Predicting material consumption in a Circular Economy oriented design methodology for pedestrian and cycling bridges

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Abstract. A Circular Economy (CE) oriented design methodology for pedestrian and cycling bridges that takes the 4Rs of the CE -Reduce, Reuse, Recycle, Recover- as basis needs to be developed. The first R, Reduce, is mostly neglected, even though it is the most important R in the CE. Nevertheless, a CE oriented design methodology also needs to consider and formalise Reduce. It is proposed to do this by measuring the material efficiency of a structure. Therefore, a reference volume of material needs to be found. This paper proposes a methodology to predict the necessary amount of material needed for the bridge structure. The methodology takes the theory of the morphological indicators as basis. Morphological indicators are used in the conceptual design phase to find the most efficient structural typology and global dimensions. However, it was found that the volume indication that results from the morphological indicators is not realistic. The main reasons are that they consider a fully stressed state for each component, and they do not consider standard profile sections. Therefore, two correction curves are proposed to correct the volume obtained from the morphological indicators into a realistic one. The limitations of this study are that it only focusses on Warren truss bridges and only considers vertical service loads. Further research will have to focus on incorporating other types of trusses and other structural typologies like arched, suspension and cable-stayed bridges. In addition, more loads like wind and snow that can act on bridges need to be considered.

Keywords: Circular construction; conceptual design; morphological indicators; structural optimisation; material consumption

1. Introduction
A Circular Economy (CE) oriented design methodology for pedestrian and cycling bridges is non-existent [1,2]. As such, said design methodology needs to be developed incorporating the four Rs of the CE -Reduce, Reuse, Recycle, Recover. By extension, the ISO20887 advocates that advances in circularity should be measurable and measured [3]. A CE oriented design strategy that coincides with a circularity indicator (CI) will therefore be key. Such a CI should assess all four R’s of the CE. Currently, most available CIs focus mostly on Recycle with Ellen MacArthur’s [4] Material Circularity Indicator (MCI) as basis. Khadim at al. (2022) performed an extensive review of several CIs for the built environment and mapped the CE related aspects they evaluate. Different aspects concerning Reuse,
Recycle and Recover were identified in the indicators, but none of them assessed the first R of the CE, Reduce [5]. Anastasiades et al. (2020) tested the influence of material reduction in their first proposal for a CI for pedestrian bridges. They concluded that the indicator measures reusability of components through the incorporation of factors that define the deconstructability of the components. It also measures the recyclability of materials, as it takes the MCI as basis, but it neglects the R of Recover for the bioeconomy. However, more importantly, it was found that a reduction of material consumption could even lead to a worse circularity score. Hence, they proposed that material efficiency should be measured in order to avoid such a discrepancy [6]. Also the Eurocodes [7] focus mostly on structural safety, rather than structural optimisation. Traditionally, a structure is designed according to the 3Ss - Strength, Stiffness, Stability - and it should always adhere to the prescribed safety and comfort standards. In addition, Vandenberghe and De Wilde (2010) emphasise the importance of structural optimisation, as a structure with less material results in a lower environmental impact, lower procurement, transportation and construction costs, and less end-of-life waste. The optimised structure will thus be more sustainable overall [8]. Unfortunately, engineers are rarely involved in the conceptual design stage. Consequently, often many design iterations are required in order to marginally optimise the structural system [17–21]. However, when the architectural concept is structurally far from efficient, the resulting optimised structure is far from efficient as well. Moreover, the lower the structural efficiency, the higher the material consumption. Additionally, the engineer’s choice of structural morphology is usually based on intuition and experience, which means that only few alternatives are taken into consideration [9,10]. Consequently, it will be key to formalise a sufficiency strategy to avoid unnecessary material consumption.

It is possible to generate structural geometries with computational methods like topology optimisation. In this way, a lightweight structure with maximum stiffness for a certain set of boundary conditions can be obtained [11]. On the downside, this requires high computation power, which is expensive, and often lots of post-processing is needed to transform the obtained morphology into a practical one [12].

Structural morphology optimisation is also possible using the theory of the Morphological Indicators (MIs). Several studies have focussed on the development of MIs [13–16]. Van Steirteghem (2006) explains that MIs are dimensionless numbers expressing a geometrical or physical property of a structure. There are multiple MIs such as the volume indicator $W$, buckling indicator $\Psi$, displacement indicator $\Delta$ and the first natural frequency indicator $\theta$. MIs should be used in the conceptual design phase [16]. They formalise the choice for the most efficient structural typology which leads to material savings[13]. However, Anastasiades et al. (2022) explain that these MIs are all inter-connected rendering their practical application very complex. Therefore, Anastasiades et al. (2022) combined the MIs for Warren trusses into an automated algorithm. The algorithm was subsequently tested on a total of 36 truss bridges, resulting in a success rate of 90%. An important observation in this study is that the volume predicted with the MIs is not realistic [1]. As the MIs predict the most suited structural typology with the least material use for the concerning span, they can be used for the said material efficiency evaluation. This study therefore focusses on the development of a methodology to correct the volume predicted with the MIs into a realistic one. This will allow to accurately predict the volume already at the start of the conceptual design stage, before a single pencil streak was put on paper. This volume can then be used as reference volume to assess material efficiency, thus the R of Reduce. Additionally, this will allow to more accurately predict the construction cost for a pedestrian bridge which will lead to an optimised tender management.

In the subsequent sections, the applied method will be explained and the results will be discussed. Lastly, a conclusion and further research recommendations are provided.

2. **Material and Methods**

The MIs are dimensionless numbers and should be used in the conceptual design phase to optimise structures based on certain criteria. Latteur (2016) explains that there are primary indicators and secondary indicators. Secondary indicators express physical quantities like material volume,
displacement, rotation, stresses, etc. Primary indicators express geometrical properties like the slenderness, the form coefficient, or the buckling indicator. Secondary indicators implicitly depend on one or more primary indicators. The most important secondary indicator is the volume indicator \( W \) [13]. Anastasiades et al. (2022) integrated the volume indicator \( W \), the buckling indicator \( \Psi \), the displacement indicator \( \Delta \) and the first natural frequency indicator \( \theta \) into an automated algorithm for Warren trusses. In addition, 36 bridges were tested and the results of the MIs were compared to the results obtained through calculations of corresponding Finite Element Models (FEMs) [17]. These results will be analysed further in order to find a methodology to correct the material volume obtained with the MIs into a realistic one.

### 3. Results and discussion

Several bridge spans were tested in [1] with the following fixed parameters:

- the bridge width is 3m
- the structural material is normal construction steel with a yield stress of 235MPa, Young’s modulus of 210GPa and density of 7800kg/m³
- the service load on the bridge is 5kN/m² with a safety factor of 1.5, both as prescribed in the Eurocode [7]
- the maximum vertical deformation is limited to L/350.

A summary of the results is shown in the left part of Table 1. For each span, the most optimal result according to the MIs is indicated in bold. The results of the FEMs that deviate are indicated in italics. Anastasiades et al. (2022) explain that the MIs do not take actual cross sections into consideration for the different bars in the truss. They consider a form factor to express the cross section’s efficiency. Additionally, all bars are assumed to be fully stressed, 100%. For the calculation of the FEMs, only standard, but efficient, profile sections were used. Bars in compression were assigned CHS profiles, L-shaped sections were used for the diagonals in tension, and for the bars in the lower beam of the truss, standard I-shaped sections were chosen [1].
Table 1. Summary of the results for Warren trusses in Anastasiades et al. (2022) on the left, extended with correction factors $V_{FEM}/V_{MI}$, shape factors $nL/H$ and weighted stress levels of the FEMs.

| L [m] | H [m] | n  | W   | $V_{MI}$ [m$^3$] | $V_{FEM}$ [m$^3$] | $V_{FEM}/V_{MI}$ | nL/H [-] | $\sigma_{FEM}$ [%] |
|-------|-------|----|-----|-----------------|-----------------|------------------|----------|-----------------|
| 4     | 2     | 2  | 2.62 | 0.050           | 0.0793          | 1.58600          | 10.00    | 30.18           |
| 3     | 2.29  |    | 0.044 | 0.0544         | 1.24201          | 12.00            | 44.89    |
| 5     | 2.31  |    | 0.044 | 0.0547         | 1.24318          | 15.00            | 51.43    |
| 20    | 5     | 2  | 2.50  | 0.048           | 0.075            | 1.56576          | 8.00     | 28.07           |
| 3     | 2.23  |    | 0.043 | 0.057           | 1.33489          | 12.00            | 38.06    |
| 5     | 2.45  |    | 0.047 | 0.061           | 1.30342          | 15.00            | 42.93    |
| 6     | 2     | 2  | 2.50  | 0.048           | 0.0740           | 1.54167          | 6.67     | 30.18           |
| 3     | 2.28  |    | 0.044 | 0.0575          | 1.30682          | 10.00            | 42.68    |
| 5     | 2.71  |    | 0.052 | 0.0699          | 1.34423          | 16.67            | 39.05    |
| 40    | 6     | 5  | 2.80  | 0.215           | 0.2473           | 1.15023          | 33.33    | 53.78           |
| 3     | 2.93  |    | 0.224 | 0.3045          | 1.35756          | 17.14            | 37.19    |
| 5     | 2.76  |    | 0.212 | 0.2468          | 1.16635          | 28.57            | 50.40    |
| 7     | 2.83  |    | 0.217 | 0.2560          | 1.17918          | 40.00            | 53.47    |
| 8     | 3     | 2.84  | 0.218 | 0.2935          | 1.34633          | 25.00            | 45.95    |
| 5     | 2.80  |    | 0.214 | 0.2614          | 1.22150          | 20.00            | 36.85    |
| 7     | 2.97  |    | 0.228 | 0.2639          | 1.15746          | 30.00            | 49.95    |
| 60    | 7     | 7  | 3.14  | 0.541           | 0.5942           | 1.09834          | 60.00    | 63.60           |
| 9     | 3.10  |    | 0.534 | 0.6174          | 1.15618          | 77.14            | 64.05    |
| 11    | 3.15  |    | 0.542 | 0.5873          | 1.08358          | 94.29            | 70.13    |
| 8.4   | 6     | 3.17  | 0.546 | 0.5940          | 1.08831          | 42.86            | 57.02    |
| 7     | 3.07  |    | 0.529 | 0.5778          | 1.09184          | 50.00            | 60.21    |
| 9     | 3.12  |    | 0.538 | 0.6016          | 1.11863          | 64.29            | 61.21    |
| 10    | 3     | 3.40  | 0.587 | 0.9225          | 1.57155          | 18.00            | 34.87    |
| 5     | 3.12  |    | 0.537 | 0.6163          | 1.14767          | 30.00            | 50.07    |
| 7     | 3.13  |    | 0.540 | 0.5305          | 0.98241          | 42.00            | 48.93    |
| 8     | 9     | 3.38  | 1.036 | 1.1215          | 1.08253          | 90.00            | 71.00    |
| 11    | 3.36  |    | 1.030 | 1.0951          | 1.06320          | 110.00           | 74.96    |
| 13    | 3.50  |    | 1.043 | 1.1287          | 1.08217          | 130.00           | 75.17    |
| 80    | 9.6   | 7  | 3.36  | 1.029           | 1.1878           | 1.15477          | 58.33    | 59.27           |
| 9     | 3.31  |    | 1.014 | 1.0717          | 1.05690          | 75.00            | 67.48    |
| 11    | 3.36  |    | 1.030 | 1.1463          | 1.11259          | 91.67            | 68.84    |
| 5     | 3.48  |    | 1.066 | 1.2878          | 1.20807          | 36.36            | 49.49    |
| 7     | 3.32  |    | 1.018 | 1.1453          | 1.12505          | 50.91            | 56.89    |
| 9     | 3.35  |    | 1.026 | 1.1432          | 1.11423          | 65.45            | 60.94    |
Anastasiades et al (2022) continue that compression bars are optimised for buckling, rather than strength. The latter combined with the use of standard profile sections has as consequence that a fully stressed condition for each bar is impossible [1].

A first obvious difference between the FEMs and the MI’s is the resulting volume. From these, the ratio of the volume obtained from the FEMs, $V_{FEM}$, to the volume obtained from the MI’s, $V_{MI}$, can be calculated: $V_{FEM}/V_{MI}$. In a first attempt to correct $V_{MI}$ to a realistic volume, this ratio $V_{FEM}/V_{MI}$ can be plotted against the volume indicator $W$ to obtain a simple correction procedure, shown in Figure 1. Unfortunately, this results in a not very well fitting curve with coefficient of determination $R^2 = 0.4916$.

![Figure 1. the volume ratio plotted against the volume indicator for Warren trusses](image-url)
Another difference between the FEMs and the MI is their stress level. As explained earlier, there are several reasons why a fully stressed design is in practice not feasible. Hence, the stress level in the bars is rarely 100%. As this is different from the assumption of the MI, the weighted stress level of the FEMs, \( \sigma_{FEM} \), is also shown in Table 1 and is calculated as follows:

\[
\sigma_{FEM} = \sum \sigma_i \frac{V_i}{V_{tot}}
\]

With:
- \( \sigma_i \): stress level in component i
- \( V_i \): material volume of component i
- \( V_{tot} \): total material volume in the structure

The weighted stress level \( \sigma_{FEM} \) can be plotted against the volume correction \( V_{FEM}/V_{MI} \) as shown in Figure 2. Now, the result is a well-fitted curve with \( R^2 = 0.9025 \). Note that one deviant value had to be omitted to achieve this curve. This value is indicated in grey in Table 1. The value deviates in the sense that a lower volume is achieved than the one indicated by \( W \), and this combined with a fairly low stress level. The reason for this deviant value is luck, because it was, unlike the other FEMs, possible to highly optimise this structure for buckling with the available standard sections.

![Figure 2](image_url)

**Figure 2.** The stress level plotted against the volume ratio for Warren trusses

The curve fits well this time, but the issue is now that \( \sigma_{FEM} \) is an unknown value at the start of the conceptual design stage. Hence, an additional curve is needed to predict the achievable stress level \( \sigma_{FEM} \). Therefore, a factor that defines the trusses was sought. In general, a Warren truss is characterised by its span \( L \), its height \( H \) and its number of panels \( n \). Hence, a new dimensionless shape factor \( nL/H \) can be defined for each calculated truss. This shape factor can be found through \( W \), as it gives you the needed height and number of panels for the concerning Warren truss. The values for this new shape factor are shown in Table 1 and were plotted against \( \sigma_{FEM} \) in Figure 3. The result is again a well-fitted curve with \( R^2 = 0.9589 \).
Combining both curves, first the curve in Figure 3 and then the curve in Figure 2, allows to obtain the correction factor $V_{\text{FEM}}/V_{\text{MI}}$ to correct the volume $V_{\text{MI}}$ obtained from $W$ into a realistic one. However, some remarks need to be considered. Firstly, the 36 bridges were designed in 2D, both with the MIs and in the FEMs. As such, only local buckling of the trusses’ components was taken into account. Additionally, imperfections that may affect the buckling behaviour were neglected. Secondly, both the MIs and the FEMs only considered a vertical service load. Hence, also the influence of wind loads on the values for the volume and stress level obtained from the FEMs should be investigated. When these issues are investigated further, it will be important to broaden the optimisation methodology to other truss types and to other structural typologies, e.g. arched, suspension and cable-stayed bridges.

4. Conclusion
Developing a CE oriented design methodology for pedestrian and cycling bridges that incorporates the CE’s 4R principle is key. In addition, the ISO20887 advocates that advances in circularity should be measurable and measured. A CE oriented design strategy that coincides with a CI will therefore be key. Also this CI will need to incorporate the 4R principle. However, the first R of Reduce is generally neglected. In order to measure Reduce, this paper proposes a methodology to make a realistic prediction of the material requirement for a Warren truss bridge structure based on the theory of the MIs. A total of 32 Warren trusses with different spans, heights and number of panels was obtained through the MIs and checked through FEMs. This pointed out that there is a discrepancy between the volumes obtained through both methods. The main reason is that the MIs assume that all structural components are fully stressed. In practice, this is nearly impossible as normally standard profile sections are used. Thus, on the one hand there is a limited number of profile sections from which one can choose. On the other hand, compression elements are optimised for buckling, rather than stress. Consequently, the FEMs indicate that a higher material volume is needed. In order to correct the volume obtained with the MIs into the volume obtained with the FEMs, two correction curves are proposed. The first curve plots a newly defined shape factor $nL/H$ to characterise the Warren trusses against the weighted stress level $\sigma_{\text{FEM}}$ in the FEM. The second curve plots the volume ratio $V_{\text{FEM}}/V_{\text{MI}}$ against the stress level $\sigma_{\text{FEM}}$. Combining both curves allows to obtain the correction factor $V_{\text{FEM}}/V_{\text{MI}}$ to correct the volume $V_{\text{MI}}$ into a realistic one.

A limitation of this study is that the trusses were designed in 2D. Hence, only local buckling of the trusses’ components was taken into account. Future work will have to research the effect of global buckling phenomena on $W$. An additional limitation is that only vertical loads are considered in the MIs.

![Figure 3](image-url)
as well as the FEMs. Hence, also the influence of wind loads needs to be investigated. Lastly, the current study only considered Warren truss bridges. It will thus be important to broaden the optimisation methodology to other truss types and to other structural typologies, e.g. arched, suspension and cable-stayed bridges.

To conclude, this study proposes a strategy to predict the needed material volume for a bridge structure. It is a first step in the development of a methodology to measure the material efficiency of a structure, thus the first R of the CE, Reduce.

References
[1] Anastasiades K, Lambrechts T, Mennes J, Audenaert A and Blom J 2022 Formalising the R of Reduce in a Circular Economy Oriented Design Methodology for Pedestrian and Cycling Bridges J 5 35–50
[2] Anastasiades K, Blom J, Buyle M and Audenaert A 2020 Translating the circular economy to bridge construction: Lessons learnt from a critical literature review Renew. Sustain. Energy Rev. 117
[3] International Organisation for Standardisation 2020 Sustainability in Buildings and Civil Engineering Works - Design for disassembly and adaptability - Principles, Requirements and Guidance (Geneva)
[4] Ellen MacArthur Foundation 2022 Material Circularity Indicator (MCI)
[5] Khadim N, Agliata R, Marino A, Thaheem M J and Mollo L 2022 Critical review of nano and micro-level building circularity indicators and frameworks J. Clean. Prod. 357
[6] Anastasiades K, Van Hul K, Audenaert A and Blom J 2020 A Circularity Indicator for Pedestrian Bridges : A Work in Progress Proceedings of the Winter Global Business Conference ed G Vlašić, Z Krupka and J Pavičić pp 8–22
[7] CEN 2002 Eurocode: Basis of Structural Design (Brussels)
[8] Vandenbergh T and De Wilde W P 2010 A review on conceptual design with morphological indicators Int. J. Struct. Eng. 1 280–98
[9] Hamidavi T, Abrishami S and Hosseini M R 2020 Towards intelligent structural design of buildings: A BIM-based solution J. Build. Eng. 32
[10] Vandenbergh T, De Wilde W P and Latteur P 2008 Optimisation at the conceptual design stage with morphological indicators: Design for strength or design for stiffness WIT Trans. Built Environ. 97 401–10
[11] Stangl T, Pribek M and Wartzack S 2014 Integration of structural optimization in the engineering design process Proceedings of International Design Conference, DESIGN 2014 pp 1989–98
[12] He L, Gilbert M, Johnson T and Pritchard T 2019 Conceptual design of AM components using layout and geometry optimization Comput. Math. with Appl. 78 2308–24
[13] Latteur P 2016 Éléments d’optimisation structurel Calculer une structure : de la théorie à l’exemple (Louvain-la-Neuve: L’Harmattan/Academia editors) pp 411–63
[14] Zalewski W and Kus S 1996 Shaping structures for least-weight Proceedings of the International Conference on Lightweight Structures in Civil Engineering
[15] Samyn P 1999 Etude comparée du volume et du déplacement de structures bidimensionnelles, sous charges verticales entre deux appuis, vers un outil d’évaluation et de prédimensionnement des structures (Université de Liège)
[16] Van Steirteghem J 2006 A contribution to the optimisation of structures using morphological indicators (Vrije Universiteit Brussel)
[17] Buildsoft 2021 Diamonds