



Article

Formalising the R of Reduce in a Circular Economy Oriented Design Methodology for Pedestrian and Cycling Bridges

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Abstract: The construction industry consumes over 32% of the annually excavated natural resources worldwide. Additionally, it is responsible for 25% of the annually generated solid waste. To become a more sustainable industry, a circular economy is necessary: resources are kept in use as long as possible, aiming to reduce and recirculate natural resources. In this paper, the investigation focuses on pedestrian truss bridges of the types Warren and Howe. Many pedestrian bridges currently find themselves in their end-of-life phase and most commonly these bridges are demolished and rebuilt, thus needing a lot of new materials and energy. The aim is thus first and foremost to reduce the amount of necessary new materials. For this reason, a design tool will be created, using the software ‘Matlab’, in which truss bridges can be evaluated and compared in the conceptual design stage. The tool is based on the theory of morphological indicators: the volume indicator, displacement indicator, buckling indicator and first natural frequency indicator. These allow a designer to determine the most material efficient Warren or Howe truss bridge design with user-defined constraints concerning deflection, load frequency, buckling and overall dimension. Subsequently, the tool was tested and compared to calculations made in the finite element modelling software Diamonds. In total, 72 steel bridge structures were tested. From these it could be concluded that the manual calculations in Diamonds in general confirmed the results obtained with the automated design tool based on morphological indicators. As such, it allows a designer to converge more quickly towards the best performing structure, thus saving time, materials, and corresponding costs and energy.

Keywords: circular economy; conceptual design; morphological indicators; structural optimisation; bridge construction



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1. Introduction

In the current linear economy, the excavation rate of non-renewable materials is alarming. If this trend continues, the annual extraction of non-renewable resources will reach 170–184 billion tonnes by 2050, which will quickly result in their depletion [1]. A way to limit the excavation is by changing from a linear economy model, where the idea is based on a ‘take, make and dispose’ model, to a circular economy (CE) model [2]. The essence of the CE can be brought back to the 4R’s—Reduce, Reuse, Recycle, Recover—signifying the desired order of the value retention of products and materials [3,4]. As such, the first step is always to ‘Reduce’ the amount of required material. This can be done by designing with material-efficiency in mind. Additionally, the product should be designed in a way that its components can be easily disassembled and ‘Reused’. Alternatively, the materials should be ‘Recycled’ when the components are not reusable anymore. Lastly, when the materials cannot be recycled, the embedded energy in the material should be ‘Recovered’ in heat and power plants. The latter is mostly reserved for the bioeconomy.

This study will focus on pedestrian bridges. Many concrete pedestrian bridges ranging from 30 to 50 years in age, presently need to be replaced as they reached their end-of-life phase and appear to be in a severe condition of disrepair [5–7]. This also corresponds to the typical design working life that is mentioned in e.g., the Eurocodes [8,9]. Typically, these bridges are not just being demolished, they are replaced by new ones. However, a CE oriented design methodology for pedestrian and cycling bridges is non-existent. Hence, a design methodology that incorporates the 4R principle needs to be developed. The R's Reuse and Recycle have been extensively researched, as they directly correspond to Design for Adaptability and Design for Disassembly (e.g., [10–15]). The R of Recover is covered in the bioeconomy. Yet, the first R of Reduce, the most important R in the CE, is generally neglected and severely underestimated. Even in the current Eurocodes there is no mention of structural optimisation. Traditionally, the engineer's role is to calculate the bridge structure according to the 3S principle: Strength, Stiffness, Stability. The aim is always to design the structure so it is fully stressed and stripped of all redundant material. Vandenberg and De Wilde explain that this is of great importance, because low material consumption limits the structure's energetic impact, and decreases procurement, transportation and construction costs. This thus lowers the environmental footprint and post-use waste, and leads to a more sustainable structure by and large [16]. However, engineers are usually involved in the design process after the architects have finished the conceptual design. This often leads to lots of additional design iterations in order to somewhat optimise the structural system [17–21]. Hence, engineers design an optimised structure for an architectural concept that may be far from ideal from a structural point of view. Unfortunately, less efficient structures require more material, even when they are designed to be fully stressed.

The calculation method for a structure is well defined, but the method for choosing the most optimal structural design is usually vague and subjective. Often, structural engineers generate conceptual designs based on intuitive knowledge and experience, which means that only few possible alternatives are considered [17,20].

A structural geometry can also be generated with computational methods like topology optimisation. This allows an engineer to obtain a lightweight design with maximum stiffness for a given set of boundary conditions [22]. However, this can be computationally expensive and often requires lots of post-processing in order to translate the generated morphology into a practical one [23]. Some studies also incorporate principles of life cycle assessment and life cycle costing analysis for the development of new optimisation and decision-making methodologies for the design of different structural members [24–30]. These optimisation and decision-making tools will then find the most optimal parameters—resulting in the lowest CO₂ emissions and economic costs—for a certain type of structural member. Hence, these optimisation tools allow to improve the sustainability of structural components, as they result in lower material consumption. However, they are not suitable for the optimisation of complete structural typologies.

For the optimisation of complete structures, the theory of the Morphological Indicators (MI) was developed as a means to formalise the search for the most efficient-fully stressed-structural typology in the conceptual design stage [31]. Considering the morphology of structures, it was in the work of Zalewski and Kus [32] that the link between the geometrical slenderness L/H and both the volume and displacement of trusses was demonstrated for the first time. This concept was developed further by Samyn [33] in a methodical study of the volume and displacement of structures. He also introduced the term 'MI'. Van Steirteghem defines MI as dimensionless numbers that represent a geometrical property or a physical performance of a structure which can be used as a design tool to optimise structures in the conceptual design stage [34]. In addition to Samyn's work, multiple MI have been developed such as the buckling indicator, self-weight indicator and the first natural frequency indicator. Where the choice of the structural typology used to be a guess based on experience, the idea of the MI is that they should easily allow to make a better guess, actually leading to material savings. However, the problem with these MI is that they

are all inter-connected and their practical application has become very complex. Hence, they are barely used.

The goal is to develop a CE oriented design methodology for pedestrian and cycling bridges. This paper optimises the application process of the MI by means of an automated algorithm. In doing so, the MI can become a standard procedure in the conceptual design stage in order to formalise material reduction in the envisaged design methodology.

In the subsequent sections, the applied method to construct the algorithm will be explained. Subsequently, the MI that will be incorporated in the algorithm and the actual algorithm are shown. Lastly, the algorithm is tested and discussed, followed by a conclusion and further research recommendations.

2. Conceptual Design According to Morphological Indicators

The MI are to be used in the conceptual design stage. They allow the optimisation of structures based on certain criteria. There are two kinds of MI: primary indicators and secondary indicators, which are both dimensionless. The secondary indicators represent the physical quantities: the quantity of material, the displacement, the rotation, the stresses, etc. Examples of primary indicators are the slenderness, the form coefficient, or the buckling indicator. Secondary indicators are implicitly dependent on one or more primary indicators. The most important secondary indicator is the volume indicator (W) [31].

Initially, the theory on MI only considered design for strength with the volume of used materials as the objective function. This strategy often resulted in a lightweight structure with a questionable lack of stiffness, which implicates a significant increase of material volume in the final design to meet the stiffness criteria [35,36]. Therefore, additional indicators like the indicators of buckling Ψ and displacement Δ were introduced, improving the results obtained with the volume indicator.

The indicator of volume W allows the designer to compare the necessary material volume for different structures. It is defined as follows: ‘The volume of a structure of identical shape with a unity span of 1 m, loaded with a unit force of 1 N with a material of allowable stress of 1 Pa’ [35,37]. In its most simple form, only considering design for strength with all elements fully stresses, thus ignoring buckling, the equation for the indicator of volume is: [34].

$$W = \frac{\sigma V}{FL} = \sum k_i \left(\frac{l_i}{L} \right) = \text{function} \left(\frac{L}{H} \right) \quad (1)$$

With:

- W the indicator of volume
- σ the allowable stress of the constituent material of the structure [N/m²]
- V the total volume of the structure [m³]
- F the total force acting upon the structure [N]
- L the span of the structure [m]
- l_i/L the ratio of the length of member i to the total length of the structure
- k_i the portion of the load F present in member i

The indicator of buckling Ψ [38], is developed to indicate the tendency to buckling of a compressed element in a structure. The higher Ψ , the higher the risk of buckling. The primary indicator Ψ should be used in combination with the secondary indicators like the indicator of volume W, the indicator of displacement Δ and the indicator of first natural frequency Θ . The indicator of buckling Ψ is defined as [35]:

$$\Psi = \frac{\mu \sigma L}{\sqrt{q E F}} \quad (2)$$

With:

- Ψ the indicator of buckling

- L the span
- q a form factor defining the cross section of the bars
- E the modulus of elasticity of the material
- σ the allowable stress to which at least one section is dimensioned
- F the total resultant force
- μ the proportion of the buckling length of the compression bars to their geometrical length, depending on the connection type

When the buckling indicator Ψ is considered, it is possible to take the buckling of the members into account. For this reason, the lengths l_i and member forces f_i need to be expressed as a function of the overall slenderness L/H . Latteur [31,38] illustrates in his work that with a given Ψ , a value L/H exists with a minimal value of W . This means the volume indicator is not only dependent on the slenderness L/H anymore but is also dependent on the buckling indicator Ψ . Latteur [38] shows that for every structure with a total length L , composed of a material which is fully stressed σ , loaded with a resultant force F working on elements i with a length l_i and following the Rankine buckling curve, W becomes:

$$W = \frac{\sigma}{FL} (V^{(T)} + V^{(C)}) = W^{(T)} + W^{(C)}$$

$$= \sum_{(T)} k_i \left(\frac{l_i}{L} \right) + \frac{1}{2} \sum_{(C)} k_i \left(\frac{l_i}{L} \right) \left(1 + \sqrt{1 + \frac{4}{\pi^2} \frac{\left(\frac{l_i}{L} \right)^2}{k_i} \Psi^2} \right) = \text{function} \left(\frac{L}{H}, \Psi \right) \quad (3)$$

This equation can be used for both Warren structures with an even and an odd number of panels. However, for both cases, the portion of loads, k_i , in the members i will be different. For more information about the theory behind the calculation of these portions of loads, one can consult the scientific literature on MI. The portion of loads k_i will be the same for an even and odd truss structure except for the middle panel, where the portion of loads in the diagonals will be 0 for a Warren truss with an odd number of panels.

The equation is divided into members subjected to tension and members subjected to compression. If $\Psi = 0$, i.e., when buckling in the members in compression is ignored, the same result is obtained as with Equation (1).

The displacement indicator compares the displacement of different truss structure systems. It is the maximum displacement of an isomorphic structure with a unit span of 1 m, with a material with a unit Young's modulus of 1 GPa and an allowable stress of 1 N/mm², subjected to a system load with a unit force of 1 N [35].

In its most simple form, considering only the slenderness L/H , thus ignoring buckling, the equation for the indicator of displacement is [31,34,38]:

$$\Delta = \frac{E \delta}{\sigma L} = \sum n_i \left(\frac{l_i}{L} \right) = \text{function} \left(\frac{L}{H} \right) \quad (4)$$

With:

- Δ the indicator of displacement
- E the modulus of elasticity of the used material [N/mm²]
- δ the maximum displacement of the structure [mm]
- σ the allowable stress of the material used for the structure [N/mm²]
- L the span of the structure [mm]
- l_i/L the ratio of the length of member i to the total length of the structure
- n_i the portion of the unitary force, applied in a node j , present in member i

When considering Ψ , it is possible to take the buckling of each member into account. First of all, not only the portion of loads k_i , but also the portion of unitary loads n_i need to

be addressed. When Δ is no longer solely dependent on L/H but also on Ψ , the equation for calculating the displacement indicator Δ for a Warren truss becomes [33,34,38]:

$$\Delta = \frac{E\delta}{\sigma L} = \sum_{(T)} n_i \left(\frac{l_i}{L} \right) + 2 \sum_{(C)} \frac{n_i (l_i/L)}{1 + \sqrt{1 + \frac{4}{\pi^2} \frac{(l_i/L)^2}{k_i} \Psi^2}} = \text{function} \left(\frac{L}{H}, \Psi \right) \quad (5)$$

Equation (5) can be used to calculate both even and uneven Warren trusses.

Until now, Latteur [38] and Samyn [33] introduced the volume and displacement indicator taking buckling into consideration. However, a structure optimised with respect to strength often does not meet the necessary stiffness requirements. Lightweight structures in which all components are optimised to be fully stressed may lack resistance to vibrations occurring during use. Therefore, it is necessary to extend the morphological indicators to include the natural frequencies of the structure. These should not coincide with the frequencies of the applied load. For this reason, the indicator of first natural frequency is introduced [34]:

$$\Theta = \frac{1}{\sqrt{\Delta}} = f \left(\frac{L}{H}, \Psi \right) \quad (6)$$

This indicator is directly linked with the displacement indicator Δ . Hence, it is also dependent on the buckling indicator Ψ .

The indicator of the first natural frequency is defined as “the natural frequency of a structure with a unit length ($L = 1$ m) composed of members working at a unit stress ($\sigma = 1$ Pa, $\beta = 1$) and with a unit Young’s modulus ($E = 1$ Pa) for which the ratio of the co-vibrating loads to the total load is equal to $z^* = 1$ in SLS” [17].

As apparent above, a hierarchy between W and Δ exists, as ‘design for strength’, i.e., the volume of material, is taken as the point of departure. Both Samyn [9] and Latteur [38] strive for the minimization of volume. Even though efficiency curves for Δ have been established, these are customarily used to verify afterwards if the displacement, i.e., the stiffness, does not exceed the normative constraints imposed by the design code. In addition, Van Steirteghem [34] proved that if buckling is considered, the displacements are smaller than when buckling is ignored. Both Samyn and Latteur proved that the slenderness optimised through the volume of material (W) is rarely equal to the slenderness that minimises the displacement (Δ). However, minimising Δ is only important to the extent that it does not exceed the normative criteria. When the indicator of first natural frequency is introduced in the optimisation, a constraint that considers the dynamic behaviour of the structure is added. Therefore, the general optimisation procedure can be formulated as follows:

$$\text{Minimise } W = f \left(\frac{L}{H}, \Psi \right)$$

$$\text{Subject to : } \Delta \leq \frac{E}{\sigma^*} x$$

$$f_i \neq f_{e,i}$$

where:

- σ^* ($\approx \sigma/1.40$) is the stress level in the structure in SLS
- f_i are the natural frequencies of the structure that must be adequately far from the excitation frequencies $f_{e,i}$ of the external load.

If this constraint is rewritten in an interval of first natural frequencies that should be avoided, in terms of the indicator of displacement, this interval will become [34]:

$$f_i \neq f_{e,i}$$

or

$$\frac{f_{e,i}}{(1 - \beta_3)} \frac{2\pi}{c_{cor}} \sqrt{\frac{z^* \beta \sigma L}{gE}} < \Theta = \frac{1}{\sqrt{\Delta}} < \frac{f_{e,i}}{(1 + \beta_3)} \frac{2\pi}{c_{cor}} \sqrt{\frac{z^* \beta \sigma L}{gE}} \quad (7)$$

or

$$\Delta \notin \left[\left(\frac{(1 - \beta_3) c_{cor}}{f_{e,i}} \right)^2 \frac{gE}{z^* \beta \sigma L}, \left(\frac{(1 + \beta_3) c_{cor}}{f_{e,i}} \right)^2 \frac{gE}{z^* \beta \sigma L} \right] \quad (8)$$

The parameter β_3 is used to define the safety interval around the first natural frequency of the structure. This constraint yields an interval on the slenderness determined by the indicator of displacement. The indicator of volume is not explicitly present in the constraint. However, the first concern is to limit the volume of material, meaning that the stress level is to be maximised. Thus, the indicator of volume is indirectly present in the formula.

3. Design of the Software

The morphological indicators, designed to be a simple conceptual design tool, have paradoxically grown into a complex system. Their practical use is therefore limited to non-existent. Hence, in this study the previously described morphological indicators will be programmed into an automated algorithm. The platform used to create the software is MATLAB [39], and more specifically the ‘app-designer’ function. The latter was chosen in order to increase the user-friendliness, taking into account the norm ISO 25010:2011 [40,41]. The aim is to create a user-friendly design tool which will determine the most optimal structure based on some user-defined constraints. The development of this tool needs to conform to the Eurocode ‘NBN EN 1991-2—part 2: traffic loads on bridges’ [42].

The design tool is divided into four sections: Home, Limits, Results and Advanced settings, as shown in Figures 1–4. Home is where the type of truss, the dimensions of the bridge, the material specifications and the loads acting upon the bridge can be defined. Limits is where the user can specify the constraints. The adjustable constraints are the pavement length, height, deflection and first natural frequency. Results is where the user determines if buckling needs to be considered, and where the result is calculated. The final tab, Advanced settings, is where the user is able to change parameters that in most cases would be a standard fixed value or to give certain values in a different form (e.g., displacement in mm instead of L/x). This prevents that the critical path to get a result, is cluttered with input options.

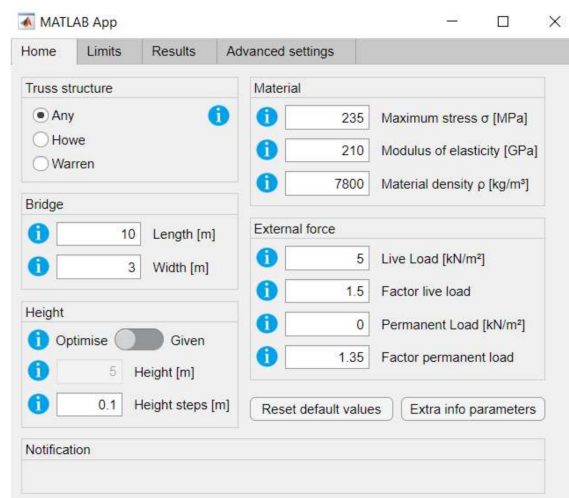
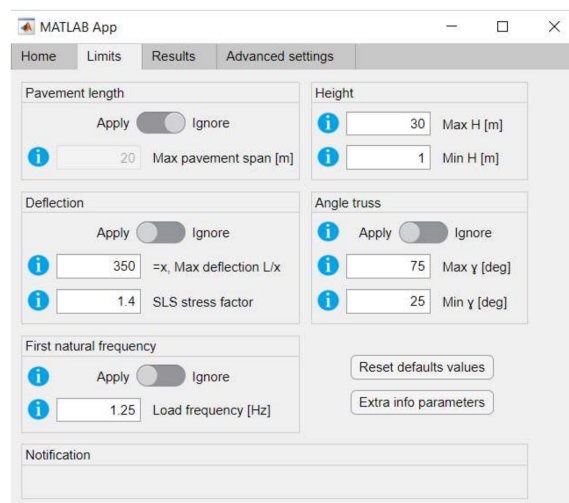


Figure 1. Software home tab.



MATLAB App

Home Limits Results Advanced settings

Pavement length

Apply ☐ Ignore

Max pavement span [m]

Height

Max H [m]

Min H [m]

Deflection

Apply ☐ Ignore

=x, Max deflection L/x

SLS stress factor

Angle truss

Apply ☐ Ignore

Max γ [deg]

Min γ [deg]

First natural frequency

Apply ☐ Ignore

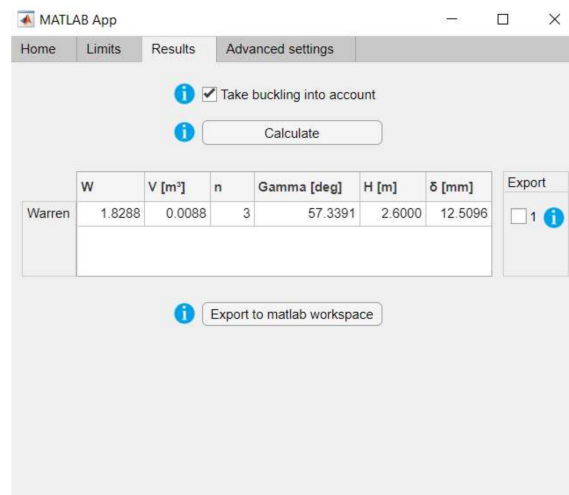
Load frequency [Hz]

Reset defaults values

Extra info parameters

Notification

Figure 2. Software limits tab.



MATLAB App

Home Limits Results Advanced settings

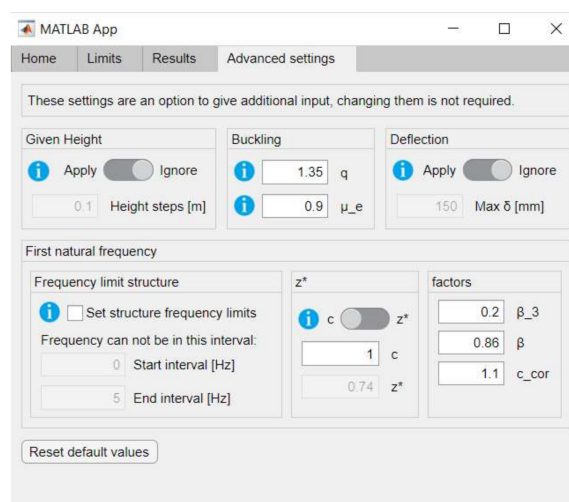
☒ Take buckling into account

Calculate

	W	V [m ²]	n	Gamma [deg]	H [m]	δ [mm]	Export
Warren	1.8288	0.0088	3	57.3391	2.6000	12.5096	<input type="checkbox"/> 1

Export to matlab workspace

Figure 3. Software results tab.



MATLAB App

Home Limits Results Advanced settings

These settings are an option to give additional input, changing them is not required.

Given Height

Apply ☐ Ignore

Height steps [m]

Buckling

q

μ_e

Deflection

Apply ☐ Ignore

Max δ [mm]

First natural frequency

Frequency limit structure

☐ Set structure frequency limits

Frequency can not be in this interval:

Start interval [Hz]

End interval [Hz]

z*

c

z*

factors

β_3

β

c_cor

Reset default values

Figure 4. Software advanced settings tab.

The result consists of six parameters: the volume indicator W , the volume V in cubic meters (derived from W), the number of panels n , the angle g that the first diagonal makes with the lower horizontal chord, the height H and the deflection d in millimetres. If the height is fixed there can be up to three results: the first is the optimal layout for the given height; the second is the absolute optimum with the optimal height; the third is the layout where the height is minimal but where the volume indicator is equal to or lower than that for the given height. If the optimal height is to be determined there will only be a single solution, the absolute optimum for the given span. The essential steps that the software runs through to calculate the result is depicted as a flowchart in Figures 5 and 6.

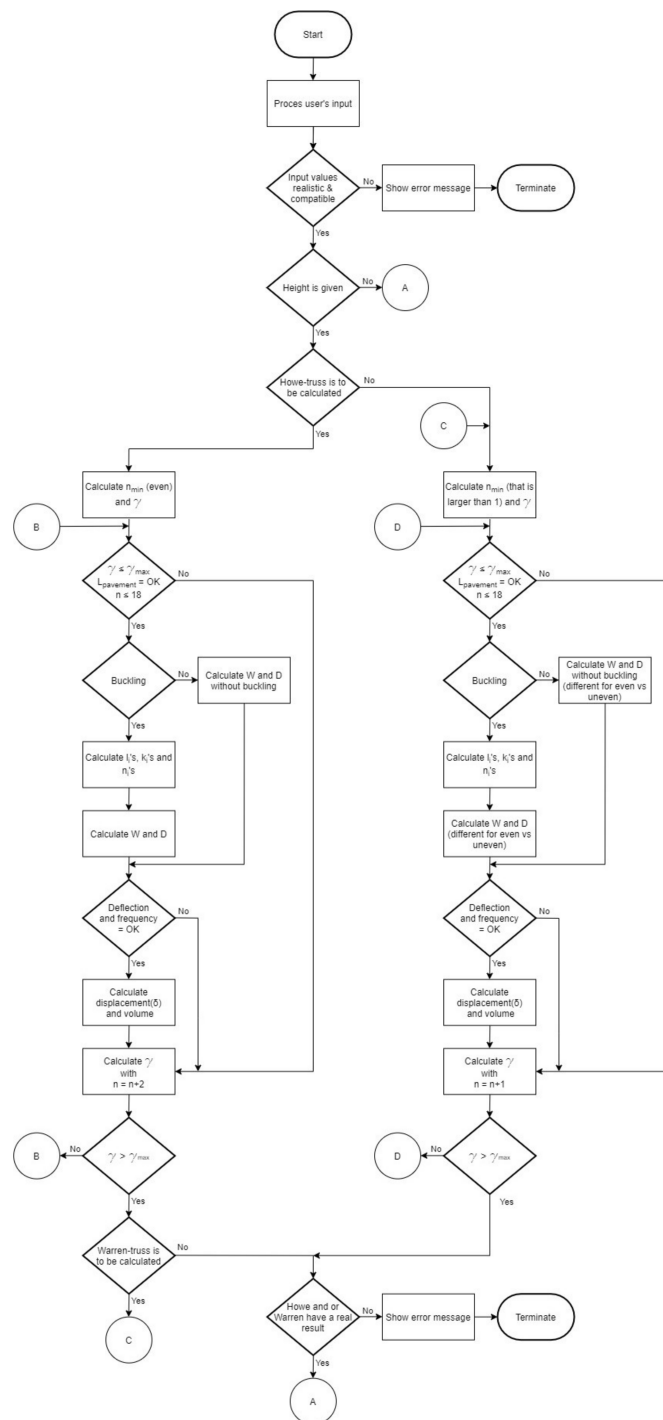


Figure 5. Flowchart software, part 1.

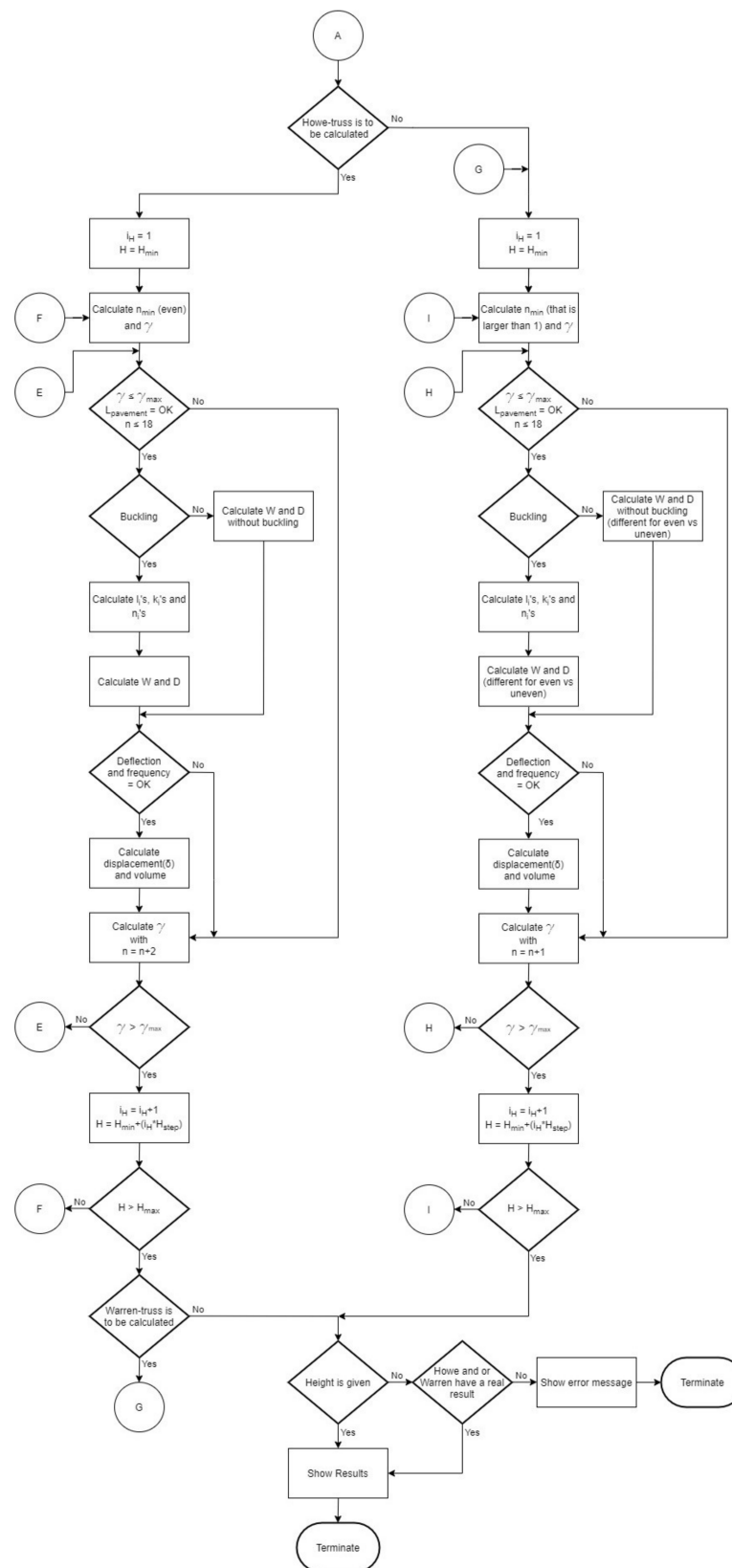


Figure 6. Flowchart software, part 2.

4. Results and Discussion

In order to check the tool's performance, a comparison is made using the finite element modelling software 'Diamonds' [43]. In this software, truss bridges are drawn with the same input parameters as the ones used in the design tool based on morphological indicators. This means that the bridges are drawn with the same span "L", height "H" and number of panels "n". Several bridge spans were tested, but some parameters were fixed: the bridge width is 3 m; the structural material is normal construction steel with a yield stress of 235 MPa, Young's modulus of 210 GPa and density of 7800 kg/m³; the service load on the bridge is 5 kN/m² with a safety factor of 1.5, both as prescribed in the Eurocode; the maximum vertical deformation is limited to L/350.

The aim is not to obtain the same volume as indicated in the developed design tool. Rather, the structural calculations in Diamonds serve as confirmation of the indicated most optimal structure according to the design tool. The results are shown in Tables 1 and 2. When reviewing the results, it can be concluded that both Diamonds and the design tool follow the same trend, independent of the span-to-height ratio. The most optimal result according to the software tool is indicated in bold, the results in Diamonds that deviate are highlighted in yellow. There are some important remarks to be made. The morphological indicators do not consider actual cross sections for the different bars in the truss. They consider a form factor which is equal for all bars, and which expresses the efficiency of the cross section. In the software tool, a highly efficient cross section is assumed. One can understand that in a truss, where the internal forces are all normal forces, this form factor is only important for bars in compression, thus bars susceptible to buckling. Additionally, regardless of the bars' susceptibility to buckling, the morphological indicators assume that all bars are dimensioned so that they are all fully stressed, 100%. When this was translated to a realistic structure in Diamonds, only standard profile sections were used, corresponding to the considered form factor. Thus, for all bars in compression, profiles of type CHS with standard dimensions available in the European Union and the United Kingdom were chosen. The diagonals in tension were appointed L-shaped sections, because these are available in very small sizes and can thus approximate a fully stressed state. For the bars in the lower beam of the truss, it was chosen to use standard I-shaped sections, because the lower bars are also very susceptible to bending considering their self-weight. Some examples are shown in Figures 7 and 8.

The use of standard profile sections implicates that there is only a limited number of profiles from which one can choose. This means that a fully stressed condition of each bar is not possible, because there may not be a standard profile section with the necessary dimensions to reach this fully stressed state. This is especially the case for compression bars, as these are optimised for buckling and will rarely be fully stressed. Additionally, for these compression bars it may even be that there is no standard profile section with the necessary dimensions to reach a 100% optimisation for buckling, again reducing the optimisation rate. These remarks are important, because they explain why the results in Diamonds sometimes deviate from the results obtained with the design tool. Nonetheless, the best performing structures according to the design tool were mostly confirmed in Diamonds. The design tool based on the morphological indicators thus proves to be useful in the conceptual design stage. It allows an engineer to converge more quickly towards the best performing structure, thus saving time, materials, and corresponding costs and energy. However, it is important to stress once again that this cannot be decoupled from an earlier involvement of engineers, preferably already in the conceptual design stage.

Table 1. Warren trusses (The most optimal result according to the software tool is indicated in bold, the results in Diamonds that deviate are highlighted in yellow).

Input		Output					Diamonds
L [m]	H [m]	n	γ [°]	W	V [m ³]	δ [mm]	V [m ³]
20	4	2	38.7	2.62	0.050	21.7	0.0793
		3	50.2	2.29	0.044	18.1	0.0544
		5	63.4	2.31	0.044	23.6	0.0547
	5	2	45.0	2.50	0.048	18.7	0.075
		3	56.3	2.23	0.043	15.8	0.057
		5	68.2	2.45	0.047	21.8	0.061
	6	2	50.2	2.50	0.048	16.9	0.0740
		3	60.9	2.28	0.044	14.7	0.0575
		5	71.6	2.71	0.052	21.2	0.0699
40	6	5	56.3	2.80	0.215	51.4	0.2473
		7	64.5	2.77	0.212	59.5	0.2494
		9	69.7	2.78	0.220	67.1	0.2566
	7	3	46.4	2.93	0.224	37.1	0.3045
		5	60.3	2.86	0.212	46.8	0.2468
		7	67.8	2.83	0.217	55.4	0.2560
	8	3	50.2	2.84	0.218	33.8	0.2935
		5	63.4	2.80	0.214	43.9	0.2614
		7	70.3	2.97	0.228	52.9	0.2639
60	7	7	58.5	3.14	0.541	99.8	0.5942
		9	64.5	3.10	0.534	109.9	0.6174
		11	68.7	3.15	0.542	119.4	0.5873
	8.4	6	59.2	3.17	0.546	89.7	0.5940
		7	63.0	3.07	0.529	88.8	0.5778
		9	68.4	3.12	0.538	99.5	0.6016
	10	3	45.0	3.40	0.587	55.7	0.9225
		5	59.0	3.12	0.537	69.3	0.6163
		7	66.8	3.13	0.540	81.3	0.5305
80	8	9	60.9	3.38	1.036	157.5	1.1215
		11	65.6	3.36	1.030	169.5	1.0951
		13	69.0	3.50	1.043	180.8	1.1287
	9.6	7	59.2	3.36	1.029	126.5	1.1878
		9	65.2	3.31	1.014	139.7	1.0717
		11	69.3	3.36	1.030	152.4	1.1463
	11	5	54.0	3.48	1.066	101.6	1.2878
		7	62.5	3.32	1.018	116.1	1.1453
		9	68.0	3.35	1.026	129.8	1.1432

Table 2. Howe trusses (The most optimal result according to the software tool is indicated in bold, the results in Diamonds that deviate are highlighted in yellow).

Input		Output					Diamonds
L [m]	H [m]	n	γ [°]	W	V [m ³]	δ [mm]	V [m ³]
20	2	8	38.7	3.04	0.058	45.6	0.0640
		10	45.0	2.98	0.057	47.9	0.0658
		12	50.2	2.98	0.057	50.2	0.0647
	3	6	42.0	2.82	0.054	31.5	0.0634
		8	50.2	2.78	0.053	34.6	0.0624
		10	56.3	2.85	0.055	37.9	0.0653
	4	4	38.7	2.93	0.056	23.4	0.0678
		6	50.2	2.83	0.054	26.5	0.0637
		8	58.0	2.95	0.056	30.5	0.0723
40	4	10	45.0	3.34	0.256	89.6	0.2889
		12	50.2	3.32	0.254	94.5	0.2781
		14	54.5	3.34	0.256	99.4	0.2984
	5	8	45.0	3.28	0.251	71.8	0.2748
		10	51.3	3.25	0.249	77.4	0.2623
		12	56.3	3.29	0.252	83.1	0.2669
	6	6	42.0	3.37	0.259	58.4	0.2776
		8	50.2	3.27	0.251	64.1	0.2806
		10	56.3	3.32	0.254	70.5	0.2860
60	5	12	45.0	3.73	0.643	155.2	0.7085
		14	49.4	3.69	0.637	161.8	0.6974
		16	53.1	3.70	0.638	168.2	0.7141
	6.6	10	47.7	3.58	0.617	120.6	0.6568
		12	52.9	3.56	0.614	128.4	0.6607
		14	57.0	3.61	0.622	136.2	0.6975
	8	8	46.8	3.63	0.626	98.9	0.6669
		10	53.1	3.60	0.620	107.3	0.6844
		12	58.0	3.66	0.631	116.1	0.6826
80	7	12	46.4	3.90	1.194	193.9	1.2908
		14	50.8	3.85	1.181	203.0	1.3113
		16	54.5	3.86	1.183	211.9	1.3302
	8.5	10	46.7	3.86	1.181	159.8	1.2701
		12	51.9	3.81	1.166	169.8	1.2658
		14	56.1	3.83	1.173	179.9	1.3017
	10	8	45.0	3.94	1.208	133.5	1.3066
		10	51.3	3.85	1.180	144.0	1.2865
		12	56.3	3.87	1.187	155.1	1.3014

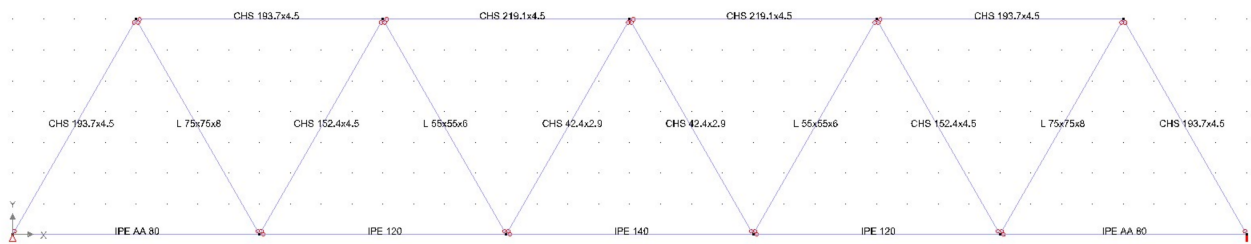


Figure 7. Warren truss, span $L = 40$ m, height $H = 7$ m, number of panels $n = 5$, optimal standard sections are indicated.

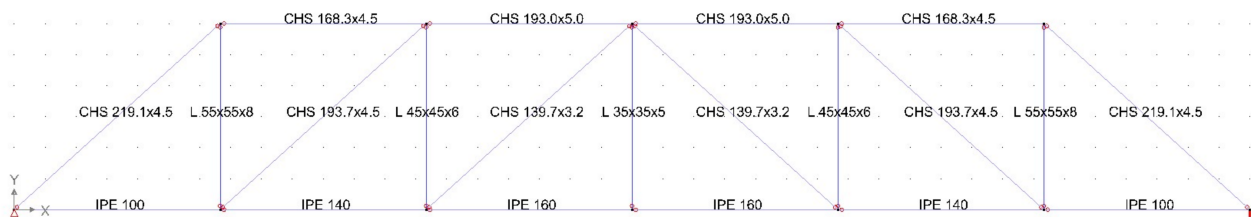


Figure 8. Howe truss, span $L = 40$ m, height $H = 6$ m, number of panels $n = 6$, optimal standard sections are indicated.

In this study, only pedestrian bridges were considered. However, the design tool based on morphological indicators can also be used when designing heavier bridge structures for regular traffic or trains. The major difference in the conceptual design stage is the increased load that needs to be considered.

The calculations of the 72 bridges were executed in a 2D design space, both in the design tool based on the morphological indicators and in Diamonds. This means that only local buckling of truss components was considered, while global buckling of the trusses was neglected. Additionally, imperfections that could affect the trusses' susceptibility to buckling were not considered. Tomei et al. investigated these buckling phenomena for grid shell structures [44]. Their research may serve as a starting point for a future investigation of the effect of global buckling phenomena on W.

The major limitation of the design tool in its current form is that it only considers Warren and Howe truss bridges. In the future, other types of structures should be integrated in the software tool as well. Important bridge typologies to be considered are arch bridges, suspension bridges and cable-stayed bridges.

Additionally, the reuse of components in the end-of-life stage of a construction not only corresponds to DfA and DfD, but also to standardisation. In this sense, the use of standard profile sections is a start, but in order to enable the reuse of components, also the standardisation of their lengths becomes important [45] whilst maintaining a balance between architectural freedom and standardisation [3]. Hence, another challenge for improving the design tool will be to incorporate standardisation to improve the applicability and concreteness of the conceptual design results.

Another parameter that can be implemented is a parameter for non-homogenous materials, as the software tool can only work with homogenous materials. Finally, higher frequencies can be implemented in the software as well to take into account other types of external frequencies, such as wind and earthquakes.

5. Conclusions

The goal is to develop a CE oriented design methodology for pedestrian and cycling bridges, a design methodology that incorporates the 4R principle. The R's of Reuse and Recycle have been extensively researched. The R of Recover is covered in the bioeconomy. Yet, the first R of Reduce, the most important R in the CE, is generally neglected and

severely underestimated. This paper optimises the application process of the MI by means of an automated algorithm. This developed design tool allows the user to quickly obtain the best structural typology, Warren or Howe, to be used for a given span. The user can also introduce additional boundary conditions, e.g., height, number of panels, fixed typology (Warren or Howe), etc. This allows the user to find alternative, but sub-optimal solutions. The design tool was tested and compared to calculations made in the FEM software Diamonds. In total, 72 steel bridge structures were tested. From these it could be concluded that the manual calculations in Diamonds mostly confirmed the results obtained with the design tool based on morphological indicators. However, some important remarks are to be considered. The theory of morphological indicators starts with the assumption that all components in a structure are dimensioned so they are fully stressed, 100%. In reality, this is very difficult to achieve as usually standard profile sections are used. This means there is a limited number of sections from which the designer can choose. Hence, especially for compression elements, the profile section is optimised for buckling, rather than stress. As a result, the calculations in Diamonds result in higher material volumes.

Important to note is that only local buckling of truss components was considered in this study. In future work, the effect of global buckling phenomena on W can be investigated.

In its current form, the design tool only considers Warren and Howe truss bridges. The most important challenge in the further development of the design tool is therefore to integrate other types of structures. Important bridge typologies to be considered are arch bridges, suspension bridges and cable-stayed bridges. Another challenge for improving the design tool will be to incorporate standardisation to improve the applicability and concreteness of the conceptual design results, and this whilst maintaining a balance between architectural freedom and standardisation.

To conclude, the design tool based on the morphological indicators proves to be useful in the conceptual design stage. It allows a designer to converge more quickly towards the best performing structure by automating the selection of the optimal structural typology, thus saving time, materials, and corresponding costs and energy. Hence, it allows the R of Reduce to be formalised in the CE oriented design methodology.

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Abbreviations

3S	Strength, Stiffness, Stability
4R's	Reduce, Reuse, Recycle, Recover
A	section area
B	width of the bridge
c_{cor}	correction factor
CE	Circular Economy
CHS	Circular Hollow Sections
DfA	Design for Adaptability
DfD	Design for Disassembly/Deconstruction
E	modulus of elasticity
$f_{e,i}$	excitation frequencies of the external load
f_i	natural frequencies of the structure
f_1	the first natural frequency of the structure
F	total resultant Force
FD*	co-vibrating load

FEM	Finite Element Modelling
g	gravitational acceleration
GPa	GigaPascal
H	Height of a truss
i	the index of an element
I	second moment of inertia
j	the index of a node
k	static stiffness
k_i	portion of load F present in member i
kN	kiloNewton
l_i	length of member I [m]
L	span of a truss
m	meter
mm	millimeter
MI	Morphological Indicator(s)
MPa	MegaPascal
n	number of panels of a truss
n_i	the portion of the unitary force, applied in node j, present in member i
Pa	Pascal
q	formfactor
q_{fk}	standard uniform characteristic load for pedestrian found in 'NBN EN 1991-2—part 2'
SLS	Serviceability Limit State
ULS	Ultimate Limit State
V	Volume
$V^{(T)}$	Volume of the members in tension
$V^{(C)}$	Volume of the members in compression
W	volume indicator
$W^{(T)}$	morphological indicator of volume of the members in tension
$W^{(C)}$	morphological indicator of volume of the members in compression
z^*	ratio of the co-vibrating load in service limit state to the total load in ultimate limit state
β	parameter for the stress level in the structure in the calculation of the displacement and first natural frequency indicators
β_3	parameter to define the safety interval around the first natural frequency of the structure
δ	the maximum displacement in the middle of the truss
Δ	morphological indicator of displacement
Θ	morphological indicator of the first natural frequency
μ	proportion of the buckling length of compression bars over their geometrical length, depending on its connection type
σ	allowable stress
σ^*	stress level in the structure
Ψ	morphological indicator of buckling

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