

25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark

## Sustainability tool to optimise material quantities of steel in the construction industry

Bernardino D'Amico<sup>a,c,\*</sup>, Francesco Pomponi<sup>b,c</sup>

<sup>a</sup>CTE, 10 Colinton Road, Edinburgh, EH10 5DT, UK

<sup>b</sup>ISC, 42 Colinton Road, Edinburgh, EH10 5BT, UK

<sup>c</sup>School of Engineering and the Built Environment, Edinburgh Napier University, UK

\* Corresponding author. Tel.: +44 131 455 2540; E-mail address: B.D'Amico@napier.ac.uk

### Abstract

The steel industry is arguably one of the most pollutant manufacturing sectors. The vast majority of steel produced worldwide is employed by the construction industry, mostly under the form of profile members for structural use, and it is primarily utilized in framed building structures. Even a small reduction of the steel amount currently used for building structures would therefore be beneficial, in terms of environmental impacts. This paper presents the findings from funded research, aiming to provide design practitioners with an effective optimisation tool to facilitate more material-efficient structural frames to be designed, hence allowing the design community to play an active role in the ongoing 'battle' to mitigate the environmental impacts linked to the construction sector. Given a small set of required input parameters, the developed tool consents to generate a wide range of (geometrically and topologically) different steel frame designs, based on optimised cross-sectional steel profiles. Overall measures of the steel mass quantities, associated with the optimised steel frame design, are then computed and outputted. In this way, the user can quantify, in an early phase of the design process, how much a chosen frame layout will affect the structural mass of the building, therefore having a design tool to explore alternative structural layout solutions, based on the range of building's shapes limitedly to the particular project at hand.

© 2017 The Authors. Published by Elsevier B.V.

Peer-review under responsibility of the scientific committee of the 25th CIRP Life Cycle Engineering (LCE) Conference.

*Keywords:* Steel Industry; Structural Design; Material Optimisation, Resource Efficiency, Assessment Tool.

### 1. Introduction

Among the range of human activities, the construction of buildings is among those with greatest environmental impacts [1, 2, 3]. From a global scale point of view, the building construction is one of the most energy-intensive production sectors; it is responsible for a great share of total carbon emissions, and waste generation. Changes to the status quo have been solicited in the last decades, driven from different sides of the wider society, and emission's reduction targets have been put in place by governments, at both national and international levels. The main strategic objective of most policies has been focused, historically, on reducing the

operational impacts of buildings, thus ignoring the embodied-related environmental impacts. As buildings become more efficient to manage, maintain and operate, the embodied part will account for a greater percentage of the building whole-life impacts. Optimisation approaches aimed at environmental impact reduction do exist [4] but a focus on the structural system is missing. Structures have been shown to be the building part responsible for the greatest share of embodied externalities, especially when steel is the structural material of choice [5]. The steel industry accounts for roughly 2.5 Gt of carbon dioxide (CO<sub>2</sub>) emission [6] representing about 25% of the total global CO<sub>2</sub> emissions. As pointed out by [7], nearly half of that steel is used in building structures, mostly under

the form of profile members for structural use (i.e. beams, columns, plates, etc.) and it is primarily utilized in framed building structures. Even a small reduction of the steel amount currently used for building structures would therefore be beneficial for the environment.

### 1.1. Environmental benefit of reducing structural steel mass.

The ultimate function of a building structure is to resist the system of actions (i.e. loads, imposed displacements, etc.) and meet the serviceability requirements associated with the building for which it has been designed. Indeed, there may be situations in which the structural mass has additional non-structural benefits to the building system as a whole —let mention for instance, the increase of thermal insulation associated with a thickness increase of masonry walls or cross-laminated-timber walls. Limiting however the discussion to steel framed structures, it is out of doubt that, for a given building project, a reduction of the overall structural mass will certainly correspond to a reduction of the environmental impacts linked to that building. A simple life cycle assessment of 1 kg of structural steel has been carried out to show the environmental benefits of reducing material masses. The LCA is based on the TC350 standards [8] to assess the sustainability of construction works, and accounts for the following stages:

- A1-A3
- A4
- A5
- C1-C4

Data have been selected, where available, from within ecoinvent 3 (allocation default database) [9]. This has not been possible for the data related to the C stage, which were missing in ecoinvent. Therefore, for this particular stage, data were taken from [10]. Academics and practitioners should strive – whenever possible – to use context-specific data to avoid generalization errors in their LCAs. It should be noted that activities related to the use stage (i.e. maintenance) have been omitted as they hardly apply to the case of framed steel structures. The impact assessment method used is CML Baseline v4.4 [11]. Table 1 shows the results of the LCA across the environmental impact categories included in the method mentioned above.

**Table 1:** LCA of 1 kg of structural steel.

Impact category	Ref. unit	Result
Acidification potential - average Europe	kg SO <sub>2</sub> eq.	0.071154
Climate change – GWP100	kg CO <sub>2</sub> eq.	11.13592
Depletion of abiotic resources, ultimate reserves	kg antimony eq.	0.000536
Depletion of abiotic resources, fossil fuels	MJ	117.9142
Eutrophication	kg PO <sub>4</sub> eq.	0.017546
Human, freshwater and marine toxicity	kg 1,4-C <sub>6</sub> H <sub>4</sub> C <sub>12</sub> eq.	16350.53
Ozone layer depletion	kg CFC-11 eq.	4.43E-07
Photochemical oxidation	kg C <sub>2</sub> H <sub>4</sub> eq.	0.003533
Terrestrial ecotoxicity	Kg 1,4-C <sub>6</sub> H <sub>4</sub> C <sub>12</sub> eq.	0.091483

### 1.2. Structural optimisation

Previous research [12] has shown that, based on current design practice, the average cross-section, of steel members employed in frame construction, is over-dimensioned in most cases, and it was also found that an overall steel mass reduction of up to 36% could be achieved “...with no loss in safety or service.” [13], if an optimisation-oriented approach were to be employed by the structural designers.

The general explanation, more often claimed to justify such overuse of structural material, is termed ‘rationalisation’ [13], which can be briefly summarised in here as the need to minimise the overall number of section profiles and maximise repetition of same-size members within a project. Allegedly, this would allow to bring down procurement costs, and other costs associated with both design and construction labour activities. As suggested in [12] rationalisation can be reduced in (at least) two ways:

- Increasing the time engineers dedicate to design.
- Increase the use of optimisation software within design practice of structural steelworks.

The main aim of this research work is to provide design practitioners with an effective optimisation tool to facilitate more material-efficient structural steel frames to be designed, eventually allowing the design community to play an active role to help mitigate the environmental impacts linked to the construction and steel industry sectors.

## 2. Minimizing members’ area section

Despite the continuously growing academic body of work in the realm of optimisation techniques applied to structural design, expert knowledge is needed to translate these methods into practical tool, usable by the busy engineers. A design engineer, who is responsibly (or forcibly) aware, of the indirect impact design practice can have on the environment, is likely to operate within a tight timeframe and budget. For this reason, the tool described in here has been built based on existing optimisation techniques, but combining them in a novel way, which enables to overcome the abovementioned constraints inherent to the design practice environment. In particular, the tool is aimed at an early design stage, when the potential for structural mass and environmental impact reduction is greatest [14].

Before describing the tool functioning, it is useful to make a distinction between the two construction methods used by engineers when designing steel frames. Namely, “simple” frame and “continuous” construction. In “simple” frames, nominally pinned connections are assumed, therefore only axial forces can be transferred from the floor system to the supporting columns, and no bending moment is carried between surrounding beams. A practical consequence is that the floor system, of primary and secondary beams for simple frame construction, can be designed (and optimised) independently from the bearing system of columns and bracings, which allows a sequential optimisation approach to be employed.

## 2.1. Input parameters

In order to run the tool, a set of input parameters must be specified by the user in order to provide information on the loading system that the structure is required to withstand and the structural geometry and topology:

- Primary span length [mm]
- Secondary span length [mm]
- Maximum (allowable) span of the floor slab [mm]
- Floor height [mm]
- N. of bays along the primary grid direction
- N. of bays along the secondary grid direction
- N of floors
- Wind pressure load [kN/m<sup>2</sup>]
- Imposed floor load [kN/m<sup>2</sup>]
- Permanent line-load of the building envelope walls [kN/m]
- Floor slab's self-weight [kN/m<sup>2</sup>]
- Floor load due to finishes, ceiling/services and partitions [kN/m<sup>2</sup>]

## 2.2. Beams

In order to minimise the cross-sectional area of steel members subject to bending (i.e. beams), the member's resistance against bending ( $M_{c,Rd}$ ), lateral torsional buckling resistance ( $M_{b,Rd}$ ) and shear resistance ( $V_{c,Rd}$ ), as well as the member deflection against the allowable serviceability limit ( $L_y/360$ ) must be all checked [15]. Let express in here the ratio between the design effect (indicated with the subscript “Ed”) and the design resistance (indicated with the subscript “Rd”):

$$\frac{M_{Ed}}{M_{c,Rd}} - 1 \leq 0 \quad ; \quad \frac{M_{Ed}}{M_{b,Rd}} - 1 \leq 0 \quad (1)$$

$$\frac{V_{Ed}}{V_{c,Rd}} - 1 \leq 0 \quad ; \quad \frac{\delta_{Ed}}{L_y / 360} - 1 \leq 0$$

Let assume to have a catalogue of cross-section profiles to choose from and we represent it as a list  $\mathbf{t}$ . If all of the available section profiles within  $\mathbf{t}$  are ordered in ascending order, according to their mass per unit length: a Direct Search approach can be employed to determine the optimal profile designation. Starting from the first item within  $\mathbf{t}$ , the algorithm checks whether Eqs. (1) are fulfilled: if not, it means the section is too weak or too flexible, therefore it passes on checking the next item, and so on until the inequalities stated in Eqs. (1) are all met. The section designation eventually found is the optimal one, because all remaining unchecked items will have greater mass per length unit. This is the reason why all items in  $\mathbf{t}$  must be ordered in ascending order according to their mass/unit-length.

## 2.3. Columns and bracings

Once the floor system optimisation is completed, the following step is to compute the optimal cross-sectional area for columns and bracings, therefore (as for beams) the

corresponding axial reaction forces must be determined, which requires a numerical method of analysis. Based on the user-provided geometrical and topological input parameters, a 3-dimensional model of the frame can be built, and a linear-elastic analysis performed via Direct Stiffness Method (DSM) [16], which involves solving a system of linear equations:

$$\bar{f} = \tilde{K} \cdot \bar{x} \quad (2)$$

In which  $K$  is a square matrix,  $x$  is the vector-list of unknown nodal displacements, and  $f$  is the vector-list of applied nodal forces, derived from the input load values described in section 2.1. Magnitude and orientation of the applied point load will depend on the node location and load combination under analysis. One permanent load case, one imposed floor load case and eight wind load cases (each oriented along a different direction) are considered in here. These ten load cases are combined together, obtaining 17 load combinations in total. For each load combinations, the system of Eqs. (2) is solved for  $x$ :

$$\bar{x} = \tilde{K}^{-1} \cdot \bar{f} \quad (2)$$

Therefore obtaining the updated position of each node, which in turn gives the shortening/elongation of each column/bracing element, and eventually, the corresponding axial design force  $N_{Ed}$ . As for beams, each column and bracing is then verified against compressive buckling and tensile stress according the design standards [15]:

$$\frac{N_{Ed}}{N_{Rd}} - 1 \leq 0 \quad (3)$$

The exact same Direct Search procedure, described in section 2.2 applies in here to minimise the section area of each bracing and column. Nonetheless, due to the static indeterminacy of the frame system, the reaction force values—upon which optimal column and bracing area section are derived—are sensitive to the axial stiffness term ( $EA/L$ ) initially set to initialise the DSM analyses. A local search procedure is thus employed in here to get round this problem, by iteratively running DSM analyses in which the (columns and bracings) cross-sectional area obtained as output of the (n-1)<sup>th</sup> iteration is used to run the set of analyses at the n<sup>th</sup> iteration. The iterative procedure is eventually stopped according to a given convergence criteria, as for instance, when the difference between total steel mass outputs, obtained from two consecutive iterations, is smaller than a given threshold value:

$$\|T_{mass}^n - T_{mass}^{n-1}\| \leq \gamma T_{mass}^{n-1} \quad (4)$$

where:  $0 < \gamma < 1$ . For  $\gamma = 0.001$  for instance, two to three iterations are usually required for the algorithm to converge to a solution.

### 2.4. Tool's limitations

The Parametric-based tool described is limited to designs of steel frames having a rectangular layout plan, and with constant span lengths. Furthermore, the Eurocode-based verification equations taken into account in here: Eqs (1, 3) are usually checked for preliminary member sizing, whereas further verifications, not considered in here, are carried out as the structural design develops, and further refinements of the members' cross-section may occur. Let remind that the main aim of this tool is not to generate detailed structural designs. Rather, it should be seen as a supporting tool for decision-making at an early phase of the design process.

### 3. Implementation

The described algorithm has been implemented using the Python programming language, to be run inside the CAD software Rhinoceros. At execution completion, output results are plotted in a table format, and a 3D model of the structural frame is generated and shown within the Rhinoceros modelling viewports (see Figure 1). The list of available cross-section profiles has been implemented based on the Eurocode Blue Book catalogue, limited to Universal Beam and Universal Column type-profiles, whereas flat section profiles are used for bracing members. The cross-section designation of each member is also shown in the Rhinoceros viewport at analysis completion.

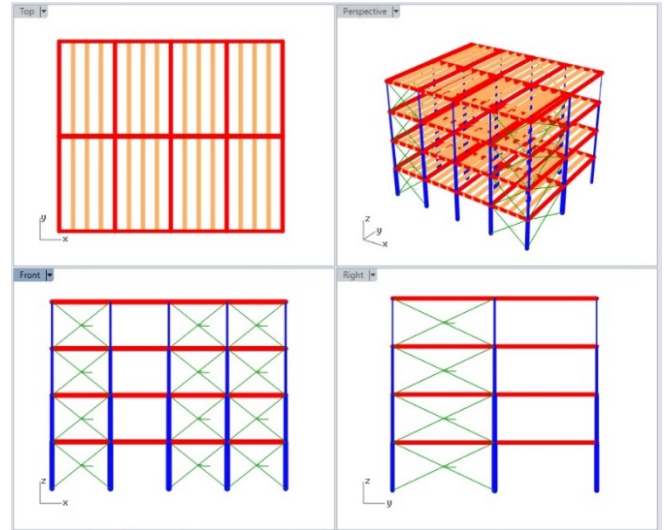
#### 3.1. Frame design example

To give a taster of the tool's capabilities, a simple frame example is considered in here. The output results (shown in Figure 1 and Table 2) are based on the following input values:

- Primary span length = 5.0 [mm]
- Secondary span length = 8.0 [mm]
- Maximum span of the floor slab = 1.5 [mm]
- Floor height = 4.0 [mm]
- N. of bays along the primary grid direction = 4
- N. of bays along the secondary grid direction = 2
- N of floors = 4
- Wind pressure load = 3.5 [kN/m<sup>2</sup>]
- Imposed floor load = 2.0 [kN/m<sup>2</sup>]
- Permanent load of building envelope = 8.0 [kN/m]
- Floor slab's self-weight = 3.0 [kN/m<sup>2</sup>]
- Floor load due to finishes, ceiling/services and partitions = 0.6 [kN/m<sup>2</sup>]

**Table 2:** typical output generated by the optimisation tool (based on the steel frame example shown in Figure 1).

Floor N.	Steel masses [kg]			
	Columns	Beams	Bracings	Columns+Beams+Bracings
1	4158		1462	25407
2	3211	19787	1053	24052
3	2529		636	22953
4	1460		217	21464
Total(s):	11359	79147	2935	93877



**Fig. 1:** a steel frame design generated with the described tool.

#### 3.2. Computing time

Table 3 shows the required computing time as a function of the model size, measured as a function of the number of elements (i.e. columns, beams and bracings) making up the frame, as well as the number of required iterations. A Hewlett-Packard computer desktop machine, running on an Intel(R) Core i5-4570 CPU, and with 4007 MB of memory RAM was used for testing.

As shown in Table 3 for the biggest model, the algorithm took about 80 seconds to converge. This would not allow for real-time user interaction, nonetheless, it is a reasonable amount of time to allow the user explore several design options in the early phase of the design process.

**Table 3:** tool's computing time as a function of the model size and number of iterations required.

N. of elements			N. of iterations	Computing time [s]
Columns	Beams	Bracings		
24	38	7	2	12.1
48	76	14	3	34.0
72	114	21	2	31.2
96	152	28	2	51.4
120	190	35	2	46.1
144	228	42	3	74.4
168	266	49	2	50.2
192	304	56	3	78.8

#### 3.3. Reduced impacts

In order to demonstrate the potential environmental benefit linked to the use of optimisation techniques (such as the tool described in here), a measure of the overall impact savings for the optimised frame design shown in Figure 1, has been quantified. First, the difference between the structure's overall mass (shown at the bottom row of Table 2) and the overall

steel mass of an equivalent “non-optimised” frame were measured. This “non-optimised” frame was assumed as a geometrically equivalent frame in which a uniform cross-sectional area is specified for columns and bracings that are vertically aligned, and it is taken as the maximum area section within that line of columns or bracings. Similarly, two maximum beams’ area sections are set, one for all primary beams and one for all secondary beams. The difference of saved steel mass so measured (= 30494 kg) is then multiplied with the LCA results obtained for 1 kg of steel (as from Table 1) thus showing the results in Table 4.

**Table 4:** LCA of 30.49 tons of steel, corresponding to the total steel mass saved using the optimisation tool (based on the frame example described in section 3.1).

Impact category	Ref. unit	Result
Acidification potential - average Europe	kg SO <sub>2</sub> eq.	2 170.
Climate change – GWP100	kg CO <sub>2</sub> eq.	339 578.
Depletion of abiotic resources, ultimate reserves	kg antimony eq.	16.
Depletion of abiotic resources, fossil fuels	MJ	3 595 675.
Eutrophication	kg PO <sub>4</sub> eq.	535.
Human, freshwater and marine toxicity	kg 1,4-C <sub>6</sub> H <sub>4</sub> C <sub>12</sub> eq.	498 593 061.
Ozone layer depletion	kg CFC-11 eq.	0.013
Photochemical oxidation	kg C <sub>2</sub> H <sub>4</sub> eq.	107.
Terrestrial ecotoxicity	kg 1,4-C <sub>6</sub> H <sub>4</sub> C <sub>12</sub> eq.	2 790.

#### 4. Conclusions

The work described in this paper addressed the unsolved problem of reducing steel masses currently utilized in structural steel construction. The main aim behind this is to mitigate the environmental impacts that are associated with such a widespread practice of using more material than what is actually needed to fulfill safety and serviceability requirements set by design standards. Based on this truth, a design tool for structural optimisation of steel framed structures, has been developed and described in here. The easy-to-use tool can be used at early design stage, to drive steel mass reduction when the possibility to do so is greatest. To increase its chances of being utilized by practitioners, the tool was implemented base on a small set of geometrical and loading input parameters, which the structural engineer is usually familiar with. Furthermore, the tool has been implemented within Rhinoceros, a CAD software widely used by design practitioners. After describing the underpinning theory, the tools functioning and related results are demonstrated with a practical example, of a small three-story frame. A brief test, showing the tool’s capability in terms of computing time, is also discussed. The test was performed using an average computer desktop machine. For a relatively big frame geometry (i.e. made of 192 columns, 304 beams and 56 bracings), it takes about 80 seconds for the tool to converge to a solution, which is completely acceptable for the user to explore alternative structural layout solutions, based

on the range of building’s shapes limitedly to the particular project at hand. To show the environmental implications of the tool, a cradle-to-grave life cycle assessment of 1 kg of structural steel has been performed. In the worked example shown in this paper on a medium size steel frame building, with a gross floor area of 2560 m<sup>2</sup>, the mass of steel saved by using the proposed tool translates into significant environmental benefits: 340 tons of CO<sub>2</sub> eq. saved or 500 000 tons of 1,4-C<sub>6</sub>H<sub>4</sub>C<sub>12</sub> eq., which is responsible for human and eco-toxicity. Future works will extend the tool to other built forms and structural materials to develop a system that can support early stage design across a wide range of building project.

#### Acknowledgements

This research was supported by the UK's Engineering and Physical Sciences Research Council (EPSRC) [Grant No. EP/R01468X/1] and internal funds from Edinburgh Napier University [Project No. 830425].

#### References

- [1] EEA, Material Resources and Waste - 2012 Update, European Environment Agency, Copenhagen.
- [2] EC, Roadmap to a Resource Efficient Europe – Communication from the Commission to the European Parliament, the Council, the European and Social Committee and the Committee of Regions COM, European Commission, 2011.
- [3] M. M. Khasreen, P. F. Banfill, G. F. Menzies, Life-cycle assessment and the environmental impact of buildings: a review, *Sustainability*, vol 1, no 3, pp. 674-701, 2009.
- [4] A. Corona, B. Madsen, M. Z. Hauschild and M Birkved, Natural fibre selection for composite eco-design, *CIRP Annals*, vol 65 no. 1, pp. 13-16, 2016.
- [5] C. De Wolf, F. Pomponi and A. Moncaster, “Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice,” *Energy and Buildings*, vol. 140, pp. 68-80, 2017.
- [6] J. M. Allwood, J. M. Cullen, M. A. Carruth, D. R. Cooper, M. McBrien, M. R. L. C. Moynihan and C. Patel, *Sustainable materials: with both eyes open*, Cambridge: UIT, 2012.
- [7] T. Wang and D. B. G. T. E. Müller, “Forging the anthropogenic iron cycle,” *Environmental science & technology*, vol. 41, no. 14, pp. 5120-5129, 2007.
- [8] BSI, “BS EN 15978:2011. Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method,” British Standard Institution, 2011.
- [9] “<http://www.ecoinvent.org>,” [Online]. [Accessed 15 08 2017].
- [10] F. Pomponi and A. Moncaster, “Scrutinising embodied carbon in buildings: The next performance gap made manifest,” *Renewable and Sustainable Energy Reviews*, 2017.
- [11] A. P. Acero, C. Rodriguez and A. Ciroth, “LCIA methods. Impact assessment methods in Life Cycle Assessment and their impact categories, Version 1.4,” 2014.
- [12] M. C. Moynihan and J. M. Allwood, “Utilisation of structural steel in buildings,” *Proceedings of the Royal Society*, vol. 470, 2014.
- [13] C. Gibbons, “Economic steelwork design,” *Structural Engineer*, vol. 73, pp. 20-20, 1995.
- [14] J. Basbagill, F. F. M. Lepech and M. Fischer, “Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts,” *Building and Environment*, vol. 60, pp. 81-92, 2013.
- [15] “BS EN 1993-1-1:2005 Design of steel structures - Part 1-1: General rules and rules for buildings,” British Standard Institution.
- [16] W. McGuire, R. H. Gallagher and R. D. Ziemian, *Matrix Structural Analysis 2nd Edition*, Faculty Books, 2000.