Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Sustainable Design Synthesis of Discrete Free-From Structures Utilizing Existing Building Objects

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Abstract

This research introduces a novel computational design synthesis framework for generating sustainable, bespoke, free-form structures using existing, cuboidal building objects. Conventionally, bespoke design typically requires precise, customized, virgin materials, necessitating the need for sustainable alternatives taking full advantage of available or reclaimed resources. However, despite considerable CO_2 emissions reduction, reclaimed cuboidal building objects, e.g. masonry blocks, are seldom adopted in the construction of free-form structures. Given a target free-form geometry and a finite set of building objects, the proposed method generates a set of Pareto-optimal discrete assemblies optimized for structural integrity, geometry approximation, and sustainability, e.g. embodied carbon. Employing a nested optimization process, the proposed process develops a novel, coarse meshing technique in the outer loop to discretize geometry for scalability. Then, the combinatorial assembly problem is formulated and efficiently solved in the inner loop as two Integer Linear Programming problems to maximize geometric accuracy and minimize environmental impact. Through a case study with reclaimed blocks, this approach achieves significantly better geometry approximation and sustainability compared to conventional methods that use virgin, standardized materials, exhibiting the potential to promote sustainable construction practices without compromising design integrity.

Keywords: generative design, free-form structures, discrete construction, reclaimed blocks, life cycle assessment, combinatorial optimization, meshing, finite element analysis.

1. Introduction

Discrete-element assemblies comprising individual rigid objects, such as blocks, offer advantages such as scalable designs, cost-effective manufacturing, easy transportation, and the possibility of assembly and disassembly. Though highly durable, many discrete structures, such as masonry structures and brickwork, are demolished long before the end of their technical service life. The majority are crushed and landfilled or otherwise used to form aggregate. With the construction sector contributing to 39% of the world's carbon emissions, urban mining and circular economy are gaining popularity for their potential to recover structural elements from end-of-service-life buildings for direct reuse [1].

There are several factors contributing to great environmental benefits of reusing bricks and blocks: (1) intensive energy consumption is associated with the fabrication process of cement-based concrete, fired bricks and tiles; (2) In Britain alone, over 2.8 billion new bricks were produced in the early 1990s, all made from virgin clay — a non-renewable resource [1], which brings significant benefits to reclaim and reuse these materials. To meet the growing demands, there exist mature markets for reclaimed blocks in countries including the United Kingdom, Denmark, and Canada. Industrial companies, such as Brique Recyc in Quebec and Gamle Mursten in Denmark, have sophisticated but practical mechanized systems for reclaiming bricks. Gamle Mursten is also able to provide CE marking for their reclaimed products to the same harmonized standard (EN 771.1) as new clay bricks with an Export Accompanying Document (EAD). From a sustainability point of view, it is estimated that 2000 recycled bricks save one ton of CO_2 compared to burning new bricks, according to Gamle Mursten. Thus, a number of industrial projects, e.g. the Lendager Group's Resource Rows project in Copenhagen and the C.K. Choi Building in Canada, have been built and demonstrated the potential of reusing brickwork. Compared to structural steel or timber, the motivation for using reclaimed blocks may not be purely for sustainability but also for aesthetic reasons (e.g. the historic London Yellow Stock bricks), which makes reclaimed blocks also architecturally interesting.

Despite the vast aesthetic and sustainable potential of reclaimed blocks, there is a research gap in using reclaimed blocks for free-form structures, which constrains the application of reclaimed blocks to conventional structures, e.g. vertical brick walls, impeding adoption for customized geometries. Thus, this research aims to address this gap by introducing a novel computational design synthesis framework for generating sustainable, bespoke, free-form structures using existing cuboidal building objects.

This paper begins by introducing related work in Section 2. Then, in Section 3, a binning strategy is modified to accelerate the search process for certain building objects, followed by the proposed computational design method using Non-Dominated Sorting Genetic Algorithm II (NSGA-II) [2] and 0-1 Integer Linear Programming (ILP), considering geometry approximation, sustainability, and structural performance. The proposed method is applied to one example case and benchmarked with a case employing virgin and standardized materials. The results are presented in Section 4 and discussed in Section 5. Section 6 concludes the paper with a summary of the contributions.

2. Background

While the vast majority of the literature focuses on reusing structural steel [3, 4] and timber [5], few research works focus on designing with existing or reclaimed cuboidal objects (e.g. masonry blocks or panels), whereas none of them investigate design synthesis for reclaimed block reuse on free-form structures. For instance, Devènes et al. [6] present a proof-of-concept prototype reusing blocks cut out of obsolete cast-in-place concrete walls for a new post-tensioned segmented arch footbridge that reduces CO2 emissions by 63% compared to a conventional concrete design. Marshall et al. [7] propose a shingled glass envelope system using reclaimed insulated glass. Though these projects successfully demonstrated the sustainability of reclaimed concrete and insulated glazing units, respectively, the design and analysis were conducted sequentially and manually. Thus, they did not shed light on how to computationally synthesize and optimize the design for free-form structures.

In 2022, the authors [8] introduced a pioneering computational design method for assembly problems using existing building components with dimensional variations. However, three factors prevent it from being adaptable to large-scale free-form structures using reclaimed blocks: (1) it is applicable to a small-scale structure with roughly a hundred blocks, regardless of the block dimensions; (2) the method is more efficient when the target geometry is either a cylinder or a regular curved surface, e.g. sine-cosine surface; (3) the algorithm has a rotation operation that does not apply to reclaimed blocks where the lengths and widths are often not interchangeable. Other existing research [9] and toolkits [10] aim to facilitate inventory-driven design while the scale is limited and dry-stacking is not always feasible. Therefore, this research proposes a more scalable method capable of handling more complex geometry to fully exploit the established reclaimed block market for large-scale, sustainable, free-form structures.

3. Method

In this section, a novel computational design and optimization method for large-scale, free-form structures using existing building objects is presented. Given a target geometry, site conditions, and a material pool of unique building objects, the proposed framework conducts statistical binning of the objects and then generates a set of Pareto-optimal discrete structures, considering two objectives including geometry approximation and sustainability performance, and one constraint on structural performance, as shown in Figure 1.

This research employs a hybrid representation, namely, a mesh and a discrete structure, for conducting multi-objective design optimization. A nested computational framework is developed and contains the following: (1) Outer loop: an NSGA-II carried out a global optimization by adjusting the mesh, which also influences the selection of the bins and blocks, and integrates objectives that cannot be formulated as a 0-1 ILP problem; and (2) Inner subproblem: 0-1 ILP to select blocks and bins for local optimality and computational efficiency.

Within the optimization, different objectives are evaluated on different representations. For example, the mesh is used for a thin-shell FEA, while geometry approximation and sustainability metrics are calculated using the actual discrete structure. The geometry approximation is further defined by vertical and lateral boundary approximations and an out-of-plane geometry approximation, where the vertical and lateral boundary approximations are mathematically formulated as ILP problems. All methods are written in a combination of Grasshopper and Python.

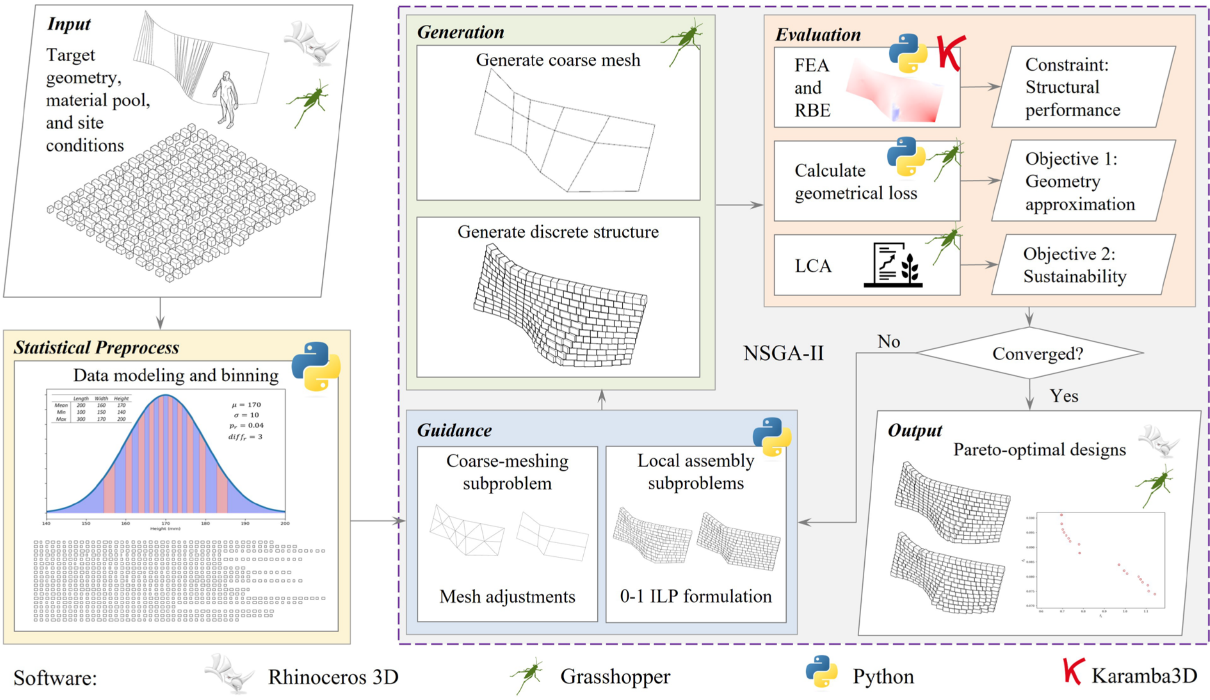

Figure 1: Flowchart for the proposed method.

3.1. Statistical modeling and binning

The proposed method starts with data quantification based on the exact dimensions of the existing objects, assuming that each object is unique. Since no existing dataset is available with exact dimensions, this research uses general measurements of reclaimed building stones from the Reclaimed Brick Company in the UK, with an example shown in Figure. 2(a). The dimensional data are assumed to follow Gaussian distribution models according to the probabilistic model code [11].

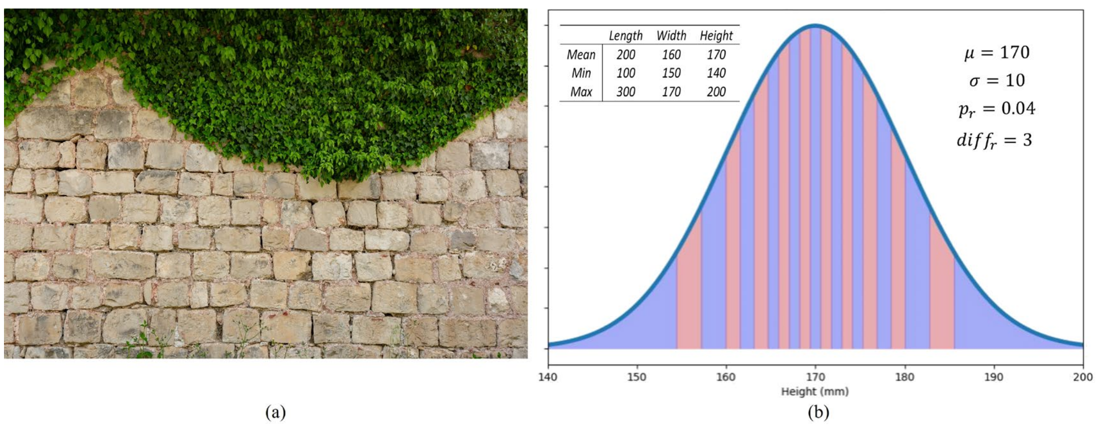

Figure 2: Example material used in the case studies and binning result for the distribution model. Image in (a) credit to © Sergey Fedoskin | Adobe Stock. Unit: mm.

Since each reclaimed building object possesses unique dimensions, searching all existing objects for one suitable object can lead to computational intractability. This research modifies an existing statistical binning strategy proposed by the authors [8], which captures the statistical distribution of the dimensional features and categorizes the building objects accordingly. The purpose of this binning strategy is to reduce the variations within each bin and, at the same time, ensure enough objects are assigned to each bin. Given the distribution of dimensions, reducing variations within each bin requires increasing the number of bins. Thus, the modification made in this research is changing the problem formulation from minimizing, as formulated in [8], to maximize the number of bins. The resulting 21 bins based on height are shown in Figure 2(b). For a height distribution *N*(170, 10), the resulting bin boundaries are [140.0, 154.0, 157.0, 160.0, 162.0, 163.0, 165.0, 166.0, 167.0, 168.0, 169.0, 171.0, 172.0, 173.0, 174.0, 175.0, 177.0, 178.0, 180.0, 183.0, 186.0, 200.0] (unit: mm).

3.2 Coarse meshing

To enhance the scalability of the design synthesis, this research proposes a novel method to first discretize the target free-form geometry into coarse meshes and then conduct assembly problems locally using ILP (introduced in Section 3.3). The rationale of coarse meshing is piece-wise linearization to cluster and align building objects in several segments to reduce the total number of rotations and overlapping objects in the structure, lowering both computational and construction complexities.

The proposed method offers two meshing options to accommodate planar and non-planar design needs. For example, larger panels such as reclaimed windows require a planar surface, while smaller blocks can enable gradual rotations between two adjacent courses and thus work with non-planar quad meshes. Planarization can be conducted independently of downstream tasks but can sometimes deviate from the target geometry. On the other hand, non-planar meshing has the advantage of being customized and showing improved geometry approximation when integrated into the framework introduced in Section 3.1. Thus, this paper mainly centers on the non-planar meshing technique.

The design variables are the number of meshes in the vertical and horizontal directions, respectively, and the locations of the mesh edges. Example results with planar mesh and non-planar quad meshes are shown in Figure 3(a). Though the planarization starts with quad meshes, two quad meshes in the middle section converged to triangular meshes during the planarization process to fit the curvature with small radii. The rest of this paper uses the non-planar quad mesh as an example to present the proposed method.

3.3. Geometry approximation

Since the aim of this work is to automatically generate a discrete assembly given a free-from geometry, geometry approximation is essential and is taken as the first objective in the design synthesis. This research considers three quantifiable criteria: vertical boundaries, lateral boundaries with inner gaps, and out-of-plane approximations.

3.3.1. Combinatorial optimization for vertical boundaries

With each course assigned one bin from Section 3.1, the combination of bins determines the vertical dimensions of the structure, which is expected to be as close as possible to the target height. Similar to the Knapsack problem formulation, the combinatorial problem is formulated as an ILP problem, as shown in Eq (1), to select bins for each course such that the gap between the actual and target height of the discrete assembly is minimized.

$$\begin{aligned} &\min_{\boldsymbol{p}} H^t - H^s \\ s.t.\quad & H^s = \textstyle\sum_{i\in\Omega_B} h_i p_i \\ & H^s \le H^t \\ & p_i \in [0,1] \qquad \forall i \in \Omega_B \end{aligned} \tag{1}$$

where H^t and H^s are the target height and actual height, respectively. h_i is the representative height of bin i. $\boldsymbol{p}$ is a vector of Boolean variables representing the selection of bins from the set of bins Ω_B. This ILP formulation can be solved by a linear programming-based branch-and-bound algorithm.

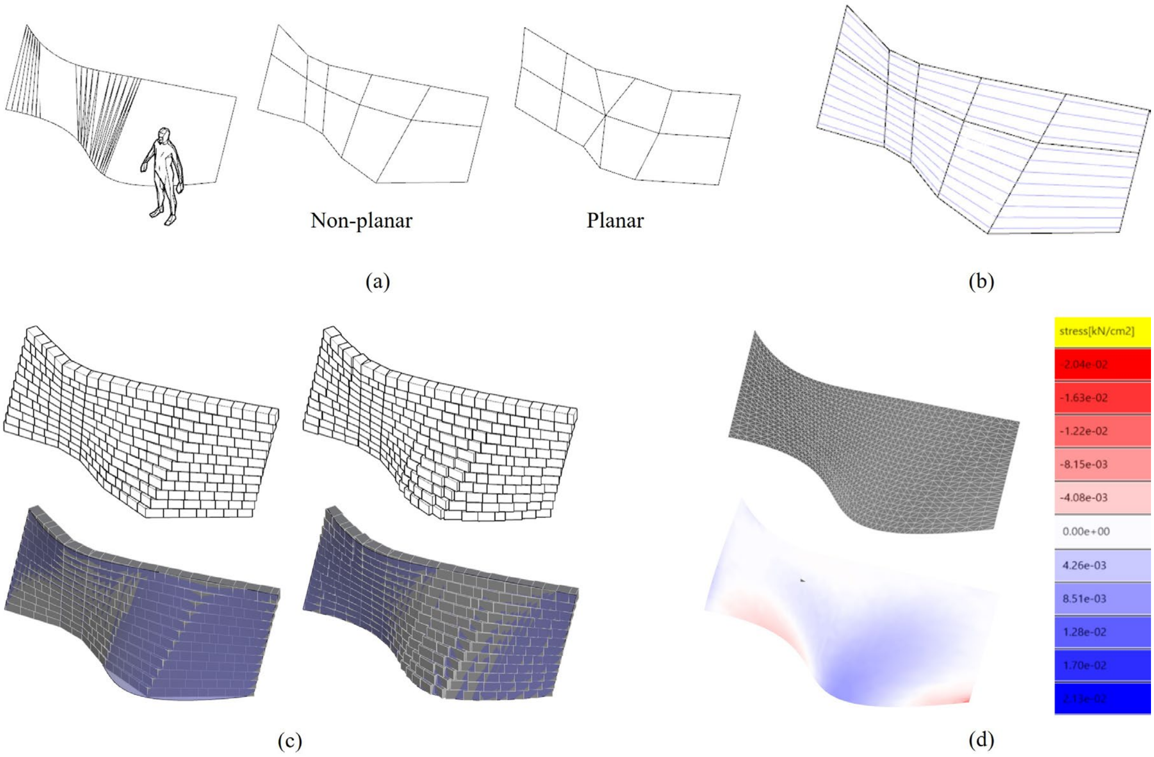

Figure 3: Illustration of the intermediate processes during design synthesis. (a) Coarse meshing module: an input target geometry (left), a non-planar quad mesh (middle), and a planar mesh (right), both generated with a 2 by 5 grid. (b) The coarse mesh is horizontally cut into line segments, which represent course segments. (c) Block layout resulting from the combinatorial optimization subproblem (left) and fine-tuned block layout resulting from out-of-plane approximation (right). The medium-transparent blue shell indicates the target geometry. (d) FEA mesh setup and example result.

3.3.2. Combinatorial optimization for lateral boundaries and inner gaps

This module quantifies and optimizes the lateral boundary fitting and inner gaps. The coarse meshing technique from Section 3.2 discretizes the geometry into small-scale panels, either planar or non-planar, depending on the use case. Then, with the resulting course height from Section 3.3.1, the coarse mesh is further horizontally cut into line segments, as shown in Figure 3(b), where each line segment represents a course segment and guides the assembly direction. The length of each line segment indicates the target sum of the length of the building objects on this course segment. With multiple segments on each course selecting building objects from the same designated bin, the combinatorial problem is formulated as Eq. (2), minimizing the sum of all the gaps on each course segment:

$$\begin{aligned} &\min_{\boldsymbol{q}} \textstyle\sum_i \left(h_i \sum_j (L_{ij}^t - L_{ij}^s)\right) && \\ s.t.\quad & L_{ij}^s = \textstyle\sum_{k\in\Omega_b} l_k q_{jk}^i && \forall j \in \Omega_i, \forall \Omega_i \subseteq \Omega_{sel} \\ & L_{ij}^s \le L_{ij}^t && \forall j \in \Omega_i, \forall \Omega_i \subseteq \Omega_{sel} \\ & q_{jk} \in [0,1] && \forall j \in \Omega_i, \forall \Omega_i \subseteq \Omega_{sel} \end{aligned} \tag{2}$$

where h_i is the maximum height of building objects on the ith course. L_{ij}^t and L_{ij}^s are the target and actual length of the jth segment on the ith course. L_{ij}^t is derived by the meshing and segmentation from Section 3.2 and Section 3.3.1 while L_{ij}^s is calculated by the sum of l_k, the length of the kth building object, multiplied by q_{jk}^i, a Boolean variable indicating whether the kth block is selected on the jth segment on the ith course. Thus, the objective function is minimizing the sum of the void area at the end of each course segment. This ILP problem can also be solved similarly to that in Section 3.3.1. One example result is illustrated in the left subfigure in Figure 3(c).

3.3.3. Out-of-plane approximation

To minimize the geometric loss resulting from the piece-wise linearization from Section 3.2, this research proposes to offset each block in the orthogonal direction to its residing line segment, with an example shown in the right subfigure Figure 3(c). This operation is conducted after the combinatorial optimization for lateral boundaries and inner gaps in Section 3.3.2.

3.4 Sustainability evaluation with life cycle assessment

With sustainability being one of the essential arguments and objectives for using reclaimed building objects, this research evaluates environmental sustainability by conducting a preliminary cradle-to-gate LCA on the material and process. In the case study using reclaimed building blocks from the UK, the functional unit is the local construction of one structure with a target geometry. System boundaries start with the separation of bricks from the obsolete structure and end with the assembly process of the target structure. The system boundary excludes transportation, maintenance, and end-of-life phases due to the undefined scenario. The impacts are calculated in terms of Global Warming Potential (gCO_2-equivalent), which is considered as the second objective in the design synthesis.

This research considers two sources of CO_2-eq:

(1) CO_2-eq from the reclaiming process: Each block reclaimed from demolition sites needs preprocessing, such as separating and cleaning. Assuming using a standard bench diamond saw, the cutting process for a unit area (1mm^2) on the interfaces emits 1.882×10^{-5}g CO_2-eq, which is obtained from Ecoinvent 3.4 and from the cleaning setup from [1]. Note that the values are based on manual processes. If the processes are automated, the rate of reclaiming bricks would be significantly higher.

(2) CO_2-eq from the assembly process: As shown in Figure 3(c), the angle between two line segments can lead to overlapping blocks. During the assembly process, overlapping blocks need to be cut. This research applies a Boolean intersection operation to obtain overlapping volumes. Then, it sums the areas of vertical faces on the overlapping polyhedron, i.e., the cutting area, and multiplies it by 1.882×10^{-5}g CO_2-eq/mm^2, assuming using the same cutting saw from (1).

3.5 Structural analysis

Two types of structural analysis, including a preliminary Finite Element Analysis (FEA) on a macroscale thin shell model [12] and the stability check using Rigid Body Equilibrium (RBE) [13], are conducted in the framework to ensure the resulting designs are structurally sound. As shown in Figure 3(d), the thin shell model is extracted from the target geometry, whose thickness in the examples given in this paper equals the average width of the block. For the FEA, the thin shell is meshed using triangular elements with a size of 0.2m. The support points are all the points of height zero, and are fixed in all degrees of freedom. For a specific site, the structure's purpose, dimensions and materials of the blocks determine the loading that must be considered. Since the case studies are low-rise structures, the ultimate limit state (ULS) design is dominant. The material selected for the case studies in Section 4 is building stone with example material properties: Young's modulus 800MPa, in-plane shear modulus 300MPa, and density 2.5tons/m^3. Note that the mechanical properties are expected to vary with specific material types and sources. The load cases prescribed as an example for the case studies include self-weight as dead load (D), and 1 kPa wind load (W), applied laterally. The load combination that dominates the ULS design is 1.35 D + 1.5 W (EN 1990, 2002). The optimization framework constrains the maximal tensile stress to be smaller than 0.1MPa and the result from RBE to be stable under self-weight.

4. Results

This section presents the results of a case study on a free-form wall using reclaimed blocks, which is compared with an assembly of the same geometry using virgin and standardized bricks. Then, the second subsection presents additional free-form structures using the proposed method with reclaimed blocks.

The hyperparameters of NSGA-II are set as follows: the population size is set to 60 and the number of generations is set to 20, according to a convergence study. In terms of sampling, Float Random Sampling method is selected. For crossover, Simulated Binary Crossover is employed, where the probability of a crossover is set to 0.9, and η_c is set to 3, which gives a more diverse spread of the offspring around the parents' genes. For mutation, Polynomial Mutation is selected while η_m is set to 1 to increase the mutation's diversity. The proposed method is implemented in Python 3.12 and Grasshopper. Gurobi® solver is employed for ILP problems, while Pymoo, an open-source framework for multi-objective optimization in Python, is employed for NSGA-II. If mesh planarization is required, this research employs Kangaroo Physics, a physical simulation engine in Grasshopper. Karamba3D is selected for FEA. Both of the optimization example cases are run on a standard laptop using a CPU with eight cores (i7-10750H) and 16 GB of RAM. For the case studies, NSGA-II is run 5 times, where the computational time for each run is around 5 hours with 1200 times of objective evaluations.

4.1 Case study: a free-form wall

This research demonstrates the proposed method in a case study of using a subset of reclaimed blocks from Section 3.1 to assemble a statically stable free-form wall, whose target geometry is shown in Figure 3(a). As discussed in Section 3, the objectives are minimizing geometric loss and minimizing CO_2-eq, while subject to constraints in structural strength and stability. Design variables for the outer NSGA-II loop are the number of meshes in the vertical and horizontal directions, respectively V_{count} and U_{count}, and the locations of the mesh edges.

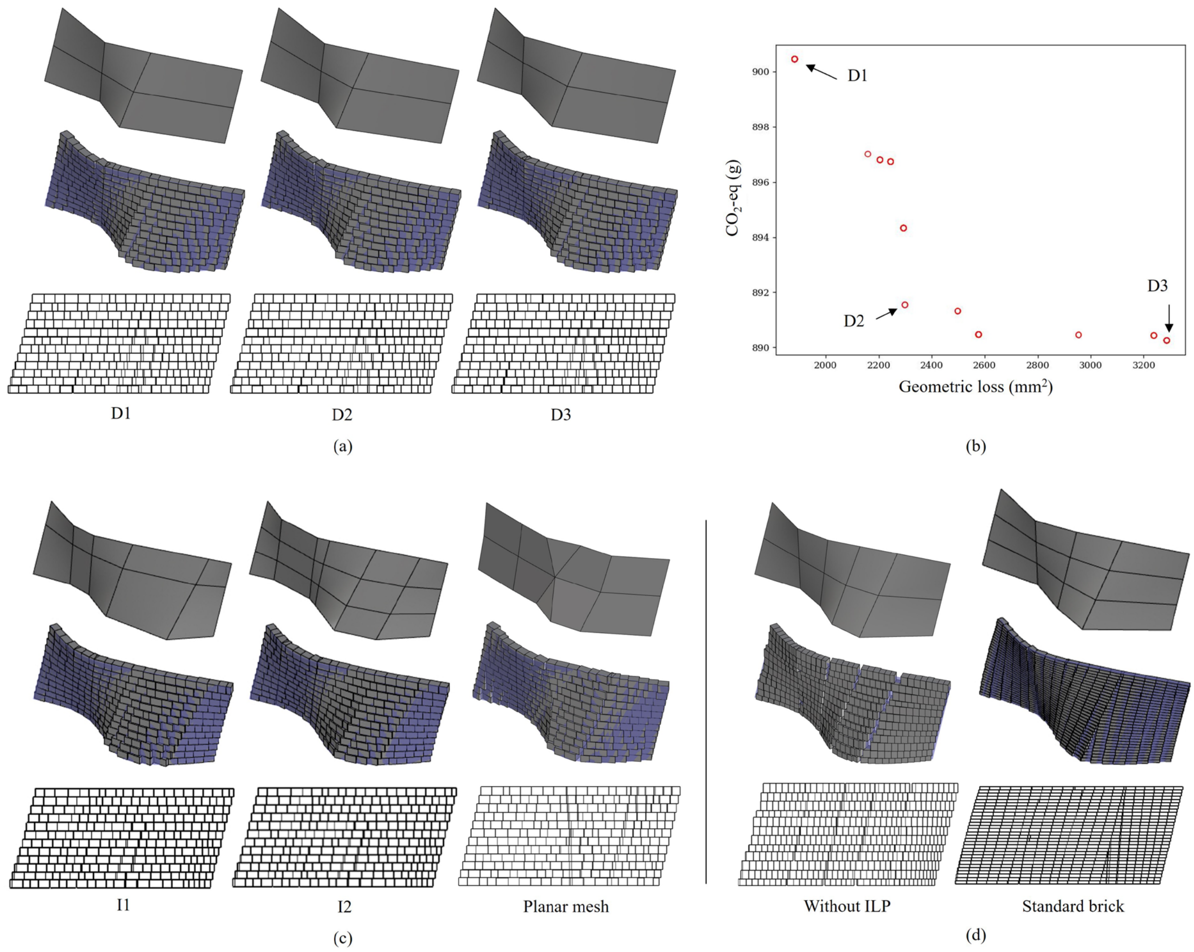

Figure 4: Illustration and comparison of different discrete assemblies for the same target geometry. (a) Three Pareto-optimal results including the coarse meshes and the perspective views and front views of the final assembly. (b) The Pareto-front from which the results are selected. (c) Intermediate designs (I1, I2) during the optimization process, and an intermediate design when a planar mesh is required. (d) Benchmarking cases: design without ILP (left) and design with virgin, standard bricks.

The illustrations of three Pareto-optimal assemblies, D1, D2 and D3, are shown in Figure 4(a), with the Pareto front shown in Figure 4(b). Notably, all Pareto-optimal results have $V_{count} = 2$ and $U_{count} = 3$, indicating the optimal mesh grid parameters for the target geometry. The first two assemblies in Figure 4(c), I1 and I2, are intermediate designs during the optimization process, while the last assembly is generated with a planarized coarse mesh, which is dropped due to its high geometric loss. To benchmark the proposed method, an assembly without the ILP optimization, as introduced in Section 3.3, and an assembly with virgin, standard bricks are shown in Figure 4(d). For consistency to the site of the example reclaimed blocks adopted in the case study, the standard bricks are assumed to be standard UK clay bricks with dimensions 215mm by 102.5mm by 65mm.

The performance of the designs in Figure 4, including the number of blocks, geometric loss, CO_2-eq, and whether the design satisfies the structural constraints, are listed in Table 1. The calculation of CO_2-eq is explained in Section 3.4, whereas the CO_2-eq associated with the virgin UK bricks is calculated based on data obtained from Ecoinvent 3.4 for a typical clay brick of this size [1].

Table 1: Performance comparison of designs illustrated in Figure 4.

	D1	D2	D3	I1	I2	Planar	No ILP	Standard
# of blocks	253	249	252	258	261	252	413	649
Geometric loss (mm^2)	1882	2299	3286	5089	8285	30939	1436021	230661
CO2-eq (g)	900.5	891.5	890.3	924.3	940.1	901.2	1008.9	491331
FEA & RBE	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Unstable	Satisfied

4.2 Additional free-form structures

This research also presents additional bespoke, free-form structures generated using the proposed method with the same set of reclaimed blocks in Section 3.1. To adapt the method to different types and scales of free-form structures, it is important to test and adjust the parameters of the NSGA-II and set the appropriate boundaries for variables. For example, circular walls should have a larger upper bound of U_{count} than a curved wall for a representative mesh. The example results, including a large-scale circular wall, a mid-scale thin-shell structure with a skylight, and two small-scale curved walls, are shown in Figure 5.

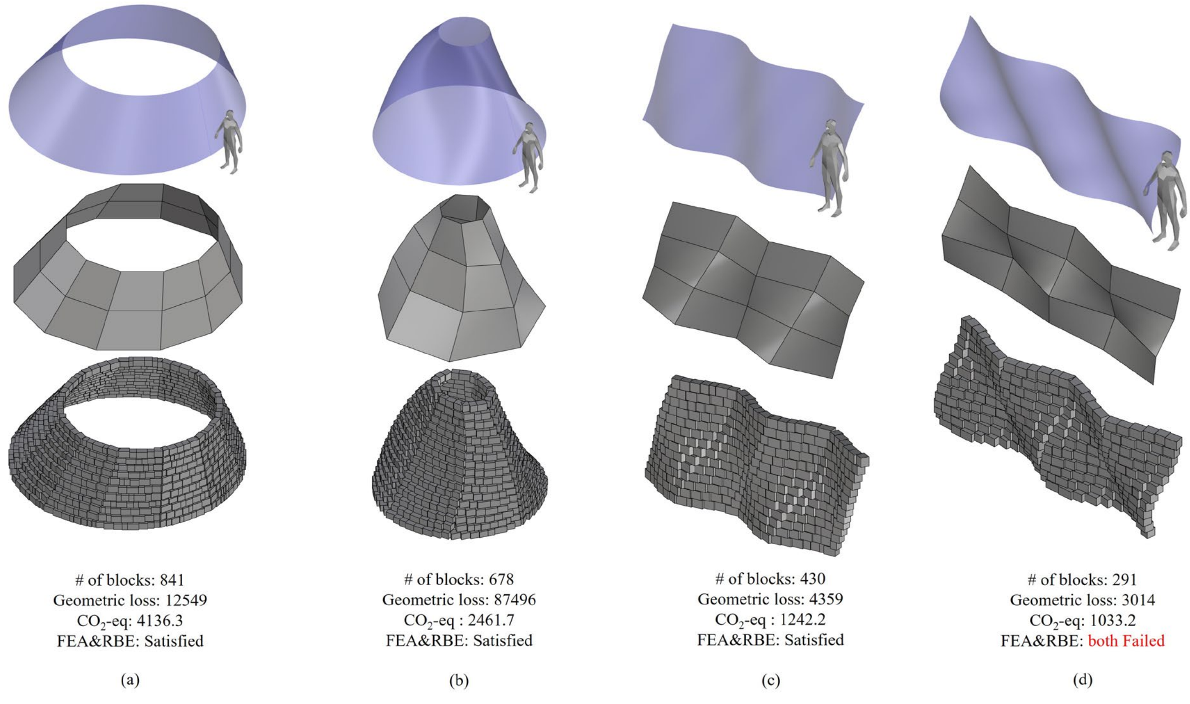

Figure 5: Other bespoke free-form structures. (a) A large-scale circular wall with a roof opening. Mesh grid: 2 by 12. (b) A mid-scale thin-shell structure with skylight. Mesh grid: 3 by 7. (c) Curved wall defined by y = 200cos(0.5x). Mesh grid: 3 by 4. (d) Curved wall defined by y = 200sin(0.5x+0.5z), structurally infeasible for dry-stacking due to failure in both FEA and RBE check. Mesh grid: 3 by 4.

5. Discussion.

This research proposes a novel computational design method for scalable free-form structures using reclaimed cuboidal building objects. Each building object is unique in terms of dimensions. Variations in structural strength are not considered since there is little documentation of this for building blocks. However, most studies on reclaimed steel elements assume no reduction in strength and suggest verification by coupon test. This research assumes using CE-marked building blocks to ensure the quality and performance of individual blocks.

The coarse meshing technique provides piece-wise linearization of each course with several benefits: (1) It linearizes curves for the ILP problems, which makes the calculation and modeling simpler and more sensible; (2) From a structural point of view, it maximizes the contact faces between adjacent blocks for a more efficient load path; (3) It reduces the number of gaps and potentially enhances thermal efficiency; (4) It helps to simplify the construction since meshing reduces the number of block orientations in the structure by 80% (non-planar) to 95% (planar), simplifying the construction process, especially for dry-stacked masonry structures where precision in location has a significant influence.

The optimized results obtained using the proposed method exhibit improved performance in geometry approximation and sustainability when compared with the design without ILP formulation and the design using virgin, standardized bricks. For instance, according to Table 1, when compared with the design "No ILP", the optimized design D1 has the number of blocks reduced by 38.7%, geometric loss reduced by 99.9%, and CO_2-eq reduced by 10.7%. This indicates that ILP formulations are significantly efficient in reducing geometric loss. Compared with the standard design in Figure 4 and Table 1 using virgin, standardized bricks, the optimized design D1 from the proposed method manages to reduce the number of blocks by 61.0%, the geometric loss by 99.2%, and CO_2-eq by 99.8%, which indicates that using reclaimed blocks has the potential to drastically reduces the environmental impact. Though the number of blocks is not directly integrated into the objectives, it shows a strong correlation to the objectives. This is because the proposed method tends to minimize the CO_2-eq associated with the reclaiming process, which may, when reflected in the optimization process, show preferences for larger blocks with smaller surface-volume ratios and thus reduce the total number of blocks.

Though the building blocks are used as an example in the case studies, the method presented has the potential for a diverse set of materials as long as the objects can be modeled as cuboids. Other promising materials or components include concrete blocks, tiles, windows, doors, wood panels, etc. Existing circular engineering applications include the recycled brick facade of the Resource Rows building in Copenhagen by Lendager Group, and the Collage house in Mumbai by S+PS Architect.

In terms of limitations, the proposed method exclusively applies to corbel structures. Thus, all structures shown in the examples in this paper have a target geometry with sloped surfaces since flat surfaces, can result in structural failure when applying the corbelling technique. For example, the structure shown in Figure 5(d) yields structural failure in both FEA and RBE, implying that the corresponding target geometry is not feasible for dry-stack corbelling. Moreover, quad meshes are generally preferred over triangular meshes in the coarse meshing process. This is because triangular meshes may result in small course segments at the edge which can be infeasible to fit even the smallest block, leaving the segment empty and yielding high geometric loss. However, planarization over free-from geometries with small radii can require triangular meshes, as shown in Figure 4(c), prioritizing out-of-plane geometry approximation over minimal voids. Future work will consider ways to make the approach computationally faster, e.g. better optimization methods and/or surrogate modeling. Extensions to other construction techniques, multiple reclaimed materials, and design synthesis on reclaimed irregular geometries such as irregular debris [14] and bespoke building blocks [15] will also be considered. The proposed work will be further used to generate datasets and contribute to a larger body of work on deep generative models for discrete assembly.

6. Conclusion

This research introduces a novel computational design synthesis method for constructing sustainable, bespoke, free-form structures using reclaimed materials, presenting a scalable, eco-friendly alternative to traditional practices dependent on precise, virgin materials. By integrating a novel coarse meshing technique and two ILP formulations into a nested optimization process, the proposed method not only verifies structural integrity but also enhances geometric accuracy and reduces environmental impact, as quantified by LCA. The method demonstrates significant advancements in reducing geometric loss and carbon emissions compared to a non-ILP method and a vanilla method with virgin, standard bricks, exhibiting its efficiency in promoting the circular economy within the construction sector. Future directions include extending this method to other construction techniques and a broader spectrum of reclaimed materials, aiming to further mitigate the construction industry's environmental footprint without compromising architectural integrity or performance.

Acknowledgments

The authors would like to thank Tom Clewlow, Alexis Harrison, and Dominic Munro from ARUP for insightful discussions on reclaimed structural components. Funding of the first author is partially provided by the NCCR Digital Fabrication, funded by the Swiss National Science Foundation (NCCR Digital Fabrication Agreement #51NF40-141853).

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Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine De Wolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

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Paper Title: Sustainable Design Synthesis of Discrete Free-From Structures Utilizing Existing Building Objects

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Date: 28.05.2024