Multi-objective optimisation of engineering design by using Excel

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Abstract

The different objectives of engineering design often conflict with one another such as achieving high product quality while reducing its cost, for example. The design of engineering systems usually involves, in addition to the technical and economic aspects, other aspects that also have to be considered such as the safety, environmental, and social factors. The task of finding acceptable trade-offs between the different objectives is made even more difficulty by the numerous available options and the increasing complexity of the systems themselves. Therefore, the engineers of today need proper tools to help them take the different design factors and options into consideration. Although such tools have been made available by the recent development of evolutionary multi-objective optimisation (MOO), unfortunately, the evolutionary MOO software are expensive to develop and, therefore, they are unavailable or unaffordable to most engineers and engineering students particularly in developing countries. This paper presents a technique for conducting MOO analyses by integrating Excel's single-objective optimisation (SOO) solver with the TOPSIS decision-making method. The Solver-TOPSIS technique (STT) is illustrated by considering the case of a tip-loaded concrete beam provided by Deb [1] who also provided optimised results obtained by using the widely-used NSGA-II algorithm [2]. The results of the technique are also compared to those obtained by using the more recent MOO solver MIDACO [3]. Finally, the paper demonstrates the capability of the technique to deal with MOO analyses of engineering design with predefined preference of the objectives involved.

Keywords: Multi-objective optimisation, Microsoft Excel, Solver, TOPSIS

1. Introduction

Without engineering, civilisation does not exist [4]. However, the construction and operation of large engineering projects lead to rapid consumption of the non-renewable energy resources and destruction of the flora and fauna. The emissions of greenhouse and ozone-layer depleting gases lead to serious environmental problems that now affect the entire globe. In order to minimise the adverse impact of their activities, our future engineers have to be more skilful and creative in their job and our educational systems has to be more effective in equipping them with the needed theoretical knowledge and analytical problem-solving skills. This view is also supported by the fact that the engineering systems themselves are becoming increasingly complicated by introducing new technologies more frequently than before. As a response to the calls from industry, the integration of software-based application with theoretical methods have now become essential in the various engineering study programs since the traditional curricula and teaching methods cannot cope with the required pace of the learning process [5]. The need to use electronically-based teaching materials during the COVID-19 pandemic also accelerated the use of computer-based demonstration methods to replace or supplement the traditional lab experiments in many engineering curricula [6,7].

The widespread availability of Microsoft Excel on most personal computers without additional cost and its powerful tools for data analysis and visualisation encouraged its uses for teaching of many engineering subjects [8-17]. According to Oke [18], Excel enables simplified program development and debugging, and the use of named ranges and labels enhance the readability of its formulae. The ability to manipulate matrices and the use of macros for looping and other high-level programming needs also promoted its acceptability. Unlike the dedicated software, the general-purpose software has an important advantage of allowing the students to develop white-box models for their analyses. According to Ahmadi-Brooghani [10], using Excel as a modelling platform in the basic engineering subjects improves the learning process, helps the students with their design assignments and final-year projects, and provides future engineers with an effective problem-solving tool for their job. A number of previous studies dealt with the conventional single-objective optimisation analyses of engineering systems [19-24]. El-Awad [25] presented a technique for conducting MOO analyses by using Excel that integrates Excel's single-objective optimisation (SOO) solver with TOPSIS decision-making method [26] and demonstrated its application by considering a vapour-compression refrigeration cycle. This paper applies the Solver-TOPSIS technique (STT) by considering the case of a tip-loaded circular concrete beam. The optimised results obtained by the technique are compared with those obtained by using the widely-used NSGA-II algorithm [2] and by using the more recent MOO solver MIDACO [3].

2. Multi-objective design optimisation

The circular concrete beam shown on Figure 1 is to be designed to carry an end load, P, of 1 kN with two objectives; minimisation of its mass (m) and minimisation of its end-deflection (δ). The optimisation problem has two decision variables, which are the diameter (d) and length (l) of the beam.

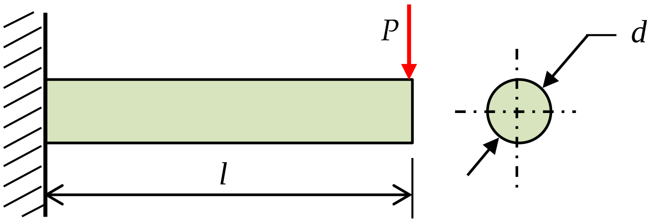


Figure 1. A schematic of a cantilever beam (adopted from [1])

Mathematically, the problem can be stated as follows [1]:

$$\text{Minimise} \quad f_1(d,l) = m = \rho \frac{\pi d^2}{4} l,$$

$$\text{Minimise} \quad f_2(d,l) = \delta = \frac{64Pl^3}{3E\pi d^4}, \tag{1}$$

$$\text{Subject to} \quad \sigma_{max} \le S_y, \quad \delta \le \delta_{max}$$

Where ρ and E are the density and Young's modulus of elasticity for concrete, respectively, S_y is the lateral yield strength, and σ_{max} is the maximum stress that is calculated as follows:

$$\sigma_{max} \quad \frac{32Pl}{\pi d^3} = \tag{2}$$

The following parameter values are to be used:

ρ = 7800 kg/m^3, E = 207 GPa, S_y = 300 MPa, δ_{max} = 5 mm.

The lower and upper limits for d and l are as follows:

$10 \le d \le 50$ mm,

$200 \le l \le 1000$ mm.

Table 1 shows five feasible solutions to this optimisation problem given by Deb [1] and Figure 2 shows part of the feasible objective space with the five solutions. The five solutions are examples of conflicting objectives of design. While the solution with the minimum weight (A) has the smallest diameter of 18.94 mm, that with the minimum deflection (D) has the largest diameter of 50 mm. The question is; which of the five solutions gives the best trade-off between the two conflicting objectives?

Table 1. Five solutions for the cantilever design problem

	d (mm)	l (mm)	m (kg)	δ (mm)
A	18.94	200.00	0.44	2.04
B	21.24	200.00	0.58	1.18
C	34.19	200.00	1.43	0.19
D	50.00	200.00	3.06	0.04
E	33.02	362.49	2.42	1.31

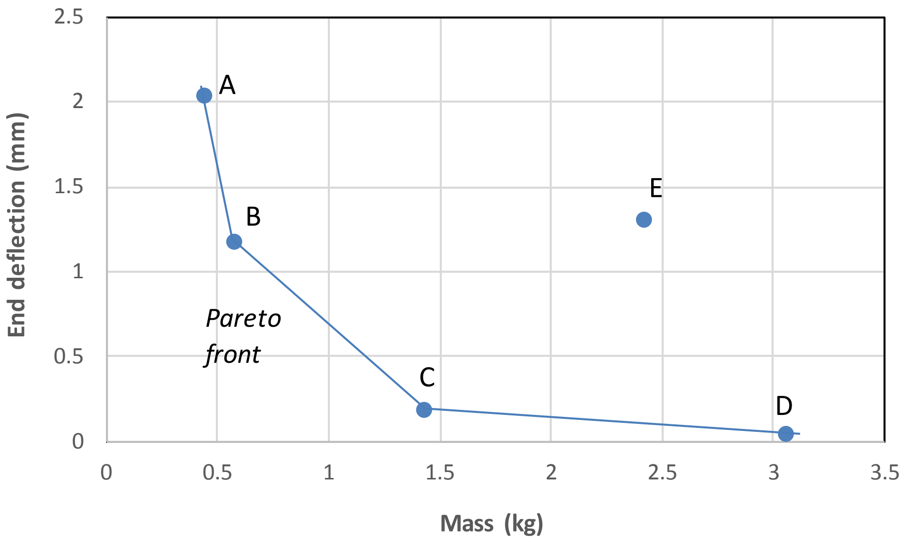


Figure 2. Five feasible solutions to the problem shown on the objective space

Figure 2 shows that solution E has a larger mass and a larger end-deflection than solution C. In this case, solution C is the better of the two solutions and, therefore, solution C is said to dominate solution E or solution E is dominated by solution C. Solution E is also dominated by solution B, but not by solution A or D. Comparing the two solutions A and D, solution A has a smaller mass, but has a larger end-deflection than solution D. Hence, none of these two solutions is better than the other with respect to both objectives. In this case, the two solutions are called non-dominated solutions. If both objectives are equally important, one cannot say for sure which of these two solutions is better with respect to both objectives. All the four solutions A, B, C, and D are non-dominated since the superiority of one of these four solutions over the other cannot be established with both objectives in mind. The curve formed by joining the non-dominated solutions on the objective space is known as the Pareto-optimal front. All solutions lying on this curve are called Pareto-optimal set. In multi-objective optimisation the task of the solver is not to find a unique optimal solution, but to find the Pareto-optimal solutions. The four Pareto-optimal solutions A to D were obtained by using the Non-dominant Sorting Genetic Algorithm II (NSGA-II) [3]. The following section deals with the selection of the best of these solutions.

3. TOPSIS decision-making method for selecting the best design

A number of decision-making techniques have been developed to automate the selection of the best design among different options based on the merits of each design according to the specified objectives [27]. One of these methods is the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [26]. The fundamental principle of this method is that the chosen final optimal point must be in the shortest possible distance from an ideal point and the furthest distance from a non-ideal one. The ideal point is the point at which optimum value of the objective is achieved regardless of satisfaction of the other objectives, while the non-ideal point is the point at which the worst value for each objective is obtained. To apply the method, the ideal and non-ideal points of each single objective are first obtained and the distances from the ideal point (S^+) and non-ideal point (S^-) are evaluated for all the options. The following closeness coefficient, C_i, is then calculated for each option:

$$C_i = S_j^- / \left(S_j^+ + S_j^-\right) \tag{3}$$

The option to be selected as the final optimal point is that with the maximum value of C_i.

TOPSIS requires the benefit and non-benefit objectives to be identified. For the case under consideration, the objectives of minimising the beam's mass and end-deflection are both non-benefit objectives. A benefit function can be created as follows:

$$W^* = 1/m \tag{4}$$

Table 2 shows the values of W^* and δ for the five solutions of the design problem.

Table 2. Values of W* and δ for the five solutions of the beam design problem

	W^* (kg^{-1})	δ (mm)
A	2.272727	2.04
B	1.724138	1.18
C	0.699301	0.19
D	0.326797	0.04
E	0.413223	1.31

Figure 3 shows the Excel sheet that applies the TOPSIS method to the five solutions. The sheet is a modified version of an example sheet available at [28]. The main body of the sheet is divided into six blocks as numbered on the figure.

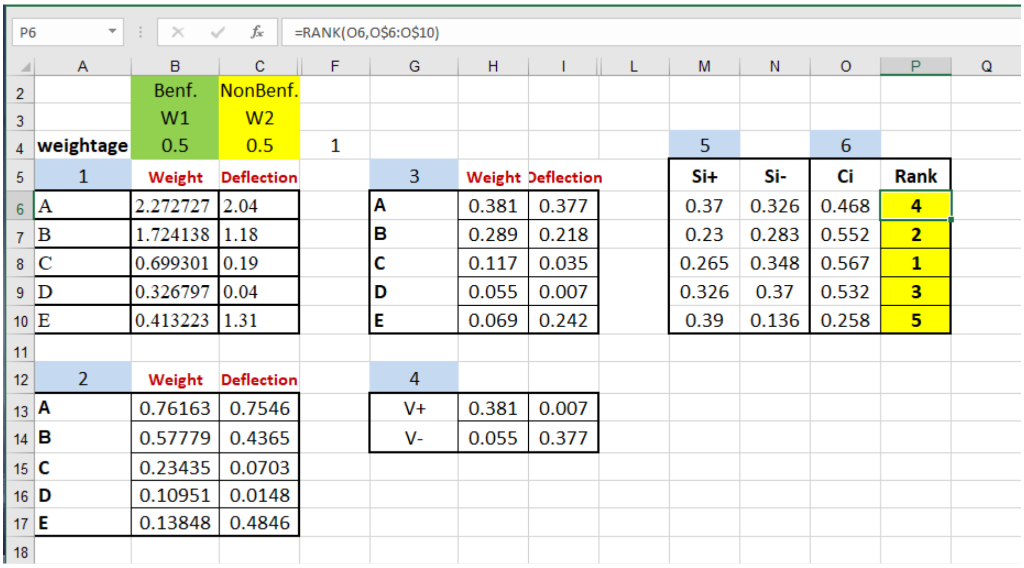


Figure 3. TOPSIS ranking of the five solutions of the beam problem

The numbers 1 to 6 correspond to the following six steps of the method:

1. Creation of the evaluation matrix [A] by entering the values of the two objectives for the five solutions as shown on the figure.
2. Normalisation of the evaluation matrix
3. Determination of the weighted matrix
4. Determination of positive and negative ideal solutions
5. Calculation of distances from positive and negative ideal solutions
6. Determination of relative closeness from the ideal solution and ranking of the solutions.

Note that the "benefit" objective for the analysis is maximising W^*, while the "non-benefit" objective is minimising the end-deflection. The sheet shown on Figure 3 applies a balanced preference scheme that gives equal weights to the two objectives by assigning the value 0.5 to each of the two weighting factors W1 and W2 stored in cells B4 and C4. The values of W^* and δ for the five solutions are stored as a matrix in cells B6:C10 which is the evaluation matrix of the method. Ranking of the five solutions is done by using Excel's function "Rank" as shown by the formula bar of Figure 3. The figure shows that the method ranked solution C as the best solution while solution E received the lowest rank. The sheet allows the importance of one of the two objectives to be emphasised by giving it more weight than the other, e.g. W1=0.6 and W2=0.4. This can lead to different ranks given to the five solutions.

4. Solution by using the MIDSCO solver

Currently, there are not many MOO solvers that can be used with general-purpose software. Fortunately, the developers of MIDACO (Mixed Integer Distributed Ant Colony Optimization) solver have made a limited version of the software publicly available for Excel and several programming languages. Excel's free version of the solver is available at [29]. Although the MIDACO solver can be used to solve single and multi-objective optimisation problems with up to thousands of variables and hundreds of objectives, its freely-available version allows only a maximum of four changing variables to be considered in the analysis. Since the present problem involves two changing variables, the free version is adequate. The steps of installing and using MIDACO to solve an example MOO problem are explained in [29].

Figure 4 shows the Excel sheet developed for solving the concrete beam optimisation problem. The left part of the sheet stores the values of concrete density (ρ), the end load (P), the elasticity constant (E), as well as the specified values of S_y and σ_{max}. The top right side stores the initially specified values of the diameter (d) and length (L). The sheet calculates the mass of the beam (f1_weight), the end-deflection (f2_deflcn), and the maximum stress (Stress). Note that with initially specified values of the beam's diameter and length of 0.025 m and 0.5 m, respectively, both the end-deflection and maximum stress exceed their specified limits.

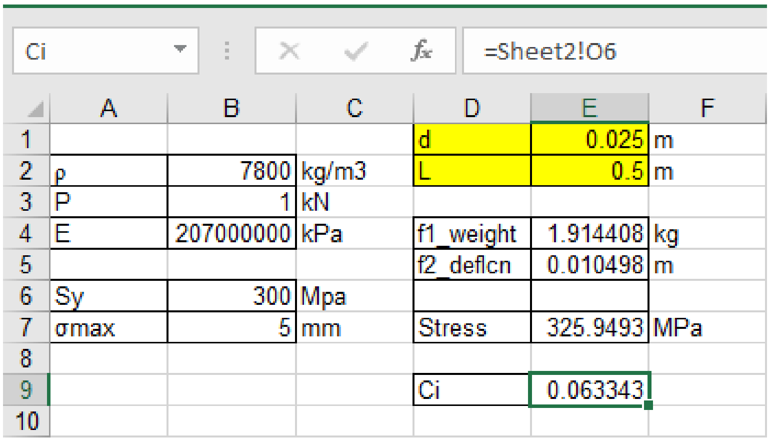


Figure 4. Excel's model for analysing the circular concrete beam

Figure 5 shows MIDACO's set-up for solving the present bi-objective optimisation problem. The two objective functions, which are stored in cells E4 and E5, are to be minimised. The two changing variables involved, which are the diameter and length of the beam, are stored in cells E1 and E2. Two constraints have been added that represent the lower and upper limits for the maximum permissible stress and end-deflection specified in Section 2. Figure 6 shows the optimal solution.

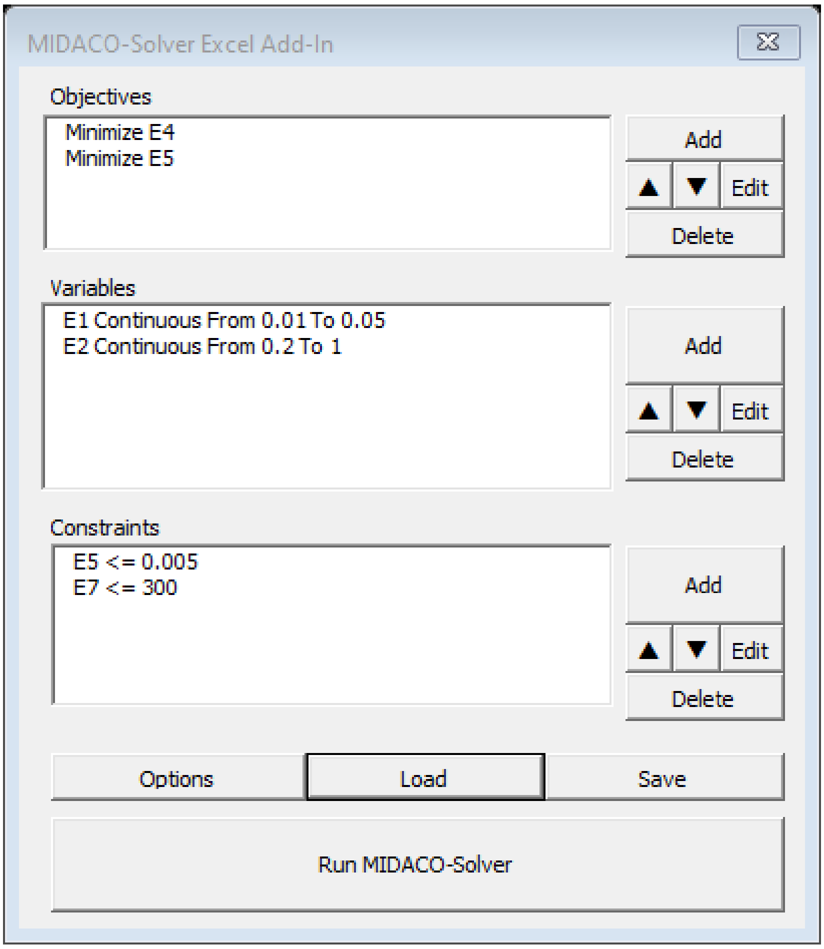
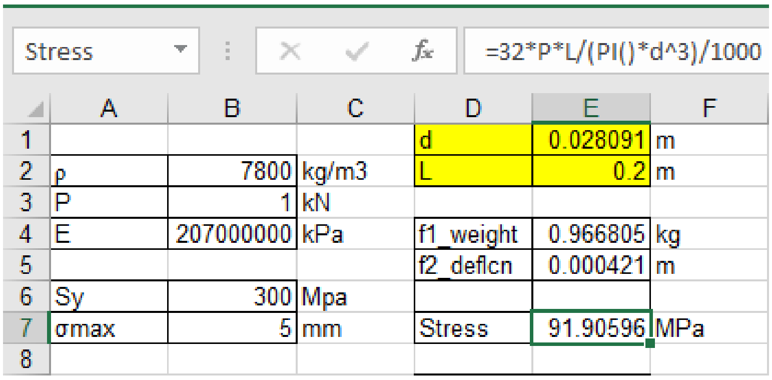


Figure 5. User form of MIDACO for the present problem



Stress =32*P*L/(PI()*d^3)/1000

	A	B	C	D	E	F
1				d	0.028091	m
2	ρ	7800	kg/m3	L	0.2	m
3	P	1	kN			
4	E	207000000	kPa	f1_weight	0.966805	kg
5				f2_deflcn	0.000421	m
6	Sy	300	Mpa			
7	σmax	5	mm	Stress	91.90596	MPa
8						

Figure 6. MIDACO's optimal solution of the beam problem

According to the optimal solution, the values of the beam's diameter and length are 28.091 cm and 200 cm, respectively. The corresponding values of the beam's mass and end-deflection are 0.967 kg and 0.421 mm, respectively, and the maximum stress is 91.906 MPa. Both the end-deflection and maximum stress are well below their maximum permissible limits. This solution will be compared to those obtained by NSGA-II and by the Solver-TOPSIS technique in the following sections.

As a multi-objective solver, MIDACO produces a Pareto front that contains all the non-dominated optimum solutions and automatically stores the data of the Pareto front in a plain text file called "MIDACO_PARETOFRONT". This file will be used to visualise the Pareto front by a plotting tool, called "PlotTool", which can be downloaded from [30]. Figure 7 shows the Pareto front produced for this problem.

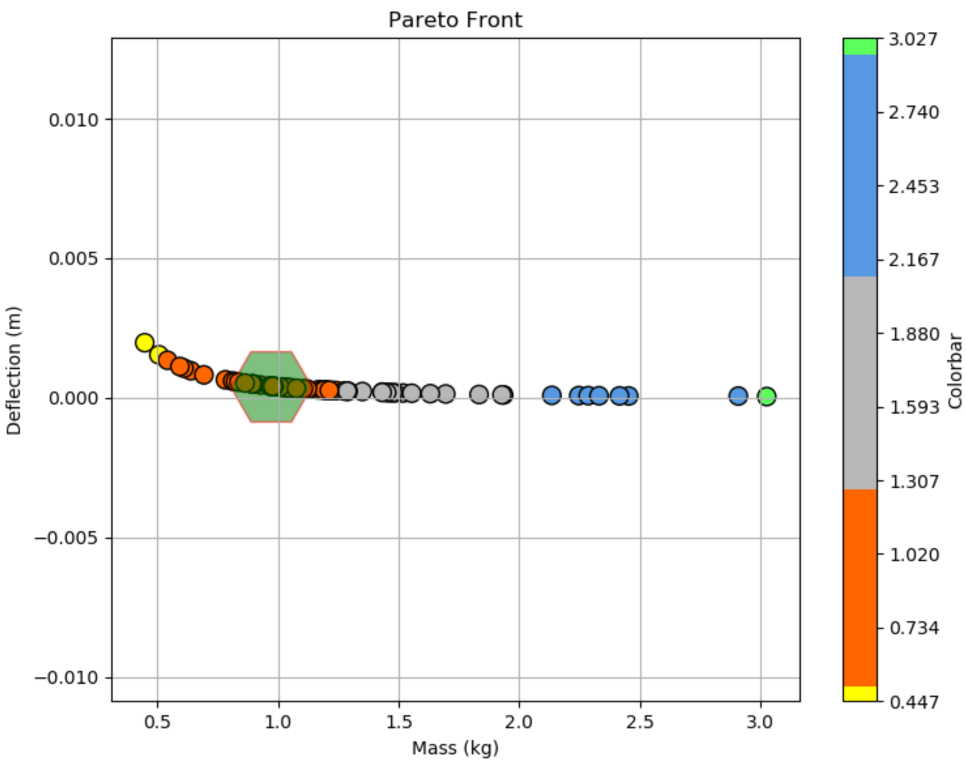


Figure 7. MIDACO's Pareto front for the beam's problem with the selected solution

5. Solution by using the Solver-TOPSIS technique

Instead of utilising TOPSIS only to select the option in the evaluation matrix with the highest value of C_i, the present technique applies it to maximise the value of C_i for a particular solution by adjusting its properties in the evaluation matrix [25]. As shown on Figure 8, in the present case elements of the evaluation matrix are values of the beam's (inversed) mass and end-deflection for three options (number of objectives plus one). The option for which the value of C_i is to be maximised is referred as the "pole solution", while the other two options are referred to as the "peg solutions". As shown later, the peg solutions are SOO solutions of the problem obtained by using Solver. While the elements of the two peg solutions in the evaluation matrix remain fixed during the optimisation process, those of the pole solution change as the diameter and length of the beam are being adjusted with Solver.

B6 =1/f1_weight

	A	B	C	F
2		Benf.	NonBenf.	
3		W1	W2	
4	weightage	0.5	0.5	1
5	1	Weight	Deflection	
6	STT pole	0.522355	10.4976	
7	f1	2.276038	2.041	
8	f2	0.326472	0.042	
12	2	Weight	Deflection	
13	STT pole	0.22153	0.9816	
14	f1	0.96527	0.1909	
15	f2	0.13846	0.0039	

	G	H	I
5	3	Weight	Deflection
6	STT pole	0.111	0.491
7	f1	0.483	0.095
8	f2	0.069	0.002
12	4		
13	V+	0.483	0.002
14	V-	0.069	0.491

	M	N	O	P
4	5		6	
5	Si+	Si-	Ci	Rank
6	0.614	0.042	0.063	3
7	0.093	0.572	0.86	1
8	0.413	0.489	0.542	2

Figure 8. Sheet 2 of the model that applies TOPSIS

The sheet shown on Figure 8 that applies the TOPSIS method is added to the sheet shown on Figure 4 and the two sheets are coupled in a manner that enables Solver to be used for maximising the value of C_i for the pole solution by adjusting the diameter and length of the beam. As shown in the formula bar of Figure 4, the first sheet duplicates the cell in the second sheet that calculates C_i for the pole solution so that the value of C_i in Sheet 2 for the pole solution is automatically shown on sheet 1. On the other hand, elements of the evaluation matrix for the pole solution in Sheet 2 are linked to the values of the mass and end-deflection in Sheet 1. The formula bar in Figure 8 shows the application of Equation (4) in in cell B6 to determine the inversed mass for the pole solution obtained from Sheet 1. The end-deflection is converted to mm by multiplying the value copied from Sheet 1 by 1000. With this arrangement, Solver can be used to adjust the values of the beam's diameter and length in Sheet 1 so as to maximise the value of C_i for the pole solution in Sheet 2. Note that TOPSIS ranked the pole solution (with d=0.025 m and L=0.5 m) in the third position compared to the two peg solutions which are optimised solutions prepared as explained below.

a. Preparation of the two single-objective "peg" solutions

The two peg solutions required by the Solver-TOPSIS technique, which are optimised solutions for the two design objectives, can be obtained by using any of

Solver's two solution methods: the GRG Nonlinear method or the Evolutionary method. Figure 9 shows Solver's set-up for minimising the mass of the beam subject to the upper and lower limits of *d* and *l* specified in Section 2 by using the Evolutionary method and Figure 10 shows the solution obtained by this method.

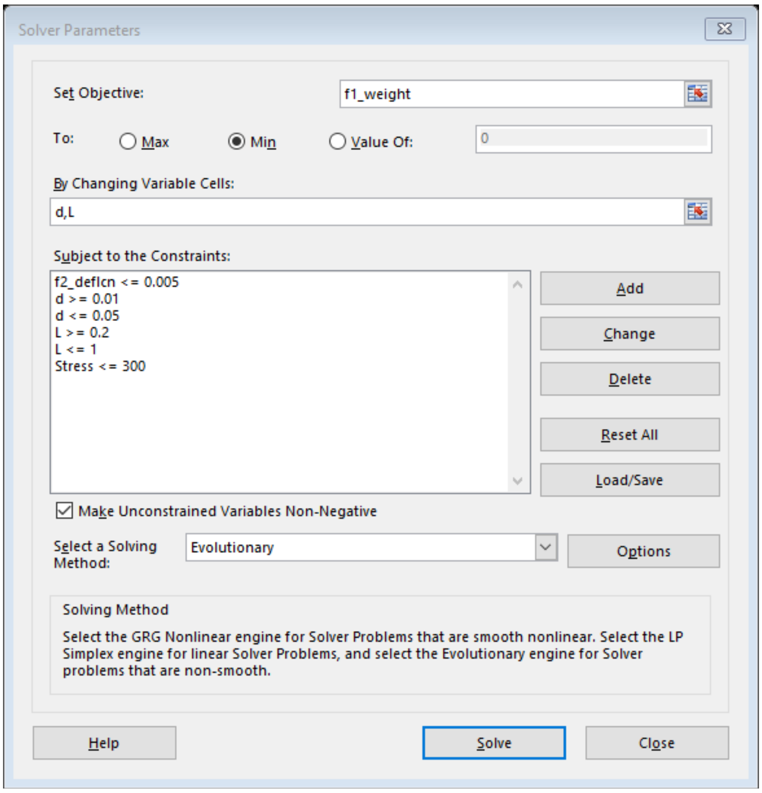
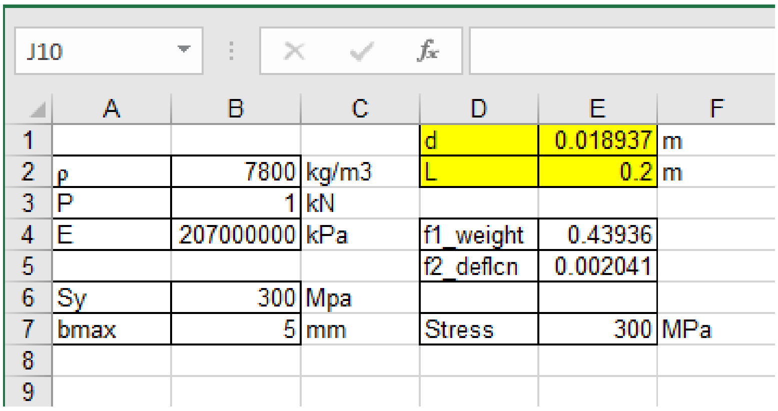


Figure 9. Solver's set-up for minimising the beam's mass by using the Evolutionary method



J10

	A	B	C	D	E	F
1				d	0.018937	m
2	ρ	7800	kg/m3	L	0.2	m
3	P	1	kN			
4	E	207000000	kPa	f1_weight	0.43936	
5				f2_deflcn	0.002041	
6	Sy	300	Mpa			
7	bmax	5	mm	Stress	300	MPa
8						
9						

Figure 10. Solver solution for minimising the beam's mass

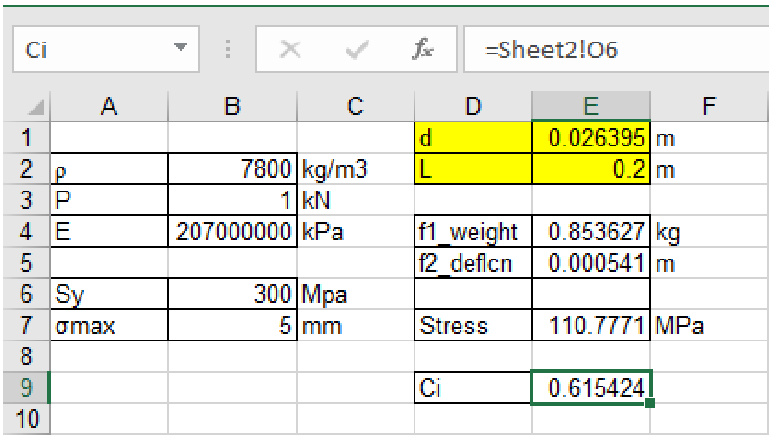
Similarly, the method was used to minimise the end-deflection subject to the same upper and lower limits. Table 3 shows the details of the two single-objective optimised solutions. Note that both optimised solutions reduced the beam's length to the minimum allowable length of 0.2 m, but have different values for the beam's diameter. Also note that the values of the "Weight" shown on Figure 8 for the peg solutions are inversed values of the masses shown on Table 3, while the values of the "Deflections" are values of the end deflection converted to mm.

Table 3. Outcome of Solver's two single-objective solutions

	d (m)	l (m)	m (kg)	δ (m)
Minimum mass	0.018937	0.2	0.43936	0.002041
Minimum deflection	0.05	0.2	3.063053	4.2E-04

b. Maximisation of C_i for the pole solution

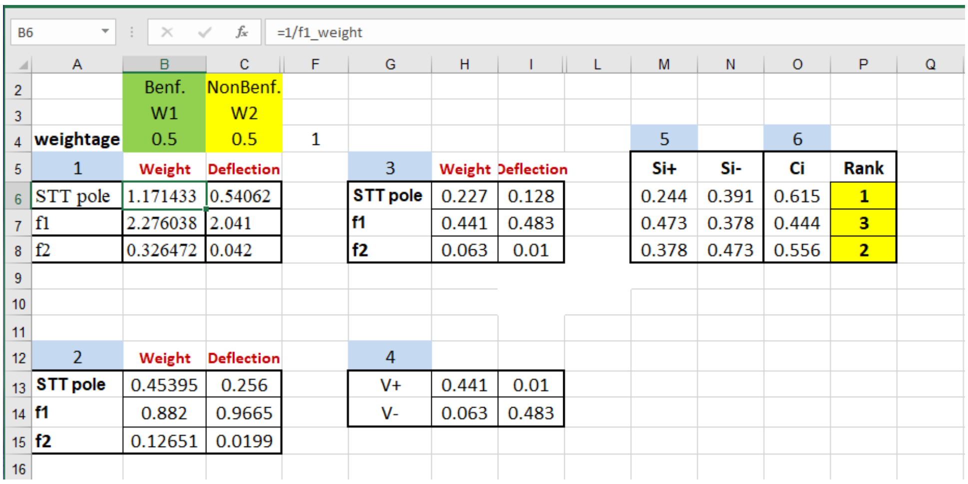
Figure 4 and Figure 8 show Sheet 1 and Sheet 2 of the model after inserting Solver's two single-objective peg solutions in the evaluation matrix, but before Solver was used to maximise the value of C_i for the pole solution. Solver was used with the same set-up shown on Figure 9 after changing the objective of the solution to that of maximising C_i for the pole solution stored in cell E9 of Sheet 1. Figure 11 and Figure 12 show Sheet 1 and Sheet 2 of the model with the solution obtained by Solver.



Ci =Sheet2!O6

	A	B	C	D	E	F
1				d	0.026395	m
2	ρ	7800	kg/m3	L	0.2	m
3	P	1	kN			
4	E	207000000	kPa	f1_weight	0.853627	kg
5				f2_deflcn	0.000541	m
6	Sy	300	Mpa			
7	σmax	5	mm	Stress	110.7771	MPa
8						
9				Ci	0.615424	
10						

Figure 11. Sheet 1 of the model with the STT solution



B6 =1/f1_weight

	A	B	C	F	G	H	I	L	M	N	O	P	Q
2		Benf.	NonBenf.										
3		W1	W2										
4	weightage	0.5	0.5	1					5		6		
5	1	Weight	Deflection		3	Weight	Deflection		Si+	Si-	Ci	Rank	
6	STT pole	1.171433	0.54062		STT pole	0.227	0.128		0.244	0.391	0.615	1	
7	f1	2.276038	2.041		f1	0.441	0.483		0.473	0.378	0.444	3	
8	f2	0.326472	0.042		f2	0.063	0.01		0.378	0.473	0.556	2	
9													
10													
11													
12	2	Weight	Deflection		4								
13	STT pole	0.45395	0.256		V+	0.441	0.01						
14	f1	0.882	0.9665		V-	0.063	0.483						
15	f2	0.12651	0.0199										
16													

Figure 12. Sheet 2 of the model with the STT solution

Note that the value of C_i for the pole solution increased from 0.063 to 0.615 and the pole solution is now in the first rank. With this solution, the optimised values of the beam's diameter and length are 2.6 cm and 200 cm, respectively, and the beam's mass and end-deflection are 0.854 kg and 0.541 mm, respectively. To assess the goodness of this STT solution, it is compared with the solutions obtained by NSGA-II and by MIDACO in the following section.

c. Comparison of the STT results with those of NSGA-II and MIDACO

Figure 13 shows the solution obtained by the STT plotted on the objective space together with the four Pareto optimal solutions obtained by NSGA-II and the best solution obtained MIDACO. The figure shows that the solutions obtained by both MIDACO and the STT are Pareto optimal solutions since none of the other four solutions are superior to them with respect to both objectives. Both solutions produced smaller masses, but larger end-deflections than solution C in Table 1.

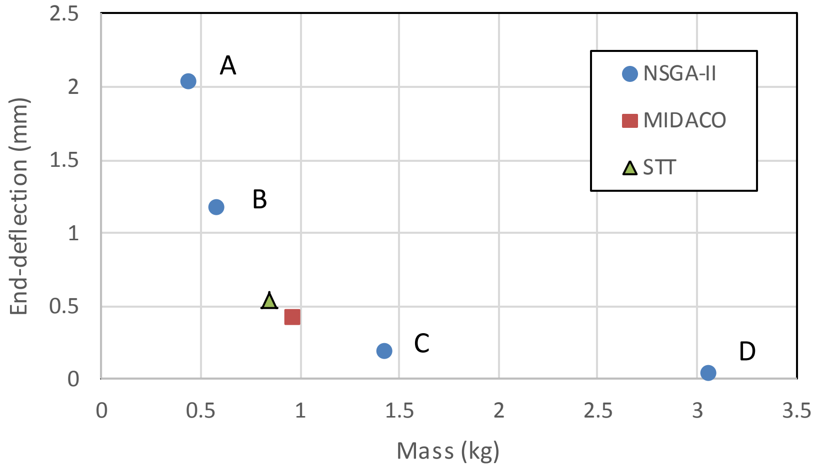


Figure 13. Objective space including the solutions obtained by MIDACO and the STT technique

To see which of the three optimal solutions came closest to satisfying the two-objectives of the problem, they were compared by using the TOPSIS method. Figure 14 shows the TOPSIS sheet that replaces solution E in Figure 3 with MIDACO's solution and adds the STT solution to the evaluation matrix as the sixth row. As the figure shows, MIDACO's solution occupied the first rank followed by that of the STT. Solution C of NSGA-II now occupies the third rank and its other three solutions followed solution C with the same order shown on Figure 3.

P11 =RANK(O11,O$6:O$11)

	Benf.	NonBenf.
	W1	W2
weightage	0.5	0.5

1

1	Weight	Deflection
A	2.272727	2.04
B	1.724138	1.18
C	0.699301	0.19
D	0.326797	0.04
MIDACO	1.034335	0.42148
STT	1.171433	0.54062

2	Weight	Deflection
A	0.67984	0.8286
B	0.51574	0.4793
C	0.20918	0.0772
D	0.09775	0.0162
MIDACO	0.3094	0.1712
STT	0.35041	0.2196

3	Weight	Deflection
A	0.34	0.414
B	0.258	0.24
C	0.105	0.039
D	0.049	0.008
MIDACO	0.155	0.086
STT	0.175	0.11

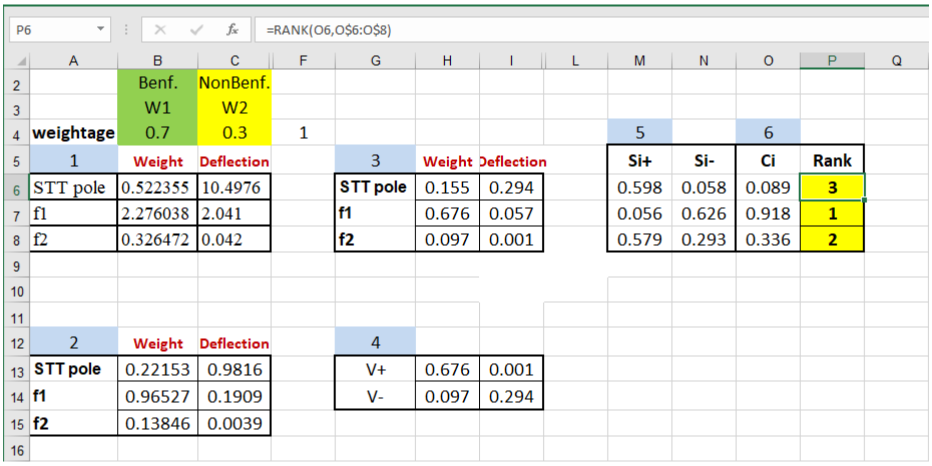
4		
V+	0.34	0.008
V-	0.049	0.414

5		6	
Si+	Si-	Ci	Rank
0.406	0.291	0.417	6
0.246	0.272	0.526	5
0.237	0.38	0.615	3
0.291	0.406	0.583	4
0.201	0.345	0.632	1
0.194	0.33	0.63	2

Figure 14. Comparison of the solution obtained by the STT to those obtained by MIDACO and by NSGA-II

6. Optimisation with predefined preference of objectives

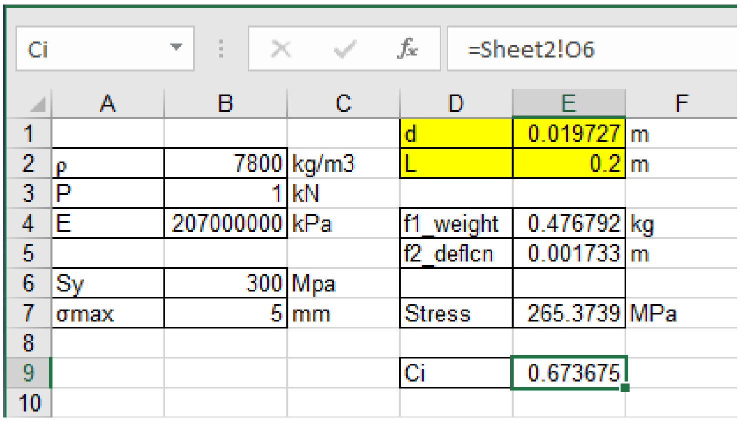
The integration of TOPSIS in the STT technique allows it to be used for MOO analyses with predefined preference order of the objectives involved by giving the objectives different weighs before optimisation. For illustration, two simulations with the technique were performed with values of the two weight factors W1 and W2 in Figure 8 changed from 0.5 and 0.5 to 0.7 and 0.3 in the first simulation and 0.3 and 0.7 in the second one. Figure 15 shows the second sheet of the model with the 0.7-0.3 choice. The figure shows that the value of C_i for the pole solution, which is the initial guess, is 0.089 before the optimisation process. Since this is very small compared to the two peg solutions, it occupied the third rank. Figure 16 that shows Sheet 1 after the STT optimisation reveals that Solver increased the value of C_i from 0.089 to 0.674 so that the pole solution occupies the first rank. Similarly, for the 0.3-0.7 choice the technique increased the value of C_i so that the pole solution occupies the first rank instead of the third rank.



P6 | =RANK(O6,O$6:O$8)

	A	B	C	F	G	H	I	L	M	N	O	P	Q
2		Benf.	NonBenf.										
3		W1	W2										
4	weightage	0.7	0.3	1					5		6		
5	1	Weight	Deflection		3	Weight	Deflection		Si+	Si-	Ci	Rank	
6	STT pole	0.522355	10.4976		STT pole	0.155	0.294		0.598	0.058	0.089	3	
7	f1	2.276038	2.041		f1	0.676	0.057		0.056	0.626	0.918	1	
8	f2	0.326472	0.042		f2	0.097	0.001		0.579	0.293	0.336	2	
9													
10													
11													
12	2	Weight	Deflection		4								
13	STT pole	0.22153	0.9816		V+	0.676	0.001						
14	f1	0.96527	0.1909		V-	0.097	0.294						
15	f2	0.13846	0.0039										
16													

Figure 15. Sheet 2 of the model with the 0.7-0.3 preference before optimisation



Ci | =Sheet2!O6

	A	B	C	D	E	F
1				d	0.019727	m
2	ρ	7800	kg/m3	L	0.2	m
3	P	1	kN			
4	E	207000000	kPa	f1_weight	0.476792	kg
5				f2_deflcn	0.001733	m
6	Sy	300	Mpa			
7	σmax	5	mm	Stress	265.3739	MPa
8						
9				Ci	0.673675	
10						

Figure 16. Sheet 1 of the model with the 0.7-0.3 preference after optimisation

Table 4 shows the results of the two simulations compared to that of the balanced 0.5-0.5 preference-order simulation. The table figures show that the 0.7-0.3 simulation gave a smaller diameter and, therefore, a smaller mass, while the 0.3-0.7 simulation gave a larger diameter and, therefore, a smaller end-deflection. The results of the two unbalanced preference simulations are shown on Figure 17 compared to the previously obtained non-dominated solutions. As the figure shows, both solutions are non-dominated by any of the previous solutions and, therefore, belong to the Pareto optimal solutions. The figure also shows how STT solutions spread widely along the Pareto front.

Table 4. Outcome of the STT solutions with different preference orders

	d (m)	*l* (m)	*m* (kg)	δ (mm)
STT with 0.5-0.5	0.026396	0.2	0.853655	0.541
STT with 0.7-0.3	0.019726	0.2	0.476775	1.733
STT with 0.3-0.7	0.032421	0.2	1.287895	0.238

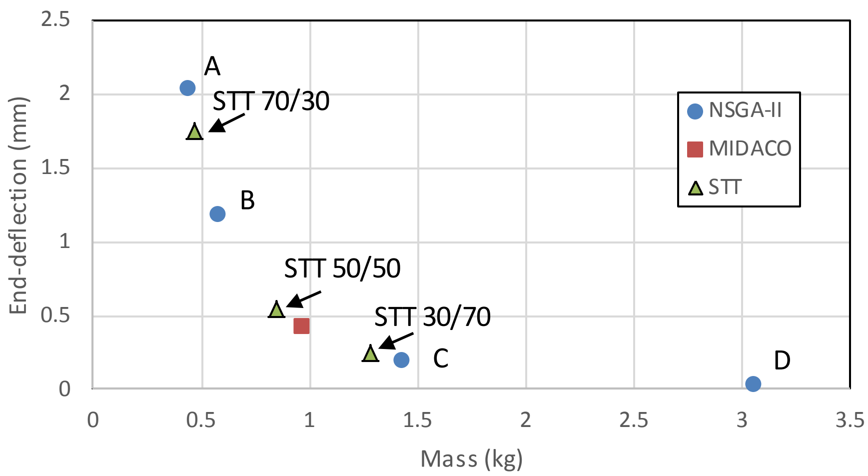


Figure 17. Objective space including the solutions obtained with the STT technique using different preference orders of the two objectives

7. Conclusions

Multi-objective optimisation of engineering design that deals with finding the best trade-offs between various conflicting objectives cannot be performed by using Excel's solver, Solver, which is suitable for optimisation analyses with a single objective only. Although, multi-objective optimisation of engineering systems is possible with Excel by using the free version of the MIDACO software [29], the free version is limited to four design variables only. This paper presents a technique for conducting multi-objective optimisation analysis with Excel by using Solver with TOPSIS decision-making method. The technique is illustrated by considering the problem of a tip-loaded circular concrete beam for which we seek to minimise both its weight and end-deflection subject to maximum deflection and stress constraints. The test case is based on the data provided by Deb [1] who also provided optimised solutions obtained by using the NSGA-II algorithm. Comparisons of the results obtained by using the present Solver-TOPSIS technique with those obtained by using the NSGA-II algorithm and those obtained by using MIDACO confirm the adequacy of the technique. The paper also illustrates the use of the technique for conducting multi-objective optimisation with predefined preference of the objectives. With the availability of an adequate add-in for fluid properties, the technique enables Excel to be used as an educational modelling platform for optimisation analyses of a wide range of conventional and innovative engineering systems [31-33].

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