the handrails to maintain the organic growth aesthetics of the final lightweight bridge design. The catch is that to achieve these weight efficiency objectives, more iterative topological optimizations were needed to minimize the materials and weights to a minimum. Within the FEA and RFEM structural fitness iterations, the pylons were reduced from seven to only three. The originally non-centred growth nodes of the hollow tubes were then finally centered, dramatically reducing the weight of the printing costs and ensuring punctual assembly. The final price inquiries and tendering showed a dramatic price reduction of nearly 225%.

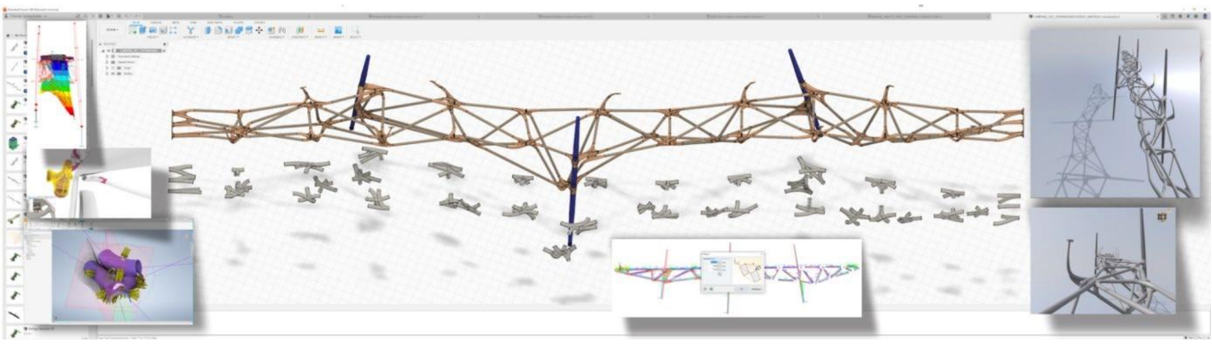

Figure 6. Autodesk InventorPro/Fusion360 Topological Optimizations (TO) of the nodes and entire geometry, with RFEM tests in Dlubal and Dynamo-Grasshopper. Renderings in Autodesk-Maya-Alias. Source:© Thomas Spiegelhalter. .

5. Permit Testing Criteria for additive Manufacturing and Assembly

The exploration of iterative-parametric design solutions that allow consolidating multiple steel components into solid prefabricated or 3d printed parts, reducing assembly costs and simplifying the chain on time is pivotal. But further investigations and scientific testing are necessary for all the 3d printed stainless steel nodes and railing posts, as the welded material in its properties is directional. After the final FEA analysis experiments and shape generation, the 3d printed stainless steel test nodes' mode of action and the design specifications will be determined experimentally using 2 or 3 mockups through a German research institute next year in January. Other challenges include aggregating data from the additive manufacturers of their different robot G-Codes for managing interferences without much file cleaning and machine path programming (Fig. 5).

6. Multiphysics Accuracy Verification

All the computational Autodesk Simulation Mechanical /Multiphysics workflows are based on the Autodesk® Simulation Accuracy Verification Examples (AVEs) Manual of the US NAFEMS benchmark publications (Autodesk®). Other examples are from theoretical sources, such as Roark's Formulas for Stress and Strain (Autodesk®). The RFEM Dlubal standalone software is based on the COMSOL Multiphysics Accuracy Verifications for Steel Design According to DIN EN 1993-1-1 (Temesgen Kindo (2015).

7. AI and Aesthetics lessons learned in the Generative Design Workflows

Once the final steel tube and nodes-centered geometry were selected and further analyzed through topological optimisations (TO), it was clear that the organic aesthetic of the noncentred steel tubes to nodes was more aesthetically appealing. Typically, TO's follows a stochastic process based on sampling a limited number of designs from the GD space. In this context, it is also important to note that the performance-based GA and EA workflow with metrics cannot represent the aesthetics of the human perception of the bridge. These aspects, such as beauty, cannot be quantified and thus need to be considered once the GD is complete and the geometry exported for further TOs. The initial best-looking GD and optimized model with organic-growing-looking non-centred geometries were less efficient and heavier than the centered geometry model. The final iteration included many 1:1 software ZOOM workshops with the additive manufacturers discussing the robotic G-code and WAAM or Laser printing capacities. Then, the approval of the FEA and EN-code-specific calculations with 3d-printed test nodes by the German Institute for Steel also required extra clarifications.

8. Conclusion & Future Work

This paper describes innovative AI-ML-assisted computational design methods which combine generative geometry models based on the bottom-up evolutionary agent-based growth processes found in natural systems with a top-down genetic algorithm for optimisation. The paper also compares the application of these methods toward a unique steel bridge design with optimized 3d-robot WAAM, Laser printing and bluemint®additive manufacturing processes. By conducting eight iterations with five different design models, the iteration outcomes demonstrated the following: Distinct computational methods can create a purely organic-growth appearing geometry that became a 'source of aesthetics, and multiphysics iterations optimize real-world configurations for affordable and sustainable hybrid additive manufacturing processes. As a result, the weight of the envisioned hybrid 3D-printed and prefabricated steel bridge was radically reduced, which also helped to minimize the overall costs for manufacturing speed to match all the other project deliveries of the 4 hectares park realizations. Finally, the developed hybrid computation method suggests future research into developing other nature-based generative EA design workflows with GNN's deep neural networks. They can extend the power of evolutionary computing to excel in more highperforming manufacturing solutions and cost reductions.

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