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Automated planar truss design with reclaimed partially disassembled steel truss components

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ABSTRACT

A promising solution to decarbonize steel construction is reusing steel structural components from existing disassembled structures as it avoids sourcing raw material and the heating associated with recycling, as well as reducing the amount of waste from construction and demolition. However, barriers associated with increasing the use of reused steel components in modern construction include concerns about an increased length of the demolition process and the dramatic changes it requires in the structural design task. To simultaneously alleviate these concerns, this work presents a new stock-constrained design and optimization framework for designing planar truss structures from a stock library of partially disassembled trusses. In contrast to existing design methods that rely on reuse at the element level, this work mitigates the demolition process requirements by avoiding the complete disassembly of all structural members. The new automated design framework eases the design process and aggregates partially disassembled triangular components while introducing new material members where necessary to ensure that the new design matches the exterior geometric requirements. The proposed approach is fast (on the order of 0.1 s to generate a trial truss), and a GA optimization module is added to select among generated trial designs. Three case studies with realistic stock libraries demonstrate the potential of partially disassembling and reusing truss components and illustrate how the user-defined design shape and the stock variability influence the resulting design.

1. Introduction

The construction industry consumes 50% of all global resources [1] and is responsible for almost 40% of global energy use and total greenhouse gas emissions [2–4]. With a growing global population whose demands increase in both buildings and infrastructure, these numbers will likely continue to rise in the coming decades [5]. In addition to new construction requiring large material volumes, construction and demolition waste is a significant portion of the total solid waste generated. In Europe, construction and demolition waste represents 37% of the overall solid waste [6]. In this context, with steel being one of the predominant global structural materials, it is relevant to recognize that steel production is the world's most energy-consuming and carbon-emitting industrial activity [7] and it is estimated that steel industry emissions must be reduced to more than 50% by 2050 to achieve net zero carbon emissions [8].

Two potential solutions to reduce the environmental impact of steel structures are (i) by optimizing the geometry of new steel structures (see e.g., optimization studies on large-scale steel truss structures [9–11]), or (ii) by recycling or reusing existing steel structures. Increased recycling and reuse of construction materials have the potential to save both material and energy and decrease

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waste and carbon emissions [12–14]. Recycling constitutes reprocessing discarded parts into raw materials for new products, while reuse is the process of recirculating material elements and using them for the same function [15]. Steel is highly recyclable, but recycling steel is associated with a high energy request. This is especially due to the high temperatures needed to reprocess the material, e.g., into new structural components [16]. Previous research reports that steel recycling only saves about 50% of energy and carbon emissions compared to sourcing newly mined steel [17]. As shown by a recent study [16], direct reuse of reclaimed components thus presents itself as a more sustainable approach to transition construction into a circular economy industry. A sustainable circular economy here refers to using resources as long as possible to lessen their environmental impact on society [18,19].

Reuse in construction is highlighted as a potential area for consequential carbon savings [12–14,20], and deemed likely to rise in coming decades [21]. Whereas direct reuse of reclaimed structural components was widespread before the industrialization of the construction sector [22], modern construction has nearly eliminated the practice [3,23]. The few existing examples include the net-zero BedZED community in South London, UK, from 2002, realized using almost entirely reused steel [24]. Success implementation has also been reported for several smaller Canadian construction projects [25]. More recently, De Wolf et al. [26] presented a case study for a larger commercial building completely realized with reused components.

Several factors impede the direct reuse of steel components in modern construction [15,27–29]. These include demolition being perceived as cheaper than disassembly [16]. Although this is a somewhat false perception as shown by Dunant et al. [27], the demolition task is dramatically elongated if direct element reuse is desired, as damage must be avoided when elements are disassembled and sorted. Likewise, the structural design task is completely different when designing new structures from reclaimed elements or components, since the new design must conform to the site-specific and time-dependent inventory or library of available parts [30,31]. As shown in Fig. 1, there generally exist three types of libraries with either (a) individual structural elements, (b) entire fully assembled structures, or (c) partially disassembled components.

Most literature on designing with a library of reclaimed structural steel stock has focused on fully disassembled structures where the stock is composed of single structural members (typically bars or beams) with a specified length and cross-section (Fig. 1a). Most works require the user to provide a new structural layout and focus on optimizing the assignment. Fujitani and Fujii [32] present a framework that assigns stock elements to planar steel frames. Bukauskas et al. [33,34] predefine a planar truss layout and assign bars from a library. Brütting et al. [35] pose the design problem as a two-step optimization problem that initially solves a Mixed Integer Linear Program (MILP) to minimize the structural weight of a predefined truss layout while assigning a combination of reused and new steel elements. This is combined with a geometry optimization step of the initial truss layout. The framework has since been extended to include a full Life Cycle Assessment (LCA) [36] and to steel frame design [37]. Brütting et al. [35,38] also include a LCA and a finite element analysis to assign stock elements to truss structures but allows the user to manually conduct form-finding through combinatorial equilibrium modelling on an input geometry. Finally, Kim and Kim [39] propose an optimization-driven framework, specifically for design steel noise-barriers with reused elements. Related research has also developed structural design algorithms for stock libraries with individual timber members [40], plastic bottles [41], wire hangers [42] and skis [43].

The advantage of a single member stock library is that it provides the widest design freedom and can result in new structures that are completely different from the ones they were originally sourced from. However, to create a library of single members from a reclaimed structure, the structure must be completely disassembled, requiring time and energy resources. In contrast, direct reuse of full structures or structural components (Fig. 1b) forces the new structural design to have the same layout as the original. The time and energy requirements for disassembly are greatly reduced, although restoration and relocation to a new site might still be necessary [44]. Pongiglione and Calderini [45] provide a computational case study that recovers steel components without completely dismantling. Three categories of steel elements are reused for the design of a railway station in Genoa, Italy: steel beams with transversal brackets, composite steel columns, and reticular steel roof trusses. A new design featuring reused steel results in 30% savings of material, energy, and carbon emissions [45]. Another recent constructed example where reclaimed steel trusses have been reused without disassembly is the Moynihan Train Hall at Penn Station in New York [46].

A third, less explored, inventory option is the intermediate case in which the libraries are composed of partially disassembled structural components (Fig. 1c). In this case, new designs consist of preassigned shapes that are defined by the partially disassembled library components. This option offers more design freedom than direct reuse of full structural systems but is more restrictive than single-member design. Existing research on designing with this type of stock library is very limited. To the best of the author's knowledge, only a single related example exists where a library of timber (tree) joints has been used in form finding of new trusses [47].

To overcome the challenges and resource requirements associated with the reuse of fully disassembled reclaimed steel structures, this work presents a new automated design approach for planar truss design with partially disassembled components. The new design is thus subjected to a stock constraint, where the stock is associated with nonlinear shapes. Specifically, triangular truss elements are chosen as the reusable components (Fig. 1c). The new design approach relies on a newly developed aggregation engine that can be combined with the Genetic Algorithm (GA) to optimize new designs with additional performance checks through Finite Element

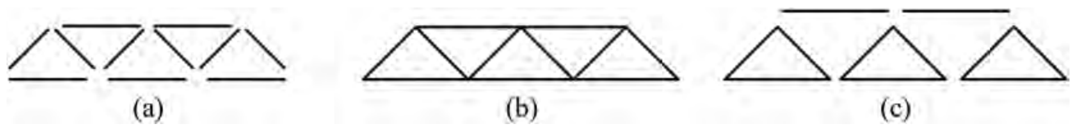

Fig. 1. Reuse options for truss structures; (a) full disassembly and reuse of individual structural elements, (b) no disassembly and reuse of complete structure, and (c) partial disassembly and reuse of structural components.

Analysis (FEA). The aggregation engine does not require the user to specify the structural layout but rather to identify a target exterior structural shape. It then places the partially disassembled library components within the design shape. The aggregation engine and its combination with GA and performance checks are detailed in Section 2, and the framework is demonstrated on three realistic case study libraries in Section 3.

2. Method

Fig. 2 gives an overview of the herein-developed new automated design framework that consists of four modules: i) input, ii) aggregation engine, iii) optimization over trial designs and iv) performance check of the optimized solution. The user initiates the design process by providing two types of input: the inventory of reclaimed steel trusses, which are herein partially disassembled into triangular components, and the design region that the new planar truss design should occupy with applied loads and boundary conditions. Once the inputs are defined, an aggregation engine constructs a trial truss in three steps:

1. Stock components are randomly aggregated horizontally along the bottom boundary of the design region. This may require cutting the last component to fit the target span.
2. The components are aggregated in height until the target height is reached. New components are added where none of the reclaimed components fit or if excessive component cutting is required.
3. The components are added to fill the sides of the design region.

When the used stock library allows for generating several distinct trial designs, GA is used to optimize the design. The performance of the final design is checked with a FEA.

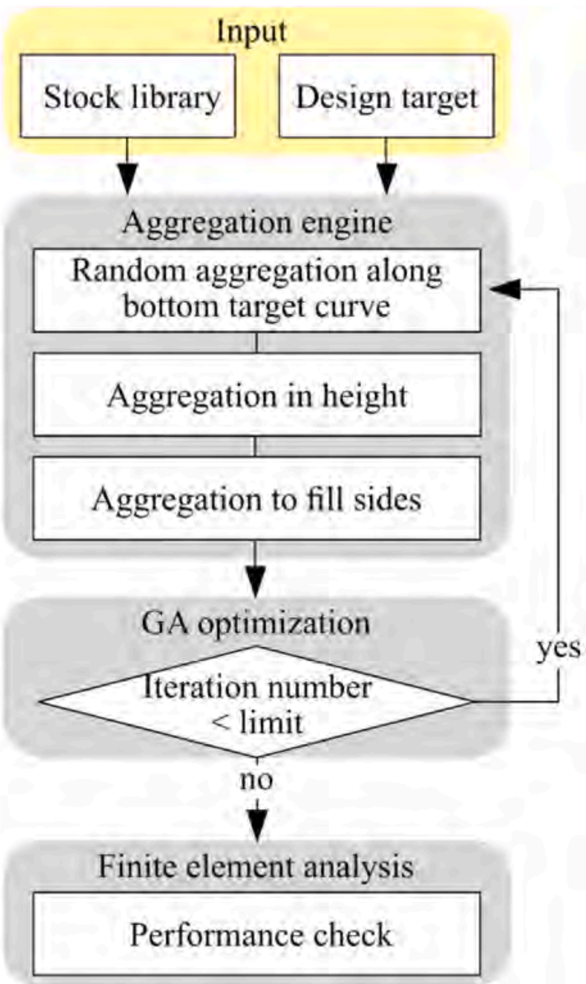

Fig. 2. The proposed design framework for partially disassembled reclaimed trusses is based on four modules; input, aggregation engine, a GA optimization loop and a finite element analysis that checks the structural performance. The aggregation engine fills the input design shape in three steps.

2.1. User inputs

As mentioned, the herein presented framework requires the user to provide two types of input: the library of available reclaimed components (Fig. 3a), and a definition of the new design that includes its exterior design shape, applied loads and boundary conditions (Fig. 3b). For this work, blue lines are used to represent reused stock components. The stock libraries in this work consist of Warren trusses that are partially disassembled into triangular components. The definition of new planar truss design carries some resemblance to the design problem domain in topology optimization [48], with the important distinction that the design shape in the current work must be completely filled by the new truss.

The design region is defined by its height H, span L and the curves that describe its exterior boundaries. The exterior boundaries can be described using generalized B-spline curve as follows:

$$y = \sum_{i=0}^{n} P_i N_{i,k}(x) \tag{1}$$

In Eq. (1), P_i defines the control points while $N_{i,k}(x)$ gives the basis functions. In the current work, demonstrated design examples use vertical side boundaries, while the bottom boundary is described by a user-defined curve that is either linear (y_{lin}, see Eq. (2)), or nonlinear using a second order polynomial (y_{poly}, see Eq. (3)) or circular (y_{circ}, see Eq. (4)) formulation. Examples with linear, polynomial and circular bottom boundaries are shown in Fig. 4. To specify the bottom boundary, the user provides the start and end points of the chosen curve type (P_{start} and P_{end}) and the a, b, and c constants that describe the bottom boundary of the design region as follows:

$$y_{lin} = bx + c \tag{2}$$

$$y_{poly} = ax^2 + bx + c \tag{3}$$

$$(x - a)^2 + (y_{circ} - b)^2 = c^2 \tag{4}$$

When defining the stock library, the user must provide the heights and base lengths of all available components. An example of a library definition of reclaimed stock components is shown in blue in Fig. 5a. To perform a structural performance check, the user must additionally provide the cross-sectional area and Young's modulus of each component. The size and the regularity of the library significantly influence the resulting designs. If the number of available reclaimed components in the library is too small or ill proportioned in relation to the design region, new elements need to be introduced. New elements can take on all possible shapes and sizes, which makes it difficult to set rules for their implementation. Herein, the angle of all new components is standardized at 45° (Fig. 5b). To distinguish from the blue lines indicating reclaimed stock components, all triangular components entirely formed by new members are indicated with solid red lines.

It is desirable to have a stock library that is at least big enough to fill the design region, but ideally, one that contains more reclaimed components than strictly necessary. This is advantageous not only to increase the design freedom but also to ensure that the designer has several options in case components are no longer available at the time of construction [31]. This concern has relevance since some reclaimed components might not be deemed fit for reuse after closer inspection or become damaged during disassembly. In addition to the number of stocks, the diversity of the components within the library influences the resulting design. A library with few variations in component geometry can be beneficial, as it will lead to more regular new truss designs. However, the disadvantage of relying on only few component sizes is that in some cases it might be ill fitted for the new design and requires the use of a significant number of new elements.

2.2. Aggregation engine

As described in the previous section, three steps are used within the aggregation engine to fill the user-defined design region. All examples in the section use the stock library shown in Fig. 5. The aggregation engine fills the design shape in the vertical and horizontal directions, row by row, from the bottom boundary to the top. The aggregation engine is constructed such that each stock component can only be used once. The residual stock library contains only stock components that are available for use and is updated every time a reclaimed component is placed in the new truss.

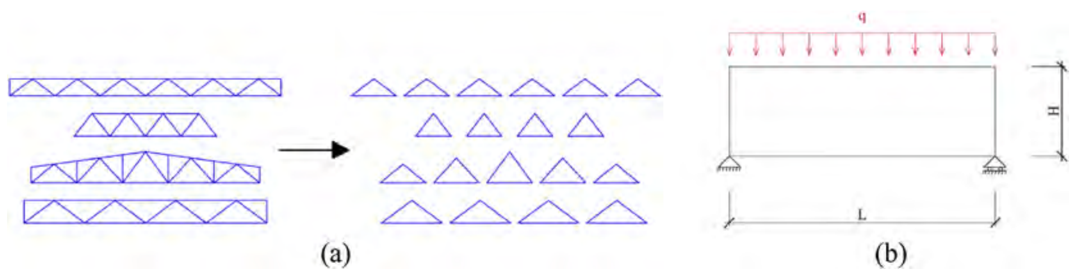

Fig. 3. The framework requires two types of input; (a) reclaimed trusses that are partially disassembled into a stock library of triangular components, and (b) requirements for the new planar truss design that includes the design shape, applied loads and boundary conditions.

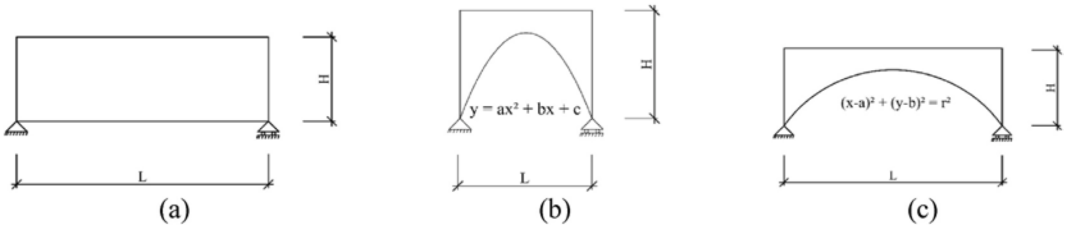

Fig. 4. Examples of user-defined design shapes with height H and span L that are; (a) rectangular, (b) polynomial, and (c) have a circular bottom curve.

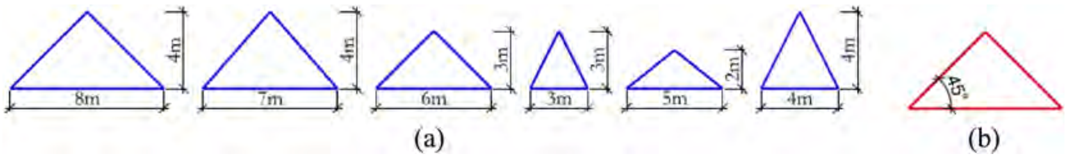

Fig. 5. (a) example of input parameters for reclaimed library components (shown in solid blue), and (b) new elements (shown in solid red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2.1. Random aggregation of bottom row

Fig. 6 illustrates how the herein developed aggregation engine fills the bottom row of the design region with reclaimed stock components. The aggregation engine generates a random order of the library components that determines the placement sequence. Once the sequence is known, the stock triangles are mapped to the bottom target curve. First, the base points of the triangles are mapped onto the target curve, and, subsequently, the top point of the stock triangle is located.

For most designs, it is unlikely that a random aggregation of the stock components reaches exactly the end of the bottom target curve. When an exact match is not possible, the aggregation continues beyond the endpoint P_{end}. This is shown in Fig. 6a in which the distance between the last component point and the target curve end point is larger than zero ($P_{last} > P_{end}$). The last component is then cut to match the endpoint. As a consequence of cutting reclaimed triangular components, the two base connections cannot be reused. Fig. 6b and c shows how the last stock triangle is made smaller by cutting the two lower corners off. The total length that has been cut is denoted L_{cut_i}. In the present work, reclaimed stock components that are cut to fit the target volume are indicated by dashed blue lines.

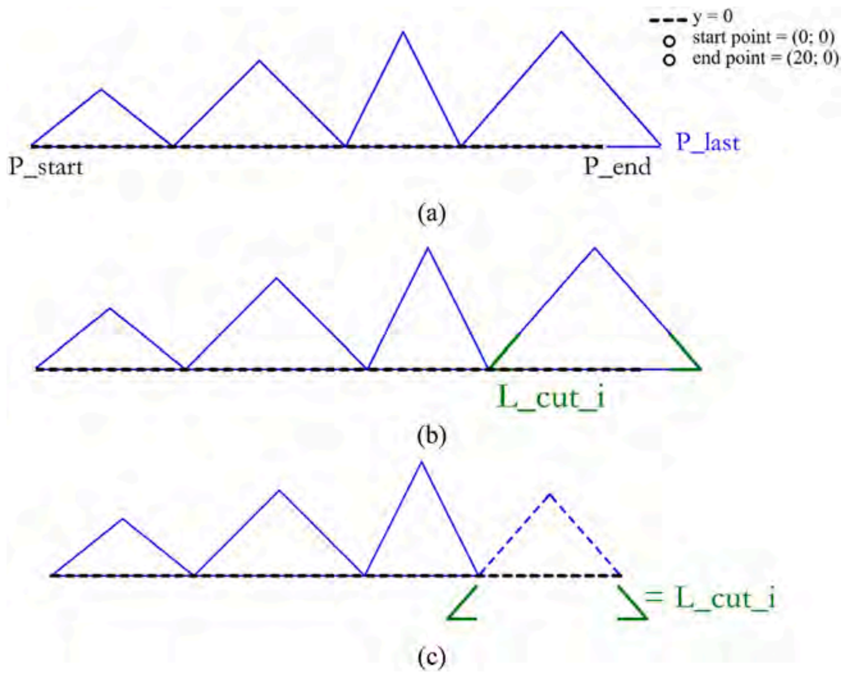

Fig. 6. Cutting the last component of the bottom row for a linear bottom target (dashed black); (a) components are stochastically aggregated till the last placed component exceeds the target end point ($P_{last} > P_{end}$), (b) the two bottom corners of the last component are cut off, (c) such that the aggregated length fits the bottom target ($P_{last} = P_{end}$).

2.2.2. Row-by-row aggregation in height

Once the bottom row of the new truss design has been aggregated, additional rows of stock triangles are added until the required target height is reached. Depending on the size and variability of the stock library, the aggregation of subsequent rows can be significantly more challenging than for the initial bottom row. The residual library is naturally more restrictive than the initial library as it has fewer available components. Moreover, the available components must fit the top of the row of triangles below it where the base points of the triangles in the second row are the top points of the aggregated triangles in the bottom row. Fig. 7 illustrates how a residual library is aggregated on top of an already established bottom row of triangles. The stock components of the residual library is shown in Fig. 7a, while Fig. 7b illustrates the required base lengths, L_j, for aggregating triangles on top of the existing bottom row.

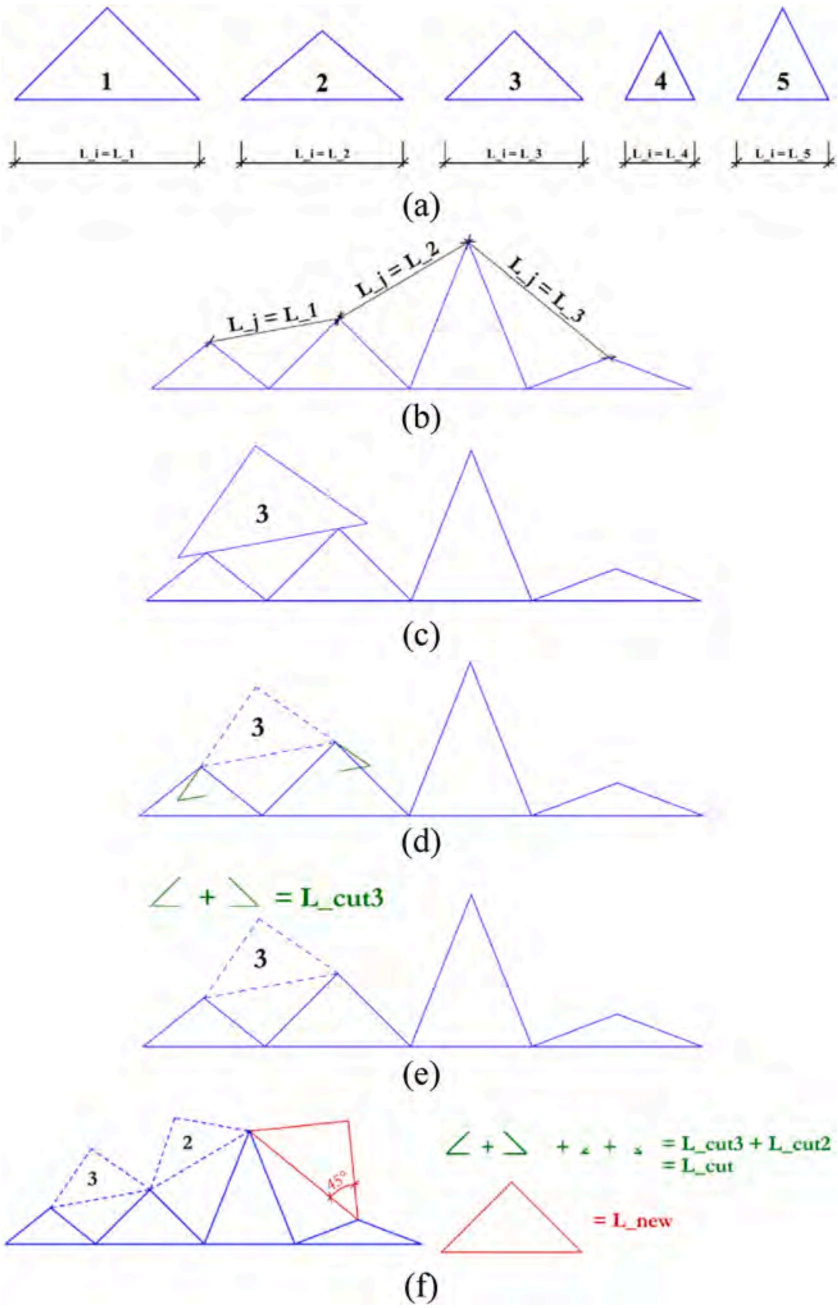

Fig. 7. Illustration on how a row of stock components is aggregated on top of an existing row. In (a) an example library is given and (b) shows the base lengths required to place a component on top of triangles in the existing row. In (c), stock component i = 3 is chosen as the leftmost location since its base exceeds ($L_i = L_3$) but is closest to the required length $L_j = L_1$. In (d,e) the two bottom corners of component 3 are cut off such that its base fits the required length. In (f) it is shown how the required length $L_j = L_3$ is larger than any available triangular base in the library and thus must be made from new material.

Moving from left to right, a stock component is matched to each L_j separately. The required distance between the base points is compared to the available base lengths L_i of the stock triangles in the residual library. For each available stock component, the cutting distance required to fit L_j is calculated when $L_i – L_j \geq 0$ (Fig. 7c–e). The component that requires the least cutting is selected. Once a stock component has been placed in the second row, the residual library is updated, and the process is repeated. When none of the available components fit the required distance, a new component is added, as shown in Fig. 7f.

The amount of waste associated with cutting each stock component i to fit the required length is denoted as the cut of length $L_{cut\,i}$ calculated as:

$$L_{cut_i} = 2\sqrt{\left(\frac{L_i - L_j}{2}\right)^2 + \left(h_i - \frac{h_i L_j}{L_i}\right)^2} + L_i - L_j. \tag{5}$$

In Eq. (5), h_i is the original height of the placed stock component and h_j is the height after cutting. The total cutting waste is the sum of $L_{cut\,i}$ for all m stock components placed in the new truss.

$$L_{cut} = \sum_i^m L_{cut_i}. \tag{6}$$

In Fig. 7f it is shown how a required distance sometimes cannot be filled by components in the residual library. In these cases, new (red) elements must be introduced. The following relation is used to calculate the length L_{new_i} required to form a new triangular component with a 45° base angle that fills the required length L_j:

$$L_{new_i} = 2\sqrt{\left(\frac{L_j}{2}\right)^2 + \left(\frac{L_j}{2} \times \tan(45^\circ)\right)^2} + L_j \tag{7}$$

The total sum of the lengths of the k new triangular component in a final truss design is defined as:

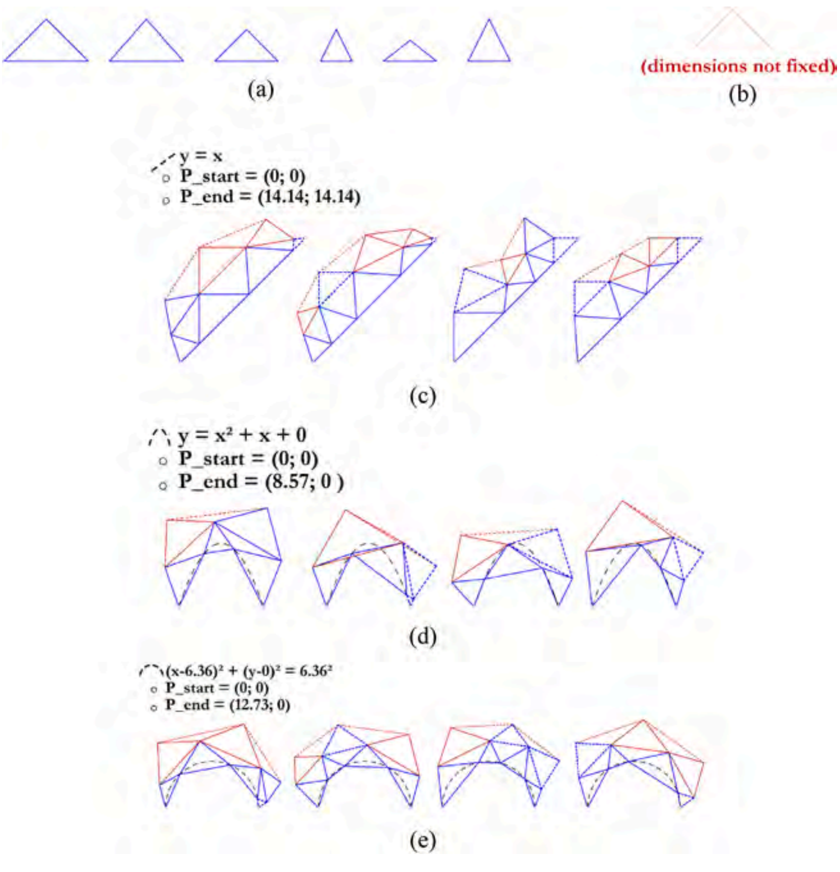

Fig. 8. Double row designs for different design shapes (dashed black), with components from a given library (blue) and new elements where necessary (red). The library stock components are shown in (a) and components made from new elements are illustrated in (b). Designs with two rows of components obtained for a bottom target curve defined as (c) linear (Eq. (2)), (d) polynomial. (Eq. (3)), and (e) semi-circular (Eq. (4)). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$L_{new} = \sum_{i}^{k} L_{new_i}. \tag{8}$$

Fig. 8 shows two-row trusses for three different bottom target curves. For each truss, the target equation of the bottom row is provided (black dashed curve). The blue triangles are reused components, the dashed lines represent components that require cutting. Red lines represent new material, full triangles are shown in solid lines and dashed lines are used for single members. The specific start and end points for each design shape are indicated in black. The used stock library with $n = 6$ components is shown in Fig. 8a. When comparing Fig. 8c, d and e, it can be seen that the design shape influences the amount of new components required. Additionally, depending on the shape of the bottom line, the components are more or less likely to fit. For each design shape, four possible designs are shown. These show the differences in the output, as a result of the component order of the first row. Due to the speed of aggregation, many different designs can be generated in a short period of time, therefore a catalogue of solutions can be created for the user to choose from. Note that the algorithm allows for triangles to cut through the bottom target curves (see Fig. 8d and e).

For most designs, it is relevant to consider a specified maximum truss height. In this work, such a requirement is implemented by the user-specified target height *H*. It must thus be ensured that the components in the last row are lower than or equal to the target height. The latter can be done by cutting, i.e. reducing the height of the top point to be equal to *H*. The top row often requires a lot of cutting as the height is limited by the target height *H*. To avoid having to dismantle and cut too many reclaimed components, a cap was introduced at a maximum of 0.5 m of cutting for the top row. Therefore, in many cases a large number of new triangles (red) can be seen in the top row.

This "cutting" principle is shown in Fig. 9 for two different values of *H*. The dashed black lines indicate the maximum height, the same target height is used in Fig. 9b and c. This target height is added to Fig. 9a as well for comparison. As can be seen the height has a big impact on the design. The more rows necessary to reach *H* the less filled the design shape is, as presented by the comparison of Fig. 9a with Fig. 9b and c. A higher value of *H* compared to the component heights can lead to a pyramid shape that sometimes does not even reach the target height (Fig. 9c).

The same process can be used for all design shapes. An example of a half-circle target is shown in Fig. 10. As can be seen in both figures, some of the new triangles on the top row have angles different from 45°, because in order to fit within the target height, the angle had to be decreased.

Additionally, to encourage the reuse of triangular components, a tolerance can be introduced to the height of the design shape. With this tolerance, the user can specify an allowable range instead of a fixed height. This can reduce the amount of necessary new elements or cutting of reused components. As can be seen in Figs. 9 and 10 when adding truss rows using a diverse stock library, the resulting new truss design can appear to have a triangular exterior shape (Figs. 9b,c and 10b,c). This tendency sometimes means that the new truss design does not reach the user-specified maximum height. To create a design region that is filled completely, elements must be aggregated on the sides, requiring additional base points to be added as the aggregation progresses.

2.2.3. Aggregation to fill sides

In this work, additional base points are added at the boundaries of the design region. The *x*-coordinate is herein set equal to either the start or end point of the bottom target curve. As shown in Fig. 11, the *y*-coordinate of the added base points is chosen to equal the *y*-coordinate of the closet point of an adjacent triangle. Base points are only added on rows where the distance between the outer components and the maximum and minimum width is larger or equal to the minimum base length within the residual stock library since this avoids creating slender triangles. Finally, triangulation is enforced at the design shape sides. This is done by introducing new

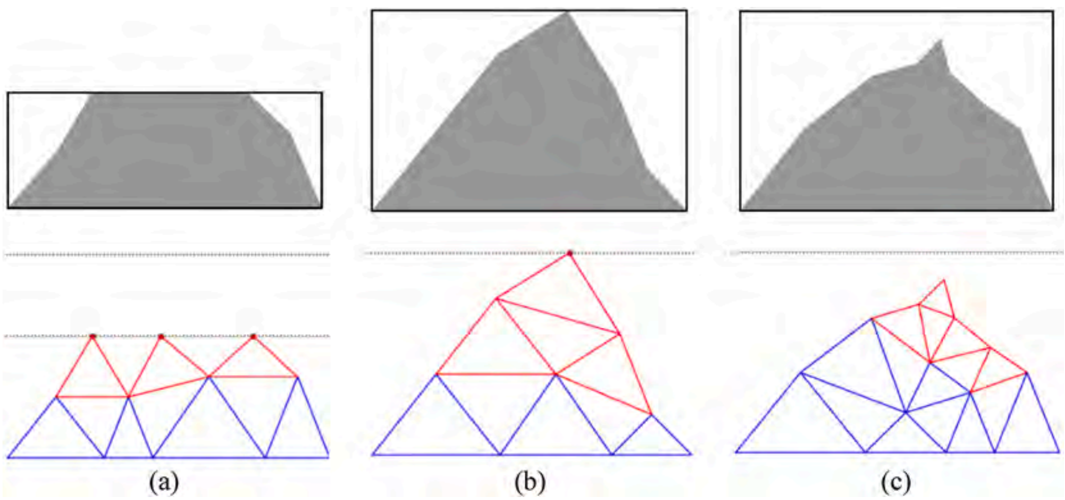

Fig. 9. Generated designs to different target heights H (black dashed line) for a linear bottom target curve, with reused components (blue) and new elements (red). The top images indicated how well the new design fills the design region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

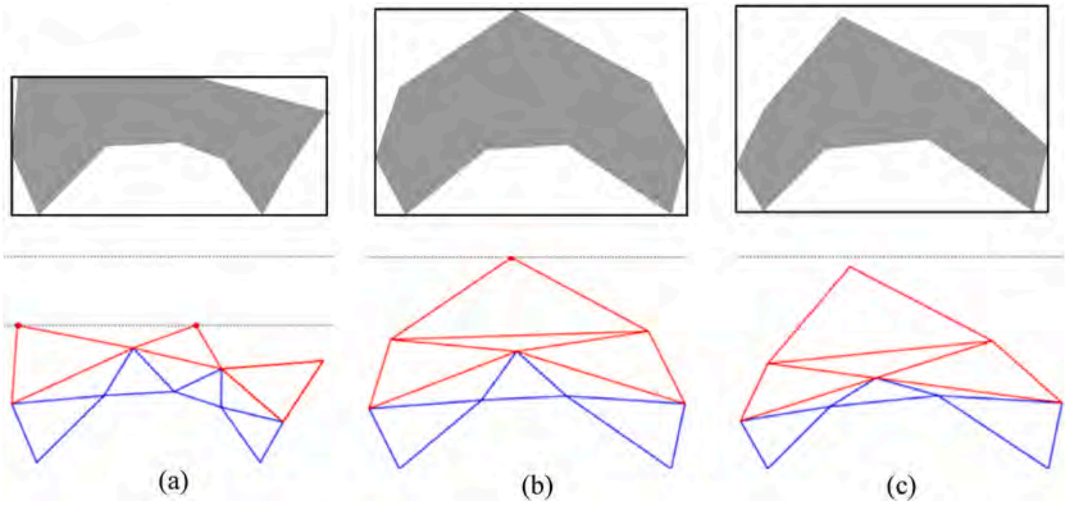

Fig. 10. Designs generated to different target heights H (black dashed line) for a half-circle bottom target curve, with reused components (blue) and new elements (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

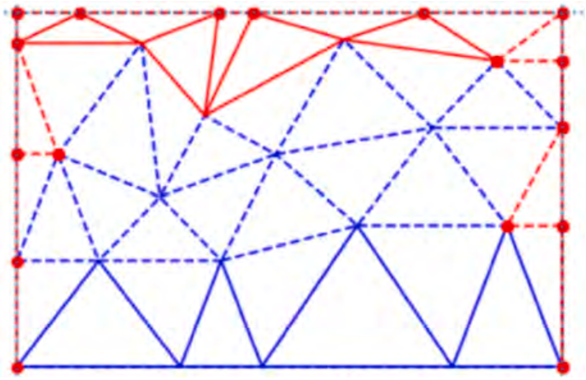

Fig. 11. Connecting the truss to the design region sides to create a closed truss design, using new single members (dashed red lines), with full reused components (full blue lines), trimmed reused components (dashed blue lines), and full new triangles (full red lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

single members to connect the top points and the design shape's boundaries. An example can be seen in Fig. 11, where the new members are shown in dashed red lines. A distinction is made between the new material used for full triangles (solid red lines) and single members (dashed red lines).

2.3. GA optimization

Since the placement sequence within the first row is random, distinctly different design solutions will be obtained when running the aggregation engine multiple times with a library containing diverse stock components. The herein-suggested aggregation engine is fast (on the order of 0.1 s to generate a trial design) and it is thus possible to use a stochastic optimizer to select a set of best designs among several different trial options. Some existing literature combines stock constrained design with optimization using either GA [40], Mixed Integer Linear Programming [35], the Hungarian Algorithm [40] or Best-Fit heuristics [38,49] as the discrete optimizer. The optimization module in this work uses GA, where a fitness function must be defined. Herein a scaled multi-objective that minimizes the combined sum of the new element and cutting lengths is used with the following optimization problem formulation:

$$\begin{aligned} \min_{x} \quad & w_1 L_{cut} + \quad w_2 L_{new} \\ s.t. \quad & x_i \in \{1, \ldots, n\} \\ & x_i \text{ unique in } \boldsymbol{x}. \end{aligned} \tag{9}$$

In Eq. (9), w_1 and w_2 are weighting factors for the two competing objectives. The design is determined by the order of the library stock components. Therefore, the design variable vector $\boldsymbol{x}$ arranges the discretely numbered components from the library. A design with $\boldsymbol{x} = [1, 2, 3, \ldots, m]$ creates a truss with its first triangle being stock component 1, followed by component 2, and so on until m. As mentioned, each stock component from the library can be used only once. Therefore, the components within $\boldsymbol{x}$ must be unique. Finally, the design variables are bound by the library such that all design variables in $\boldsymbol{x}$ should be discrete and between 1 and n, where n denotes the total number of stock library components.

Since the design variables in Eq. (9) are linked discrete variables that point to inventory components in the stock library, the objective function $f(x)$ is nonlinear and neither continuous nor differentiable. This warrants the use of a stochastic optimizer, such as GA, to find an approximation to a global minimum. However, as always when using GA, there is no guarantee that a global optimum will be obtained [50]. The optimality of the obtained design solutions in this work is therefore not verified. Such verification can only be made by generating and ranking all possible combinations within the design space. While an exhaustive search might be tractable for small libraries, this is not generally the case.

2.4. Structural performance check

To ensure that the structural performance of an aggregated truss is adequate, a finite element module is added to check the defections of the final design. For all examples in this work, a distributed line load is specified on the top boundary of the design shape (Fig. 12a). The design shape is simply supported and symmetry is enforced by only designing and modelling half the domain. The distributed load is converted to point loads at the truss nodes, where it must be considered that each node has its own tributary area (Fig. 12b). The following standard relation is used to calculate the point load P_{t_i} applied at the truss node t_i:

$$P_{t_i} = qL_{ti} \tag{10}$$

where q is the magnitude of the line load and L_{ti} is the tributary length for truss node t_i.

In the finite element model (Fig. 12b), the support at the left-hand side is defined as a roller that is free to move in the x-direction and fixed in the y-direction. Along the symmetry line, rollers that are free to move vertically (y-direction) but are fixed horizontally (x-direction) are applied as shown in the example in Fig. 12b.

3. Results and discussion

This section presents three case studies, each one using a stock library with different levels of variation of the reclaimed triangular components to showcase the last three modules of the framework, namely: the aggregation engine, the GA optimization, and the finite element performance check. In contrast to the illustrative examples in the previous section, the case study libraries are more realistic. The libraries contain isosceles triangular components originating from Warren trusses, which are commonly used for bridges, warehouses and hangars.

3.1. Case 1: stock library with uniform components

The components within the first case study library are based on an existing roof structure with planar trusses, as shown in Fig. 13. Each of the planar roof trusses consists of 4 equal triangular components with height of 0.3 m and a total span of 3.2 m (Fig. 13b). The geometrical dimensions are shown in Fig. 13c. For the library a total of 12 planar trusses are used, which means 6 trusses for half-size designs as shown in Figs. 14 and 15. Since all stock components within the library have the same size and shape, the aggregation engine will give the same design result when executed multiple times. Therefore, the results of the designs presented for the first case study library focus on a discussion of the aggregation module.

Fig. 14 shows new designs generated with the first case study library for a symmetric, rectangular design shape (Fig. 4a) with different dimensions for the height H and span L. In Fig. 14, the full blue lines are reused triangles with no cutting, and the dashed blue lines indicate reused components that need to be cut at least 0.1 m. The red lines show where new members need to be added to fill the design shape. The dashed red lines are single new members, and the full red lines are new triangles with standard angles of 45°. However, to fit the target height smaller angles are also allowed.

As shown in Fig. 14, the regularity of the new truss design depends on the compatibility of the target dimensions with the available components of the stock library. When the target height and span are multiples of the height and base length of the triangular components, the aggregation engine generates a regular and symmetric design as seen in Fig. 14a. New or reused steel elements (dashed red) are only needed at the left, right and top boundaries of the design shape. This is also the case of slightly different dimensions, but a tolerance on the target dimensions is considered as acceptable. This is shown in Fig. 14b, where the target height $H =$ 0.57 m is too low to allow for two rows for reclaimed components, but a user-set tolerance allows the target height to be modified to

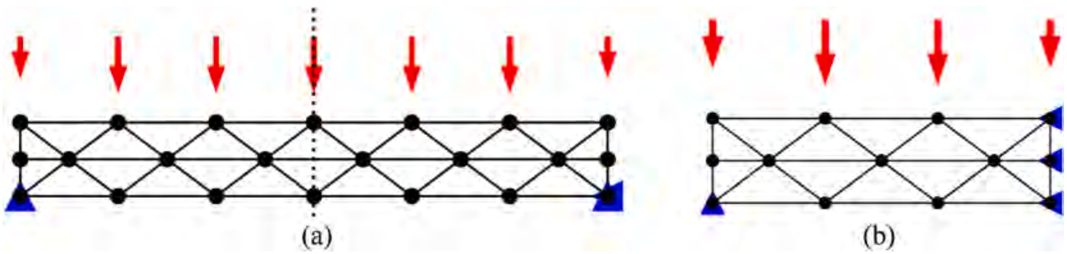

Fig. 12. Illustration of how (a) a symmetric (dashed black symmetry line) target design with applied loads and boundary conditions is (b) analyzed in the finite element module. This work focuses on symmetric target designs, and consequently only half the domain is analyzed in (b).

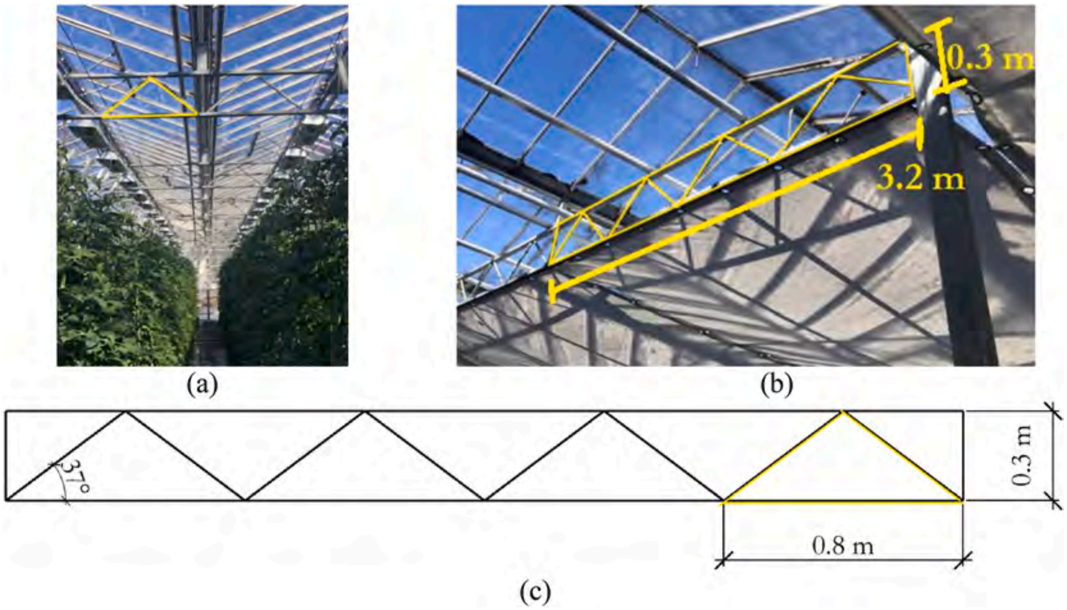

Fig. 13. Case study library 1: reclaimed triangular components from straight uniform-component Warren trusses; (a,b) images of example truss and (c) used truss dimensions.

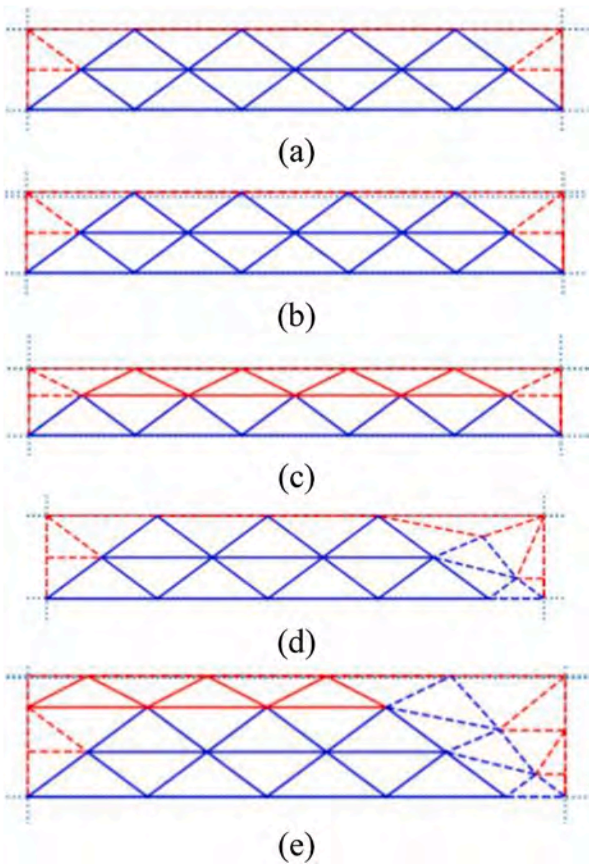

Fig. 14. Case study library 1: designs obtained for a symmetric rectangular design region with a stock library consisting of uniform triangular elements for different target heights and spans; (a) H = 0.6 m and L/2 = 4 m, (b) H = 0.57 m (tolerance > 0.03 m) and L/2 = 4 m, (c) H = 0.5 m and L/2 = 4 m, (d) H = 0.6 m and L/2 = 3.6 m, and (e) H = 0.7 m and L/2 = 4 m. Only half the design region is shown.

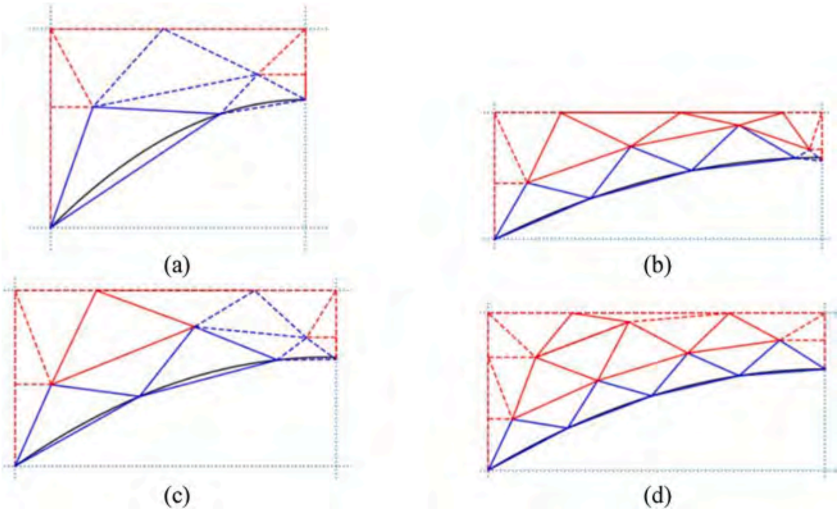

Fig. 15. Case study library 1: designs obtained for symmetric design shapes with polynomial bottom curves (black line) (Eq. (3)) with c = 0 and (a) a = −0.5, b = 1, and H = 0.6 m, (b) a = −0.1, b = 0.5, and H = 1 m, (c) a = −0.2, b = 0.7 and H = 1 m, and (d) a = −0.1, b = 0.5, and H = 1.4 m. Only half the designs are shown.

better accommodate the use of the available stock. In contrast, cutting of reclaimed components and/or the introduction of new elements are necessary when the target height or span is not multiples of the triangular stock components. In Fig. 14c the target height is too low to use reclaimed stock and the entire top row must therefore be constructed with new (red) triangular components. In Fig. 14d the span is reduced, and the reclaimed center triangular components are cut (dashed blue) to fit the desired length. Finally, Fig. 14e shows a specified design shape that requires both cutting of reclaimed components and the introduction of new elements.

The first case study stock library is also used to design the symmetric design shape in Fig. 4b with reclaimed components. Here, the bottom surface of the design shape is defined by the polynomial function in Eq. (3). Fig. 15 shows designs obtained with four different polynomial target curves. As for the previous example, the extent to which the target span matches the available stock components is seen to influence the required amount of cutting existing and adopting new components. Cutting of the bottom component closest to the symmetry line is required (Fig. 15a–c) unless the length of the bottom curve matches a discrete number of multiples of the stock triangles' base length (Fig. 15d). However, contrary to the rectangular design shape examples in Fig. 14, the uniformity of the library results in a second row made from either cut components or new members, regardless of the target height. This is because the distance between two components increases when the design shape is curved and therefore the reclaimed components do not fit the distance between the top points of the row below. For design shapes with curved bottom boundaries, direct reuse of components in the second row can only be achieved if the stock library contains a set of triangular stock components with diverse base lengths.

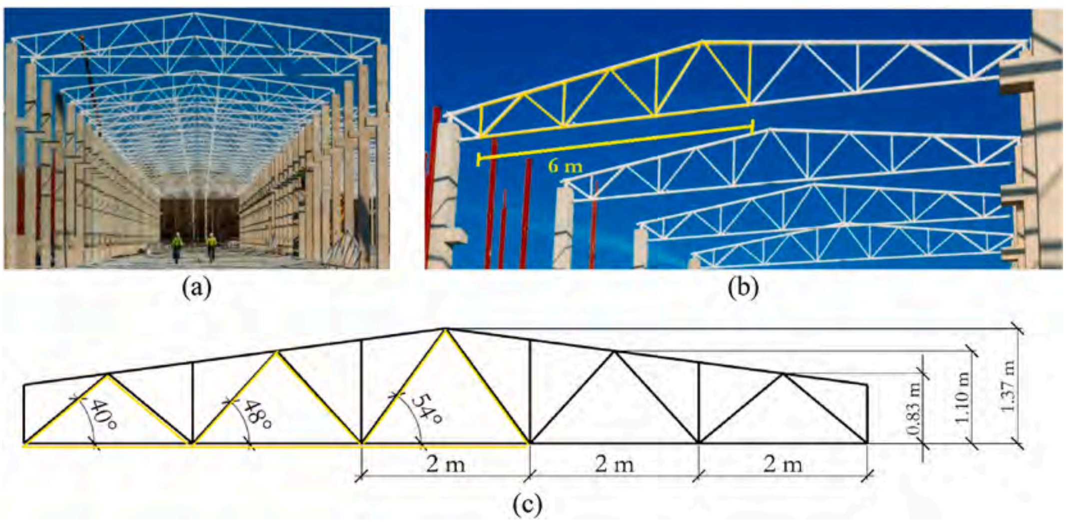

Fig. 16. Case study library 2: reclaimed triangular components from sloped Warren trusses; (a,b) images of example truss [51] and (c) used truss dimensions.

3.2. Case 2: stock library with non-uniform component heights

The second case study stock library uses planar trusses from a sloped roof structure as shown in Fig. 16. The library reclaims components from pitched trusses where the components vary in height but can have the same base lengths. Each planar truss has 5 components of 3 different sizes. The dimensions of the components are given in Fig. 16c. For the designs shown in Figs. 17 and 18 a total of 6 trusses are used.

The second case study stock library is used to design a new symmetric truss with a rectangular design shape as shown in Fig. 4a with $H = 3$ m + 0.3 m tolerance and $L/2 = 8$ m. Since the library contains a diverse set of stock components (three types of triangular components), the randomness associated with generating the first row will result in distinctly different new truss designs when the aggregation engine is executed multiple times. This is shown in Fig. 17 where different designs obtained by executing the aggregation engine multiple times are compared. The figure plots the sum of the length of new elements L_{new} (solid and dashed red) on the x-axis against the sum of the cut length L_{cut} (dashed blue) on the y-axis. The performance of 10 designs that are obtained by executing the aggregation engine 10 times are indicated with dots. As Fig. 17 illustrates, the quality of the designs varies significantly. As an example, a design is obtained with a minimum cutting length of the reclaimed components ($L_{cut} = 0.28$ m), but at the cost of using a relatively large amount of new elements ($L_{new} = 42.75$ m). In contrast, other designs require larger cutting portions or even more new elements. Finally, the magnitude of the axes in Fig. 17 reveals that for the current example, the average number of new material meters required (L_{new}) is always much higher than L_{cut}.

As previously mentioned, the GA module is added to aid in selecting the most competitive trial design. The current case study's average execution time for one aggregation (including plotting the result) is 0.1 s. On average, generating 100 designs (i.e. 1 generation) and plotting the design with the lowest fitness value takes approx. 1.4 s, where the actual time varies with the number of required iterations and the objective settings. The maximum number of function evaluations is in this case study set to 10,000. This number is chosen after a convergence study where the population size was varied.

Fig. 18 shows the designs obtained by solving Eq. (9) with GA for different weighting parameters w_1 and w_2. To illustrate the built-in randomness in GA, the figure gives designs obtained for the same case when running it twice. In Fig. 18a and b, the weighting parameters are set as $w_1 = 1$ and $w_2 = 0$, meaning that the objective is to minimize the sum of the cutting lengths L_{cut}. As the figure reveals, the total length of wasted material is zero for both designs. However, this also results in many new (red) members being used as these are not discouraged. In contrast, the results in Fig. 18c and d are obtained for $w_1 = 0$ and $w_2 = 1$, thus minimizing the sum of the length of new members L_{new}. Both obtained designs contain many reclaimed stock components that require cutting (dashed blue) but have significantly decreased lengths of the required new material. Finally, the designs in Fig. 18e and f are obtained by minimizing the sum of L_{cut} and L_{new} with $w_1 = 1$ and $w_2 = 1/45$. Since generated designs are typically associated with a higher amount of new material length than the required cutting length (see axis in Fig. 17), this weighting scheme has been found to give the two objectives similar levels of importance. The fact that the obtained solution with GA is not necessarily the global optimum is seen by comparing these results, as they differ by in their length requirement for new steel members with $\Delta L_{new} = 0.54$ m. As seen by Fig. 18e and f, the multi-objective designs appear more regular, require no cutting of reclaimed stock components, and require a relatively low amount of new material.

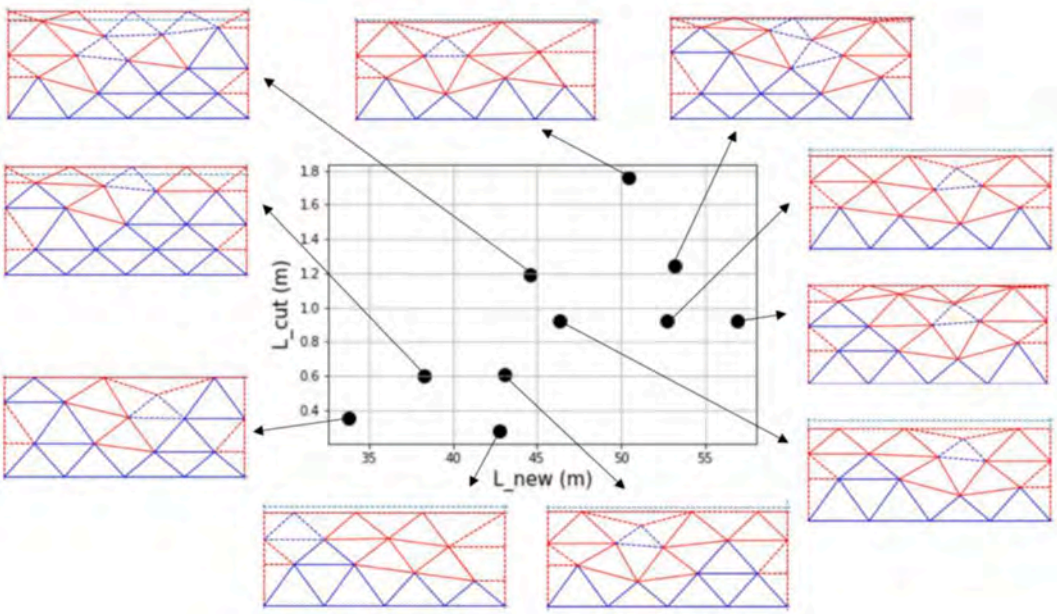

Fig. 17. Case study 2: Designs obtained when executing the aggregation engine 10 times for H = 3.3 m with 0.3 tolerance and L/2 = 8 m. The quality of the designs in terms of required cutting and new member lengths is illustrated by plotting the designs against these two metrics.

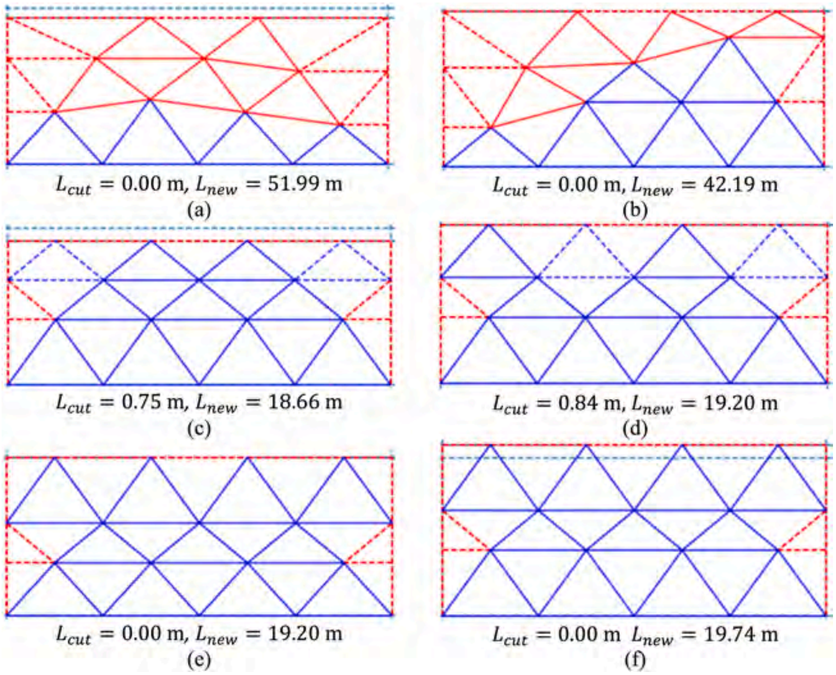

Fig. 18. Case study library 2: designs obtained for rectangular design shape with dimensions H = 3.3 m and L/2 = 8 m by solving Eq. (9) with GA and (a,b) $w_1 = 1$, $w_2 = 0$, (c,d) $w_1 = 0$, $w_2 = 1$, and (e,f) $w_1 = 1$, $w_2 = 1/45$.

Just as in the first case study, the curved design shape designs can only have one row of direct reuse of components. This is because all the base lengths are the same and do not fit within the required lengths of the second row and on, therefore no examples are given for this case study.

3.3. Case 3: stock library with non-uniform components

For the last case study library, the original trusses from the Galérie des Machines are used. The Galérie des Machines was the largest wide-spanning iron framed structure ever constructed when it was completed for the Universal Exposition of 1889 in Paris [52]. It consisted of twenty three-hinged truss arches, spanning the 115 m hall, as shown in Fig. 19a. The structure was demolished in 1910.

Fig. 19b provides a construction drawing of half truss arch. The partially disassembled triangular components that would emerge from such an arch are indicated in red on the drawing. In this work, all lines are assumed straight. Seven different types of triangular components are identified and shown with their dimensions in Fig. 19c. Similar to the first two case studies, symmetry of the new designs will be enforced for the third case study by aggregating components in half design shape and mirroring the obtained design. The library, therefore, contains the components of half one truss arch from the Galérie des Machines with a total of 50 triangular components.

Fig. 20 shows a truss detail from the Galérie des Machines with corresponding cross-sectional dimensions (in mm). To simplify, the cross-section has been kept the same for all the truss elements and the area has been calculated as $A = 0.0066$ m^2. When introducing new members, the cross-sectional area can be chosen freely by the user. Herein, an area of $A_{new} = 0.01$ m^2 is selected. The Young's modulus of all truss elements is set to be $E = 200$ GPa.

The components from the Galérie des Machines are herein used to design two new 20-m long pedestrian bridges with design regions as follows: the rectangular design region has $L = 20$ m and $H = 3$ m, and the one with a polynomial bottom curve has $L = 20$ m and $H = 5.9$ m. Both bridges have two planar trusses that carry a 3-m wide central deck. The prescribed loads are taken as outlined in Eurocode 1 [54]:

$$q = 2 + \frac{120}{L+3}\left[\frac{kN}{m^2}\right], \tag{11}$$

where L is the loaded length in meters which is here the total span of the bridge. Additionally, the Eurocode specifies that the distributed load is bound by 2.5 kN/m^2 $\leq q \leq$ 5 kN/m^2.

Fig. 21a shows the optimized design for a rectangular design region with $w_1 = w_2 = 1$. The solution is obtained with a population size of 10 and 100 GA generations in 14 s. The solution requires cutting most of the reclaimed components to fit within the design shape. The total cutting length is L_{cut} = 4.22 m, but the required length of new members is kept low. The new design is analyzed with a linear-elastic static FEA to evaluate its structural performance. The applied loads and boundary conditions are shown in Fig. 21b. The deformed shape obtained from this analysis is given in Fig. 21c. As expected, the maximum defections occur at the nodes in the middle

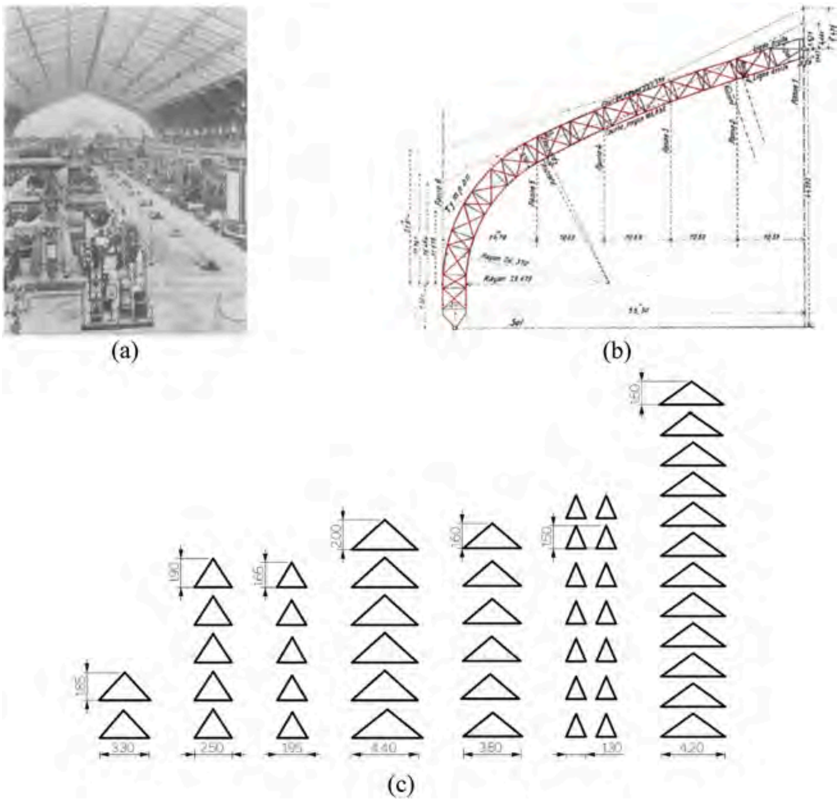

Fig. 19. Case study stock library 3: Galérie des Machines [52]; (a) image of Galérie des Machines, and (b) construction drawing from Ref. [53]. The resulting triangular component stock library used herein is shown in (c).

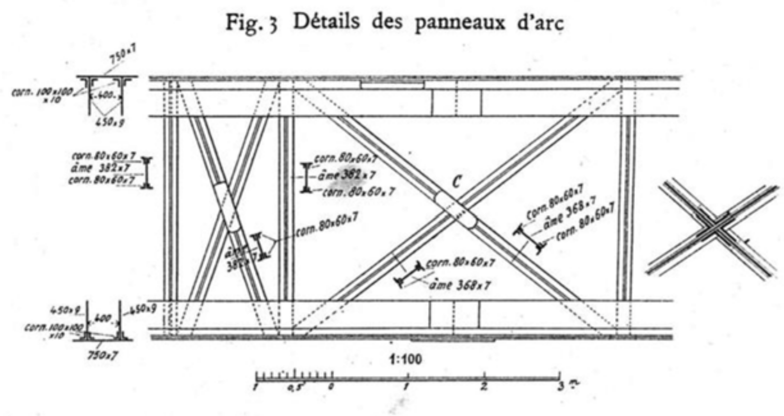

Fig. 20. *Galérie des Machines detail of truss cross-sections* (Atlas of Places).

of the span (rightmost nodes in Fig. 21c). The defections of all three nodes is here $u_{y,max} = 1.93$ mm. The left support displaces $u_x = 0.46$ mm to the left. Assuming that the maximum allowable live load defection is $L/500 = 40$ mm, the found maximum displacement is significantly lower than the allowable. This indicates that the new truss is perhaps slightly over dimensioned. However, it is emphasized that only a static truss analysis is performed and that buckling and vibrations have been ignored which often have a significant influence in the design of pedestrian bridges. Additionally, the material properties of the reclaimed components can have changed over time, necessitating a more conservative design solution. A rendered image of the final design is given in Fig. 22.

Fig. 23a gives the pedestrian bridge obtained for a design shape with a polynomial bottom curve described by $y = -0.03x^2 + 0.6x$. The design obtained is the best solution of the 1000 designs generated by 100 generations, each with a population size of 10. For the same objective function and weights, this design is seen to be able to use a higher number of unaltered components from the Galérie

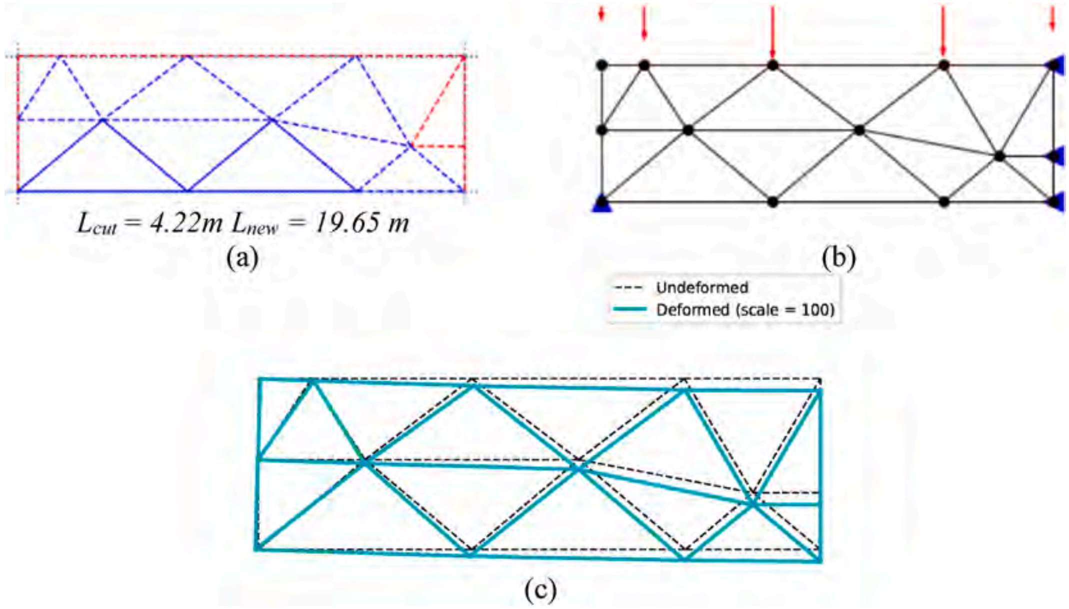

Fig. 21. (a) obtained design result of linear design shape with H = 3 m and L/2 = 10 m, (b) load and boundary conditions used in FE analysis, and (c) resulting plot of deformed shape.

Fig. 22. Rendered images of a pedestrian bridge, reusing the components of the Galérie des Machines with a rectangular design region.

des Machines stock library than what was possible for the rectangular design shape in Fig. 21a. Whereas two uncut triangular stock components is used in the rectangular target case, the polynomial design shape uses four uncut components. In addition, three stock components require some level of cutting with a total cutting length equal to $L_{cut} = 2.61$ m which is a 38% reduction compared to the rectangular case. The curved bottom design is analyzed with finite elements and loads and boundary conditions applied as indicated in Fig. 23b. The resulting deformed shaped is shown in Fig. 23c. The maximum defections are determined as $u_y = 2.16$ mm at the three mid-span nodes. These defections are well below the maximum allowable $u_{y,max} = 40$ mm. A rendering of the final pedestrian bridge design for the design shape with a curved bottom surface is shown in Fig. 24.

3.4. Discussion on extensions and limitations

The present work provides a new GA-based approach to design new truss systems within a predefined design region from a stock library of partially disassembled existing trusses. Although the method provides promising results with limited computational resource requirements, it has some limitations.

Since the herein suggested design problem formulation (Eq. (9)) uses discrete design variables in a nonlinear objective function, the optimization problem must be solved by a stochastic optimizer such as GA. This induces non-negligible built-in randomness and the inherent issue of having no guarantees of finding the global optimum. Obtained solutions are also sensitive to the choice of the weighting parameters (w_1 and w_2). The weighting parameters need to be set such that L_{new} and L_{cut} are balanced in accordance with both the library and the design region. Through the settings of the weighting parameters, it is possible to emphasize certain aspects that are of particular interest in a given design situation (e.g. maximize the reuse of material). In cases where minimizing L_{new} and L_{cut} are of equal importance, the weighting parameters must be calibrated. This can be done by running the aggregation engine once (which only takes 0.1 s) and calculating the ratio between L_{new} and L_{cut}.

A significant limitation of the current work is that the design of connections between adjacent reclaimed components has not been considered. When designing with diverse stock libraries and/or non-rectangular design shapes, the new design often contains more

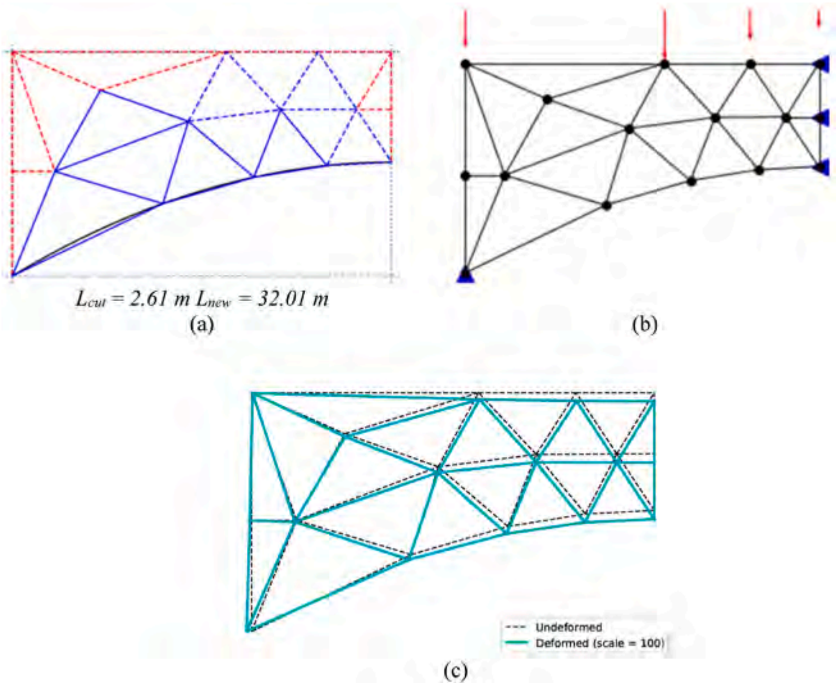

Fig. 23. (a) obtained design result of linear design shape with polynomial bottom target and H = 5.92 m and L/2 = 10 m, (b) load and boundary conditions used in FE analysis, and (c) resulting plot of deformed shape.

Fig. 24. Rendered images of a pedestrian bridge, reusing the components of the Galérie des Machines, with a polynomial bottom target curve as input.

complex connections than typically seen in modern steel structures. Here the potential of additively manufactured steel connections offers an immense opportunity to realize non-standard joints by adopting the geometrical freedom of optimization techniques thanks to digital fabrication processes (see e.g. Ref. [55–57]). In addition, future work on the investigation of efficiently connecting partially disassembled truss components is highly encouraged.

Additionally, this work has been limited to show the opportunities of reusing triangular components with at least two equal sides. This is not an exhaustive description of existing planar truss geometries nor the possibilities of partial truss disassembly. Future research extension could include considering two or more connected truss components, not necessarily forming a triangle. The first case study in this work (Section 3.1) illustrates this potential. Recall that the case study designs a rectangular design region using a single type of stock components. The resulting designs (Fig. 14) could easily be realized by grouping multiple components where building with larger components can be advantageous as it reduces the need for (dis)assembly and construction of new joints.

Although not done herein, this work provides the basis for several other possible extensions. A relevant extension could for example be to increase the complexity of the FEA check to include buckling, dynamic loading and/or multiple load cases. This will of course increase the computational time. However, since the FEA check is conducted after the optimization is complete, a single execution of a more computational expensive analysis is possible. Other extension possibilities include increasing the number of metrics that are evaluated in the objective function such as a measurement of the goodness of fit with a nonlinear exterior target curve, or a measurement for the structural weight or efficiency. Finally, the framework is also conceptually extendable to 3D truss systems.

4. Conclusions

Direct reuse of structural elements has the potential to greatly reduce the environmental impact of construction as it avoids sourcing raw material and the heating associated with recycling, while reducing the amount of waste from construction and demolition. However, the demolition task is dramatically elongated if direct element reuse is desired, as damage must be avoided when elements are disassembled and sorted. Likewise, the structural design task is completely different when creating a new design that must conform to a library of existing stock elements or components. To simultaneously alleviate these concerns, this work has presented a new stock-constrained design and optimization framework for designing planar truss structures from a stock library of partially disassembled trusses. In contrast to existing design methods that rely on reuse at the element level, this work mitigates the demolition process requirements by avoiding the complete disassembly of all structural members. The design process is also automated to ease the discovery of possible solution layouts.

The new framework requires the user to define a target design region for the new design and aggregates partially disassembled triangular components row by row. It introduces new material members where necessary to ensure that the new design matches the design shape. The new framework is demonstrated for new planar truss design using three case study libraries containing isosceles triangular components from real inventories of Warren trusses with increasing levels of component diversity. The design is initiated by a random operator, and if the stock library contains different component sizes, diverse designs can be generated. The framework is fast (on the order of 0.1 s to generate a trial truss), and a GA optimization module is therefore added to select among generated trial designs. The case studies demonstrate the potential of partially disassembling and reusing truss components and illustrate how the user-defined design shape and the stock variability influence the resulting design.

Finally, the herein cast optimization problem minimizes the cutting length and the length of the required new material. This objective function can relatively easily be extended to include minimizing the discrete number of components that need cutting before reuse, maximizing the structural efficiency, or minimizing the carbon emissions. Whereas including the structural efficiency requires finite element evaluations of all trial designs, minimizing the carbon emissions demands a Life Cycle Assessment to be included as in Brütting et al. [49]. Adding either of these considerations is also likely to increase the computational time.

CRediT authorship contribution statement

Albertine Van Marcke: Conceptualization, Methodology, Software, Writing – original draft. **Vittoria Laghi:** Methodology, Supervision, Writing – review & editing. **Josephine Voigt Carstensen:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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