SSA 8

Refinement of Numerical Method and Applications

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Goal

- Improve the numerical optimization algorithm to remove chaotic results and apply the new algorithm to *The Croissant* design.

Conclusion

- *The Croissant* design does indeed better distribute compressive loadings.
- The numerical results of the optimization for *The Croissant* are as follows:

Parameter Weight	Description	Weighting Value
ω_d	Buckling distribution	20.27
ω_m	Material consumption	95.59
ω_b	Buckling failure penalty	30.41
ω_u	Compressive load uniformity	14.86
ω_a	Average loading magnitude	36.49

Problems

- The main failure point in some of our designs was buckling.
- The second thing that piqued my interest was the diagonal extension part.

Follow up Steps

- Incorporate the optimization of not only nodes in the structure but the truss members themselves; this allows for varying the connection points within the design to create a more complete optimization framework.
- Create a new finite element solver and data pipeline to support the optimization of truss structures in 3D.

Work Division

- The designs were created by other team members which allowed for efforts to go towards improving both the accuracy, stability, and usability of the optimization application.

Time Division

- Debugging issues with the chaotic results in the optimizer. **1 hours**
- Normalization of component objective parameters. **2 hours**
- Implementing a new modular code structure for better data handling. **2 hours**
- Improving the graphical user interface for the optimizer. **2 hour**
- Application to the latest crane design *The Croissant* **1 hour**
- Completion of writing this SSA. **2 hour**

Total of 10 hours

Goal 1 - Improvements to Numerical Method

Synopsis of previous work

In the previous SSA, the numerical method was updated to employ a multi-parameter approach, in which several different objective functions were combined via a weighted sum to obtain a total design score Ω, which the algorithm attempted to minimize to create the best structure. A summary of the parameters has been included below:

Objective	Description	Mathematical Formulation	Dependencies
O_d	Buckling distribution	$O_d = \gamma + 2s_\mu$	T_i, $L_{0,i}$, λ, cross-section
O_m	Material consumption	$O_m = \sum_{i=1}^{n} A_i L_i$	$L_{0,i}$, cross-section type
O_b	Buckling failure penalty	$O_b = 0$ for $\mu_i < 0.95$ $O_b = c \cdot e^{\mu_i - 0.95}$ for $\mu \geq 0.95$	T_i, $L_{0,i}$, λ, cross-section
O_u	Compressive load uniformity	$O_u = \nu_\mu = \gamma s_\mu$	T_i, $L_{0,i}$
O_a	Average loading magnitude	$O_a = \frac{1}{n} \sum_{i=1}^{k} \lvert T_i \rvert$	T_i

Table 1: Table of multi-parameter objectives.

During testing with the numerical optimizer algorithm and various different truss structures as inputs, an issue that consistently emerged was that the optimizer appeared to be highly sensitive to minor fluctuations in the truss solver (FEM simulation) outputs.

Although in theory these fluctuations should remain negligible, they were amplified by the multi-parameter weighting system in practice. Due to the disparities between the magnitudes of the component objective functions, the total design score Ω would approach minimum values with truss configurations that exhibited irregular node distributions and extreme member dimensions; the optimizer would often fall into 'wells' in which unfeasible and unstable structures appeared to be ideal. As such, the optimizer was highly sensitive to changes in input weights and exhibited chaotic behavior when varying them. Hence, the first part of this SSA will focus on improvements to the optimizer objective system.

Improvements to objective handling

Chaotic result amplification

In the previous multi-parameter approach, the overall design score Ω was obtained from a weighted sum of the individual component objective functions:

$$\Omega = \sum \omega_i O_i \tag{1}$$

where O_i represents the contribution of any objective i multiplied by its corresponding weighting factor ω_i. Although the weights were intended to balance the contributions of each parameter to the overall design score Ω, the component objectives varied significantly in their magnitude.

Consequently, when multiplying the individual component objectives O_i by fixed weights, small chaotic variations from the truss simulation could become disproportionately amplified, thereby influencing the overall design score Ω. Under certain initial conditions (the selected target points and weighting parameters), this sometimes led the optimization algorithm to explore truss configurations with irregular or unstable node positions, resulting in suboptimal or structurally unsound designs.

Dynamic normalization approach

To address this issue, a dynamic normalization approach was introduced, where each objective that is not already normalized–which includes the average loading magnitude O_a and the material consumption O_m. This process involves dividing the unnormalized value of the objective by a characteristic reference value O_i^{ref} derived from the original truss geometry. This results in the normalized objective value $\tilde{O}_i$:

$$\tilde{O}_i = \frac{O_i}{O_i^{\text{ref}}} \tag{2}$$

which may then be substituted into the overall design score for O_a and O_m. This approach ensures that each component objective function contributes comparably to the rest and with similar response characteristics for the full range of input values.

Average loading magnitude O_a

The characteristic reference value for the average loading magnitude may be derived from the average loading magnitude for the original truss structure. Thus, the normalization process would not only quantify the average scale of forces within the truss structure but also the relative improvement compared to the initial truss design. This approach intuitively makes sense as the optimization process attempts to iteratively improve the truss structure compared to the initial input. As such, the normalized average loading magnitude $\tilde{O}_a$ can be expressed as:

$$\tilde{O}_a = \frac{O_a}{O_{a,0}} \tag{3}$$

where O_a is the regular mean of the magnitudes of axial forces for a given iteration of the truss structure during the optimization process, and $O_{a,0}$ is the same value calculated for the unmodified structure at the start.

Material consumption O_m

Similarly, the material consumption may be normalized using a characteristic reference that is derived from the initial input parameters. As such, the normalized material consumption $\tilde{O}_m$ may be expressed as follows:

$$\tilde{O}_m = \frac{O_m}{O_{m,0}} \tag{4}$$

where O_m is the sum of all the member lengths multiplied by their cross-sectional areas, and $O_{m,0}$ is the same value calculated before the optimization algorithm is called.

Stable numerical algorithm

By normalizing these values, which typically differ significantly in magnitude (for instance, the average forces were roughly 1000 times larger than the other objectives), the objective functions have relatively similar contributions to the total design score Ω. This results in the relative importance of the weights being consistently applied between the different parameters, thereby improving the numerical stability of the optimization process, preventing the algorithm from producing extreme or unstable truss configurations, and creating consistency among the weighting for each parameter.

Therefore, the stabilized objective function for the multi-parameter framework may be written as follows:

$$\boxed{\Omega = \omega_d O_d + \omega_m \tilde{O}_m + \omega_b O_b + \omega_u O_u + \omega_a \tilde{O}_a} \tag{5}$$

where the component objective parameters for average loading magnitude and material consumption have been normalized to remain consistent with the others.

Goal 2 - Application to *The Croissant* Design

Design background

As the numerical optimizer has now been improved to ensure numerical consistency among its parameters, it may be readily applied to the current crane design proposed by our team. This design, colloquially referred to as *The Croissant* during discussion, is an iteration upon the previous Crane Design 3. This design has rounded the upper chord and the lower base near the wall to align with a cylindrical shape. In theory, this should better distribute the compressive loadings around the lower base by aligning the 'forceflow' in the truss structure overall.

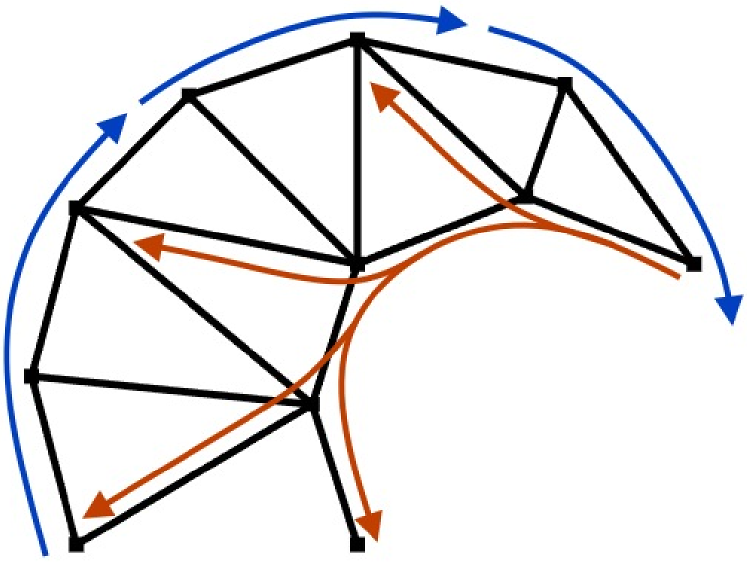

Figure 1: Diagram of the 'forceflow' in *The Croissant*

As can be seen in Figure 1[1], the compressive loadings in this curved design allow for compressive loadings to be distributed by spreading the loading into horizontal elements rather than sustaining the entire compression via vertical elements perpendicular to the ground plane. As such, the upper chord carries the tensile forces while the inner portion of the truss distributes compressive loadings among various elements to minimize overall loading.

Additionally, after discussion during the last meeting, the node in the lower left was removed and replaced with a vertical member in order to reduce the material usage of the overall truss structure. As such, the design used in this SSA will reflect these modifications.

Furthermore, the set of points and trusses used in this optimization will be in 2D as the algorithm has thus far only been implemented via a 2D finite element method (FEM) solver; however, future improvements will work toward creating a 3D implementation. Thus, the set of points used in the optimization is derived from the upper-most chord of the 3D design, which is a center-aligned spine connected via triangles to form a series of pyramids.

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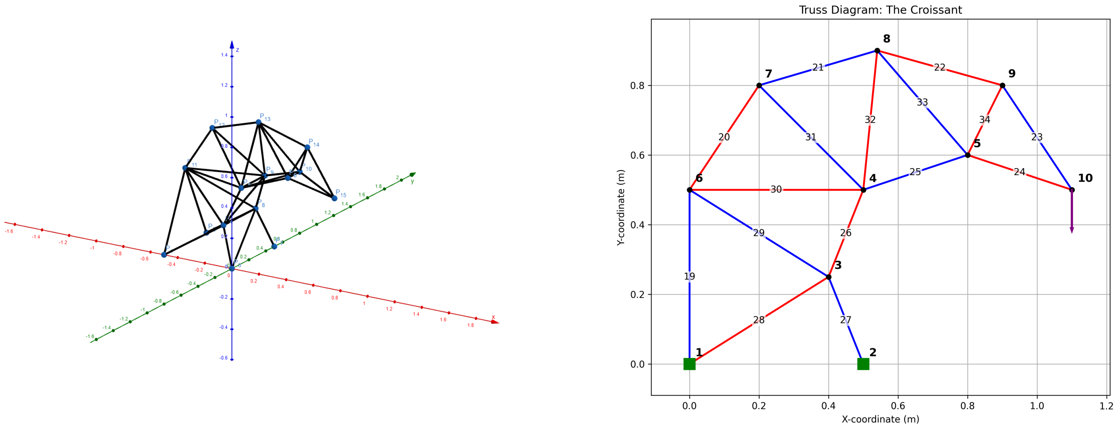
[1]Diagram by Niels Kuipers



(a) 3D diagram of *The Croissant*

(b) 2D diagram of *The Croissant*

Figure 2: 3D and 2D diagrams of *The Croissant* crane design.

As can be seen in Figure 2(a), the 3D version of the design utilizes a unified central spine that splits into two along the bottom in order to save material as opposed to the conceptual drawing from Figure 1. When copying the points from this cross-section of the 3D design for optimization in 2D, the lower portion of the base appears somewhat odd which can be seen in Figure 2(b). However, for the purposes of optimization, the 3D angle that this lower element forms with respect to the vertical axis will not be taken into account, and the results will serve as guidance for improving the base shape of the upper chord rather than to modify surrounding components of the truss.

Optimization Process

After manually testing various optimization weighting parameters and target points for optimization, the following input parameters were used in the final optimization via the numerical truss optimization software[1]:

Optimization Weights

Parameter Weight	Description	Weighting Value
ω_d	Buckling distribution	20.27
ω_m	Material consumption	95.59
ω_b	Buckling failure penalty	30.41
ω_u	Compressive load uniformity	14.86
ω_a	Average loading magnitude	36.49

Table 2: Objective parameter weighting with associated values.

Targeted Nodes

- Nodes `6, 7, 8` (refer to Figure 2(b)).

After running the optimization, the following table of values for each objective component was obtained:

Objective	**Metric**	**Value**
O_d	Buckling Distribution Factor	0.0004
O_u	Compression Uniformity	0.2923
O_b	Buckling Penalty	0.0000
O_m	Material Usage	0.9973
O_a	Average Force Magnitude	0.9690
Total Score: 70.0362		

Table 3: Final metric values and total score (weighting applied).

Analysis of the data obtained from the optimization process reveals a low buckling distribution factor of 0.0004, indicating that the curved design and its optimized result efficiently distributed compressive loadings throughout the truss structure. The compression uniformity value is similarly low at 0.2963, indicating both minimal spread in compressive forces among elements and low mean compressive magnitude. This suggests that a curved geometry does indeed better distribute compressive loading in the truss and that the average magnitude of the internal forces did not increase. Furthermore, the buckling penalty remains 0, which indicates that no element in the structure as at risk of buckling.

Additionally, the normalized metrics for the material usage and average force magnitude are both less than 1. Given the normalization procedure described in Goal 1, values within the range $[0, 1]$ correspond to the relative reduction of these quantities with respect to the original. Consequently, values below 1 indicate that the optimization process was successful in reducing both the average internal forces and material usage of the truss structure–both of which contribute to a more efficient and structurally robust truss design.

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Optimized Design

Below, a diagram of the optimized design has been included, which reflects the previous findings that a curved upper chord better distributes the compressive forces. This is further reinforced by the quantitative data provided by the metrics.

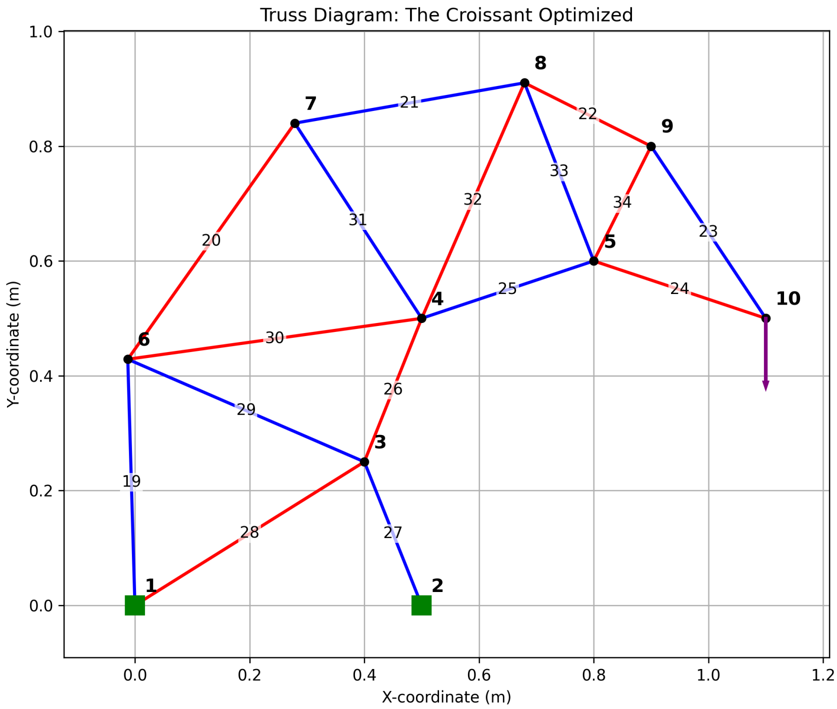

Figure 3: Optimized design for *The Croissant*

By incorporating the quantitative findings observed in metrics from Table 3 to form a qualitative assessment of the truss design. Among the nodes targeted in the optimizer (Nodes `6, 7, 8`), both Nodes `6` and `7` moved lower in height and the distance between them increased. Node `8` moved further along the x-axis, which therefore shifted truss member `22` from being under tension to being under compression. Although the quantitative scoring reveals that the forces are better distributed and have lower average magnitudes, the layout of compressive and tensile members in the structure is significantly altered.

This may possibly reveal that the optimization process was not entirely successful in recognizing how the layout of truss members also plays a role in the design of the crane. This is due to the fact that the optimization algorithm only accounts for the positioning of points and observes their effect via normalized average values or grouped datasets. Therefore, a possible follow-up could be to incorporate the analysis of the truss members themselves and allow for varying the connection points within the design to create a more complete optimization framework.

Additionally, this optimization was performed in 2D which may show significantly different data than for a 3D design. In particular, truss member `19` is shown as a single connection between the ground and the upper chord, whereas the 3D design in Figure 2(a) can be seen to have two such elements connecting the upper chord to the ground–thereby better distributing tensile forces and altering the stability of the structure as a whole. Thus, another follow-up may involve creating a new finite element solver and data pipeline to support the optimization of truss structures in 3D as well.

A Numerical Optimization Software

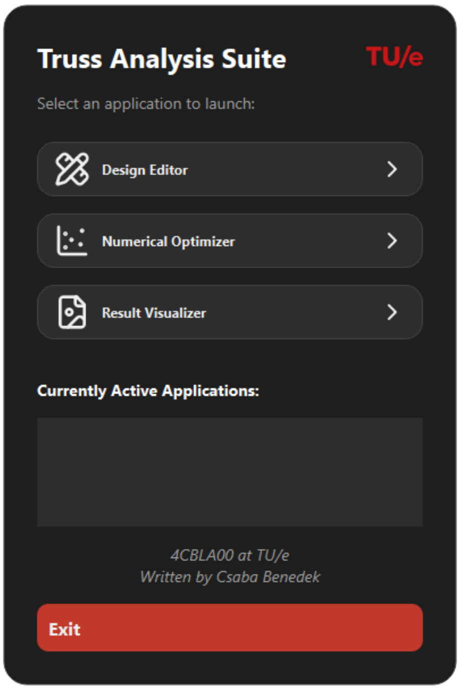

Figure 4: Truss Suite - Launcher Page

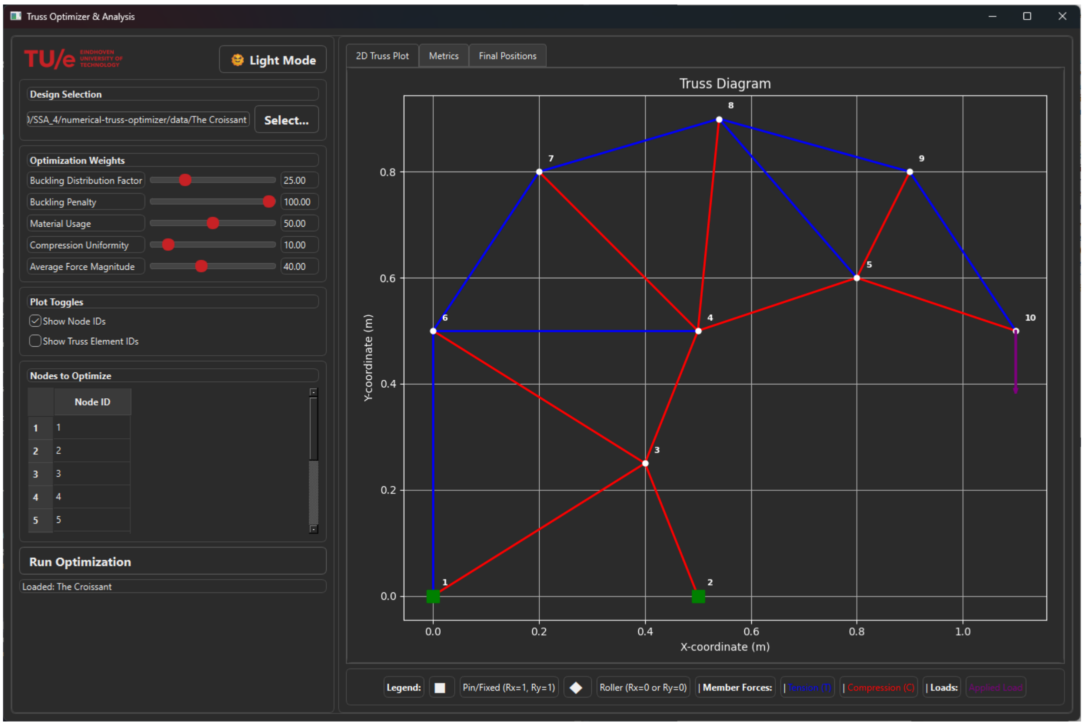

Figure 5: Truss Suite - Numerical Optimizer

References

[1] C. Benedek. *GitHub - madeofcloud/numerical-truss-optimizer: A numerical truss optimizer written for TU/e course 4CBLA00 to optimize the design of truss structures.* Accessed: 2025-10-06. Oct. 2025. URL: https://github.com/madeofcloud/numerical-truss-optimizer (visited on 10/06/2025).