USE OF SW TOOL TO SUPPORT TEACHING TECHNICAL SUBJECTS

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Software tool for beam design was invented for educational purposes. SW Tool is based on standard formulas enhanced by Ashby's theory. It is therefore a SW tool for structural design of profiles, considering its stability and enabling shape optimization for the most efficient use of the material. SW Tool is specialized to help the students evaluate suitable profile quickly and easily. This article deals with a software tool that is used for educational purposes and was tested in practice as a part of a university subject.

The goal was to verify on several assignments, whether students are able to use this new software tool, and collect data about their approach and results. All the data were compared and evaluated. The evaluation showed that the software tool is user-friendly and students can use them immediately without any problems.

KEYWORDS

Cross-section shape, Material efficiency, Materials selection optimization, Teaching support, SW tool.

INTRODUCTION

For designing structures or parts of mechanisms it is necessary to choose suitable profiles with appropriate parameters (material, shape and dimensions). Sophisticated tools like topological optimization or finite element method are commonly used for more complex systems and basic formulas for stiffness and strength are used for simpler application. During the study, students come into contact and learn both ways of approaches where they start with practising basic formulas on very simple examples and then continue directly with SW calculation with finite element method. This leap is so huge that students cannot realise all bonds between profiles parameters sufficiently.

For these reasons a SW tool called TOY (Numerical optimizer) was created. The aim of SW is to teach students how changing of individual parameters affects a final design and how big of an influence individual parameters really have. With SW tool TOY students can design and evaluate hundreds of variations of profiles in a very short time, which standard SW based on basic formulas cannot do. SW also allows students to compare several different designs at once or find the best solution automatically. Moreover, SW can evaluate limitations due to loss of stability of profiles (so-called Limits imposed by local buckling) which basic formulas cannot do. This ability allows SW use also outside the university field for fast and easy preliminary profile design.

The mentioned tool is based on the theory of prof. Ashby. It uses numerical solver and is capable to provide partial or full profile optimization. This article is a follow up article [Kalina 2021].

BASES FOR CREATING SW

Before students start using the SW tool TOY, they are introduced to these principles in detail in the form of a lecture with a discussion and examples of the application of the given theory.

In the case of profiles loaded with torsion and bending, it is generally known which profile shapes are suitable for the load (for example I-profile is suitable for bending load and CHS is suitable for torsional load), and how changes in dimensions for a given shape affect changes in second moment of area values and stability.

However, there are no general rules for finding optimal boundaries between these parameters, i.e. designing a profile to use the material as efficiently as possible (i.e. using as little material as possible) while ensuring structural stability.

The theory of Prof. Ashby'S

This problem is solved by prof. Ashby's theory [ASHBY 2011], which introduces the so-called Shape factor, a dimensionless quantity that takes into account shape efficiency. The shape factor [Nelson 2016] for elastic bend (1) is defined as the ratio of the bending stiffness of the profile considered **(S)** to the bending stiffness for the square reference section **(S_0)**, which is considered to be a square bar with side width b_0.

$$\phi_B^e = \frac{S}{S_0} \ [-] \tag{1}$$

Where: *ϕ_B^e - Macro shape factor for elastic bending deflection [-], **S** - Bending stiffness [N/m], **S_0** - Bending stiffness for the square reference section [N/m]*

We put in (1) [Ashby 2011, pp.248] the formula for bending stiffness (***S*** [N/m]) (2) and after ***I_O***, which is the second moment of area for the square reference section, we substitute a spaced formula (3). And if we consider comparing beams from the same material, we get an adjusted formula (4). This newly obtained formula is generally valid for comparing all different beam shapes from the same material. We can also see from the formula (4) that the shape factor does not depend on the absolute size, but only on the ratio of the second moment of area. The shape factor de facto indicates the number of times the cut beam is stiffer against a square bar of the same cross-sectional area (square reference section).

$$S = \frac{E\,I}{L^2} \left[\frac{N}{m}\right] \tag{2}$$

$$I_O = \frac{{b_0}^4}{12} = \frac{A^2}{12} \left[m^4\right] \tag{3}$$

$$\phi_B^e = \frac{S}{S_0} = \frac{E\,I}{E\,I_0} = \frac{12\,I}{A^2} [-] \tag{4}$$

Where: *ϕ_B^e - Macro shape factor for elastic bending deflection [-], **S** - Bending stiffness [N/m], **S_0** - Bending stiffness for the square reference section [N/m], **I_0** - Second moment of area of the square reference section [m^4]*

The Shape factor for onset of plasticity or failure in bending is based on the ratios of the Section modulus of the section (***Z*** and ***Z_0*** [m^3]) and the resulting formula is expressed as (5) [ASHBY 2011, pp.254].

$$\phi_B^f = \frac{Z}{Z_0} = \frac{6\,Z}{A^{\frac{3}{2}}} \ [-] \tag{5}$$

Where: *ϕ_B^f - Macro shape factor for onset of plasticity or failure in bending [-], **Z** - Section modulus of the section [m³], **Z_0** - Section modulus of the square reference section [m³]*

Similarly, the above applies to the shape factor for elastic torsional deflection, where the final formula (6) is obtained. See more - theory of prof. Ashby [ASHBY 2011, pp.251].

$$\phi_T^e = \frac{S_T}{S_{T0}} = \frac{K}{K_0} = 7.14\frac{K}{A^2}\ [-] \qquad (6)$$

Where: *ϕ_T^e - Macro shape factor for elastic torsional deflection [-], **K** - Torsional moment of area [m⁴], **K_0** - Torsional moment of area for the square reference section [m³], **S_T** - Torsional stiffness [N.m], **S_{T0}** - Torsional stiffness for the square reference section [N.m]*

Furthermore, as the formula above the formula for the shape factor for onset of plasticity or failure in torsion (7) is given. See more - theory of prof. Ashby [ASHBY 2011, pp.256].

$$\phi_T^f = \frac{Q}{Q_0} = 4.8\frac{Q}{A^{\frac{3}{2}}}\ [-] \qquad (7)$$

Where: *ϕ_T^f - Macro shape factor for onset of plasticity or failure in torsion [-], **Q** - Torsional section modulus [m³], **Q_0** - Torsional section modulus for the square reference section [m³]*

The unique idea of this whole theory (which does not occur in other theories) is that limit values can be set for individual shape factors, which guarantee that compliance with them will not result in a limitation due to loss of stability (so-called Limits imposed by local buckling).

Formulas (8) and (9) [ASHBY 2011, pp.260] are empirically determined formulas, which indicate the limits that should not be exceeded for a given material, otherwise there is a risk of loss of beam stability, although according to analytical calculations will comply.

$$\left(\phi_B^e\right)_{MAX} \approx 2.3\left(\frac{E}{\sigma_f}\right)^{\frac{1}{2}}\ [-] \qquad (8)$$

$$\left(\phi_B^f\right)_{MAX} \approx \sqrt{\left(\phi_B^e\right)_{MAX}}\ [-] \qquad (9)$$

Where: *σ_f - Yield or failure strength of the material of the section [MPa], $(\phi_B^e)_{MAX}$ and $\left(\phi_B^f\right)_{MAX}$ [-] - Upper limits on shape efficiency.*

The theory is explained in more detail in paper [Kalina 2021]. The entire comprehensive theory is described in the book [Ashby 2011].

Another example of the application of prof. Ashby's theory is given in paper [Florian 2017]. This paper deals with connection of prof. Ashby's theory with optimization interface of software ANSYS. This link allows solving complicated multi-criterial problems that cannot be solved analytically.

Basic knowledge for the design of beams

From the basic formulas for **I** (second moment of area of the section) and **Z** (section modulus of the section) it is known that for solid bars their value (and thus their stiffness and strength) increases dramatically faster with increasing height than width. The same applies for profiles, which, however, include the influence of wall thickness or material distribution within the stands. In general, if we neglect the effect of stability, the material is used more efficiently, the more it is the neutral bending axis, which is indicated in Fig. 1.

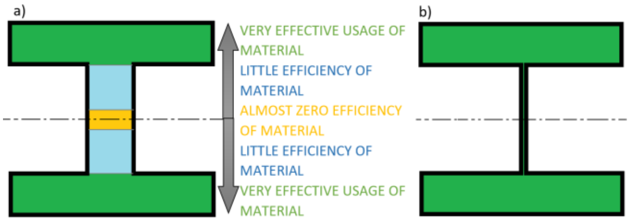

Figure 1. a) A description of the efficiency of material use on the real I-profile, b) "ideal" I-profile for the most efficient use of the material, without taking stability into account [Kalina 2021]

The same applies for torsion, where the efficiency of material utilization increases with its distance from the torsion axis. For more see the introductory part [Kalina 2021]. However, this approach has its limits and that is stability. However, with common analytical formulas, we cannot take into account the stability of the profile or assess it quickly.

The calculator presented below take into account the stability of the profile using ie. "Shape-factors" from the theory of prof. Ashby.

The table in Fig. 2 below gives an overview of the dependence of safety, deflection and weight on external dimensions and thickness under bending load (applies generally to square and elliptical pipes).

Dimension **B** is the width and dimension **H** is the height of the profile when loaded according to Fig. 2. Indicated parameter **T** is profile thickness, **s (x)** are safety factors against the given parameters, **w max** is maximal deflection of profile and **m real** is total weight of the profile.

INPUTS *(control parameters)*	**B**	x	↑	x	x	↓	x	
	H	x	x	↑	X	x	↓	
	T	↑	x	x	↓	x	x	
OUTPUTS *(dependent parameters)*	***s σ y***	↑	↑	↑	↓	↓	↓	
	s φBe max	↑	↑	↓	↓	↓	↑	
	s φBf max	↑	↑	↓	↓	↓	↑	
	deflection w max	↓	↓	↓	↑	↑	↑	
	m real	↑	↑	↑	↓	↓	↓	

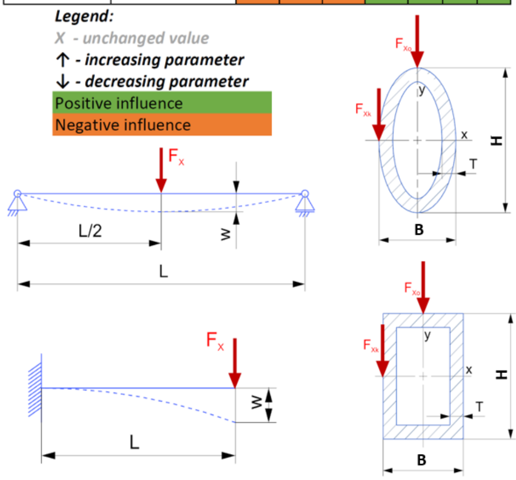

Figure 2. Overview of the dependences of safety coefficients, deflections and weights on external dimensions and thickness.

SW TOOL TOY (NUMERICAL OPTIMIZER)

TOY is a free education application that supports the practice of material selection optimization and the shape of cross-section selection. The aim of the application is to facilitate the optimisation process by implementing certain calculations that are necessary to find the optimal solution. The program should filter out the mechanical work associated with an optimization process, so the student can focus on choosing the appropriate strategy and optimization parameters.

The program offers

- simple control calculation (manual)
- suggestion of optimal dimensions for the specified shape (semi-auto)
- suggestion of optimal dimensions in the specified range (full-auto)

The program consists of a graphical user interface and a kernel (Fig. 3). GUI is used to select a solution method, input parameters, and show results. On the top there is an Option bar and at the bottom there are two windows. The left window called User Input is for specifying parameters by user and the second window called Results for displaying the solution of the specified job. The kernel contains a collection of mini-scripts for solving individual tasks, addressed memory and a master script that controls every operation done by the kernel. Two new mini-scripts, a report generator, and an export to a text file have been created to share data with the teacher. The report generator has ability to convert a part of the memory into structured text form. The export to the text file writes the structured text to the file every time the program performs a calculation. To increase user´s convenience, the export can create output file and write additional data to its end even after TOY is restarted. Another good feature is the possibility of the student to open the output file in any text editor and to assess the data before they sent it to the teacher. For exercise needs ~~in 2021~~, the program has been adapted (Fig. 3)

- only simple control calculation allowed (Manual)
- the program continuously exports each input and results to a text file (report)

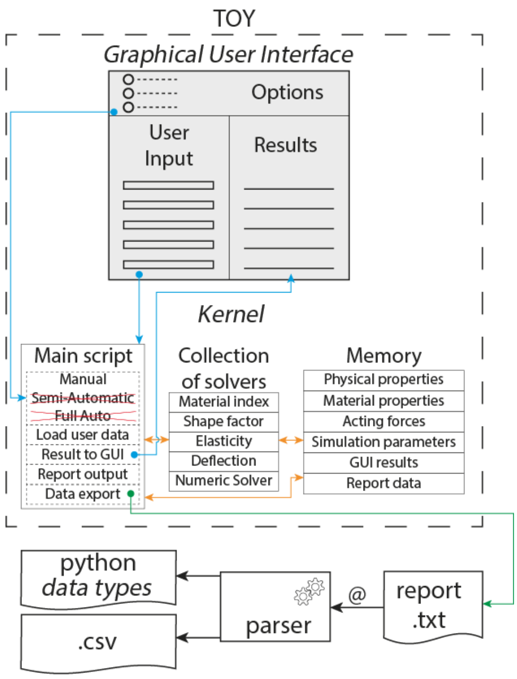

Figure 3. TOY block diagram

A more detailed description of the function and user´s interface is described in [Kalina 2021].

USE OF SW TOOL TOY IN TEACHING

After the students were introduced to the theory, see the previous chapter, the SW tool TOY was introduced to the students and then they were given a test example to solve. They were allowed to ask any questions they had about the matter.

Parameters of the solved example

With the program TOY the students tried to find the lightest variation of a beam on two supports loaded by force in the middle. They knew the length of the beam, the maximum allowed dimensions of the beam, the maximum deflection, the type of the material - steel S235JR and the maximum allowed stress. The students could choose what kind of shape of the beam they wanted to solve – CHS, EHS, SHS, RHS (SHS = Square Hollow Section, RHS = Rectangular Hollow Sections, CHS = Circular Hollow Section, EHS = Elliptical Hollow Section).

Students solved one type of assignment in two runs with different parameters. First run was intended for testing purposes and verify that everyone has understood the assignment.

Loaded force	**F = 8000 N**
Length	L = 3000 mm
Maximum height of the beam	$H_{max.}$ = 200 mm
Maximum width of the beam	$B_{max.}$ = 200 mm
Maximum thickness of the beam	$t_{max.}$ = 20 mm
Maximum deflection	$w_{max.}$ = 10 mm
Young's module	E = 210 GPa
Density	P = 7850 kg/m^3
Tensile yield strength	σ_y = 250 MPa
Tensile strength	σ_{ts} = 350 MPa
Maximum allowable stress	σ_a = 150 MPa
Price index	P = 1

Table 1. Entered values of 1st run of assignment solved using tool TOY

The second run of assignment for TOY program was evaluated. The only difference is that students did not have the specified maximum dimensions of the beam instead of it the students needed to input ratio between the height and the width of the beam (H/B) and its thickness (T). Maximum allowed ratio H/B =< 5. All values were the same as in the previous assignment except for the loaded force, the length and the maximum deflection.

Loaded force	**F = 15000 N**
Length	L = 5000 mm
Maximum deflection	$w_{max.}$ = 15 mm

Table 2. Entered values of 2nd run of assignment solved using tool TOY

Student results

Eighteen students participated in the ranked test, 18 files were delivered into teacher's e-mail.

Eighteen students generated 3673 attempts, average number of attempts is 204 per student. The most active student generated 2.33 times the average number of attempts, the least active one created only 11% of the average of submitted results. The least active student was also the only one who did not reach the maximum recommended weight of 90 kg. Most of the classroom was able to suggest design lighter than 85 kg (Table 3).

student	mass [kg]	σ_{Bmax} [MPa]	y_{max} [mm]	Φ_{Be} [1]	Φ_{Bf} [1]	Φ_{Be} lim [1]	Φ_{Bf} lim [1]
Q	84.52	150.00	11.12	43.28	7.51	56.34	7.51
O	84.53	150.00	10.99	43.77	7.50	56.34	7.51
A	84.54	149.95	11.23	42.84	7.51	56.34	7.51
N	84.59	149.99	11.00	43.67	7.50	56.34	7.51
H	84.66	149.88	11.09	43.24	7.49	56.34	7.51
G	84.67	150.00	11.06	43.36	7.49	56.34	7.51
K	84.72	149.47	10.94	43.78	7.51	56.34	7.51
L	84.74	149.44	10.94	43.77	7.51	56.34	7.51
J	84.90	148.99	10.99	43.41	7.51	56.34	7.51
P	84.90	149.74	11.00	43.35	7.47	56.34	7.51
R	84.91	149.91	11.31	42.18	7.46	56.34	7.51
M	84.93	149.09	10.95	43.52	7.50	56.34	7.51
B	85.24	149.93	12.93	36.59	7.41	56.34	7.51
I	85.24	149.93	12.93	36.59	7.41	56.34	7.51
D	85.47	149.96	12.93	36.38	7.38	56.34	7.51
C	85.58	149.58	12.90	36.38	7.39	56.34	7.51
F	85.72	149.17	12.92	36.21	7.39	56.34	7.51
E	102.99	119.60	8.47	38.25	7.00	56.34	7.51

Table 3. Classroom results

Student **Q** (the most active) made two times more attempts than student **O** and probably tried to disrupt achieved results during first 200 attempts. Then he reached maximal allowed H/B ratio 5 and got best weight of all (Fig. 4). Student **O** has a slightly different approach, when trying to find an optimal design, he polished dimension with minimal disturbances (Fig. 5).

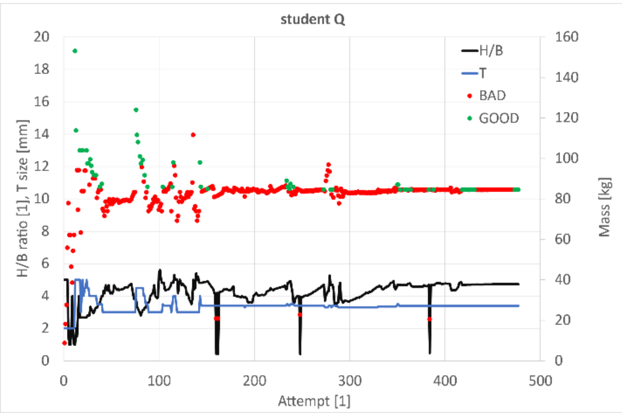

Figure 4. Histogram of student Q (best by mass)

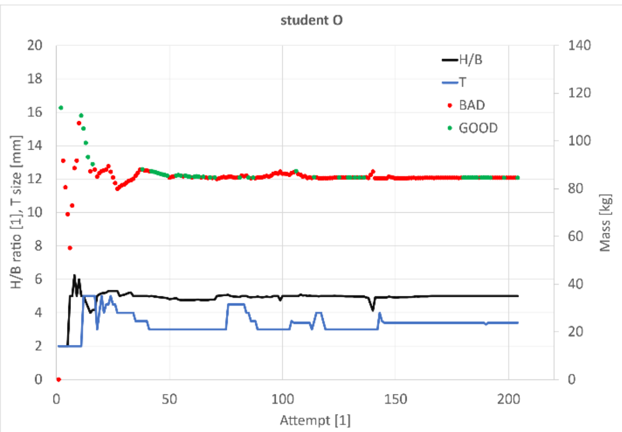

Figure 5. Histogram od student O (best by EF metrics)

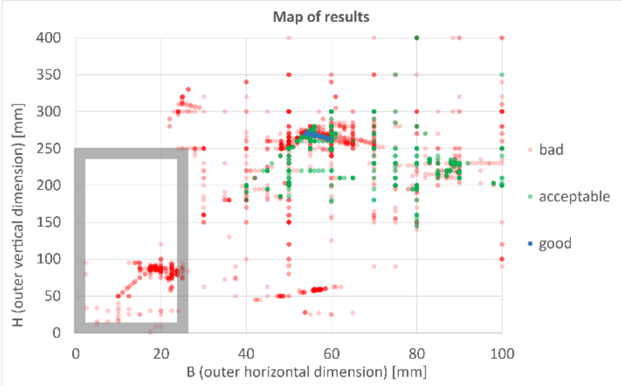

Figure 6. External dimension and weight (coloured by result)

By sorting each student's best minimum weights into a chart (Fig. 8), it shows approximately asymptotic dependence on the optimal (absolutely lowest) weight of the task, which was expected. From this result we can imply that most students tried to reach a maximum weight of less than 90 kg, although this was not necessary.

No significant correlation was found between the number of attempts per student submitted and the minimum weight achieved (Fig. 7). The best result was achieved with more than twice the attempt of the 2nd best result. All students fit into the time limit of 45 minutes. In terms of effective use of the exercise time pool, the original 45minute time limit for the solution could be shortened.

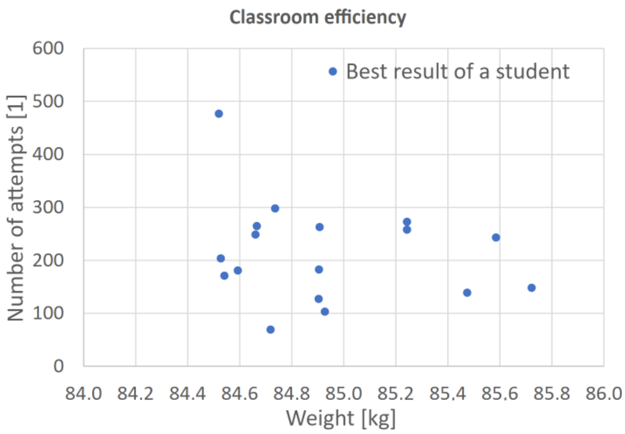

Figure 7. Best result of student compared to number of attempts

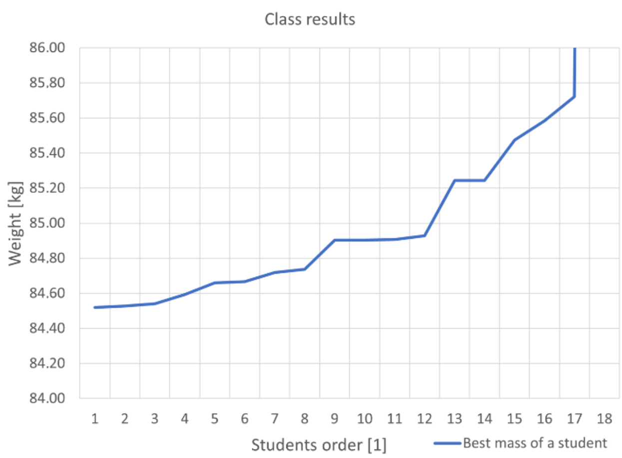

Figure 8. Student's order and mass

Analysis of the results in terms of errors

Of all the correct solutions, 930 are acceptable. Another 202 submitted results met strength and deflection conditions, but the aspect ratio was greater than 5, which was a limit of the external dimensions ratio. The most common reasons for discarding results were failure to meet the strength condition (711), exceeding the limit of shape factor of plasticity (506), and simultaneously exceeding the conditions of strength and stiffness (635). These three most common errors caused 53.4% of the submitted results to be rejected. Of the 31 possible classes of erroneous results (given by its combinations) of errors, 15 occurred (Fig. 9).

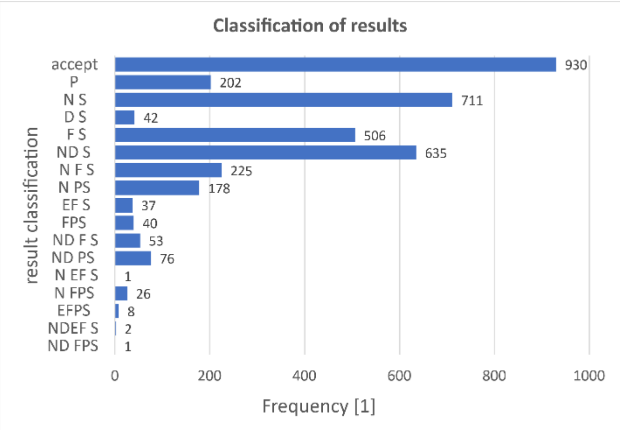

Figure 9. Result classification

A (accept)	Design ok
S	Design has some flaws
N	Allowed stress of material limit exceeded
D	Allowed deformation limit exceeded
E	Elastic shape factor limit exceeded
F	Fatigue shape factor limit exceeded
P	Height/width max. ratio exceeded

Table 4. Error symbol description

Below is the frequency of correct results (A) and their errors for each student, combinations are not considered. Although the occurrence of a particular type of error depends in part on specifying beam dimensions and boundary conditions, it is surprising that the elasticity shape factor limit was exceeded in only 24 cases (Fig. 10). Although there is a certain relationship between stress, deformation, and its corresponding shape factors, in this case a statistically significant relationship has not been established. A subjective description of the custom strategy was not required of students.

student	A	N	D	E	F	P
Q	12	57	5	1	60	1
O	26	47	2	0	34	13
A	38	42	5	1	27	7
N	26	43	3	0	3	60
H	28	40	16	6	29	13
G	20	47	6	1	36	31
K	29	32	6	0	42	4
L	37	46	3	0	16	16
J	10	29	2	0	30	61
P	39	54	20	1	9	5
R	42	43	24	2	12	9
M	45	35	3	0	29	4
B	12	83	72	1	6	14
I	12	85	75	0	8	4
D	41	39	12	1	14	10
C	17	69	54	0	10	12
F	32	26	27	10	31	4
E	23	68	64	0	9	0

Figure 10. Error frequency per student (without combination)

The relationship between the mass achieved or the order and the number of errors does not show a significant statistical dependence, the correlation coefficient is less than 0.2.

Analysis of the results based on prof. Ashby's theory

Although the smallest achieved beam weight proposed by the student was accepted as the final correct result, the results should also be evaluated in terms of the prof. Ashby's theory. Since the specified material was the same for all students, the parameters of the material indicators were also the same (with the exception of one student, who used different material, but his results were evaluated with the parameters of the specified material).

An EF metric has been created for this assessment, see formula (10), (11). This metric has no deeper mathematical or other meaning other than comparing the relationship between shape factors and weight.

The introduced EF metric is a comprehensive evaluation of the achieved results, as it evaluates all three parameters simultaneously. The higher the value of the EF parameter in tab.5, the more efficiently the material is used.

$$EF \uparrow \{\phi_B^e \uparrow \quad \phi_B^f \uparrow \quad m_{best} \downarrow\} \qquad (10)$$

$$EF = \frac{\phi_B^e \cdot \phi_B^f}{m_{best}} \; [kg^{-1}] \qquad (11)$$

The significance of the nature of both shape factors is clear. However, the shape factor does not include actual dimensions, only their proportions, therefore the product of shape factors is divided by the achieved weight.

student	mass [1]	ΦBe [1]	ΦBf [1]	EF [kg⁻¹]
O	84.53	43.77	7.50	3.89
K	84.72	43.78	7.51	3.88
L	84.74	43.77	7.51	3.88
N	84.59	43.67	7.50	3.87
Q	84.52	43.28	7.51	3.84
M	84.93	43.52	7.50	3.84
J	84.90	43.41	7.51	3.84
G	84.67	43.36	7.49	3.83
H	84.66	43.24	7.49	3.83
P	84.90	43.35	7.47	3.81
A	84.54	42.84	7.51	3.80
R	84.91	42.18	7.46	3.71
B	85.24	36.59	7.41	3.18
I	85.24	36.59	7.41	3.18
D	85.47	36.38	7.38	3.14
C	85.58	36.38	7.39	3.14
F	85.72	36.21	7.39	3.12
E	102.99	38.25	7.00	2.60

Table 5. Results with EF metrics

5 DISCUSSION

5.1 *Learning objectives for SW Tool TOY*

The central idea of learning objectives is that of shape efficiency and the ability to quantify it in a single set of dimensionless shape factors ϕe and ϕf . They measure the factor by which the shaped section is stiffer or stronger than one of a standard shape, which we take to be a solid square section of the same area.

Learning Outcomes are based on a taxonomy of knowledge and understanding as the basis, skills and abilities as necessary for the practical use of knowledge and understanding, followed by acquired values and attitudes enabling assessments and responsible use of these abilities.

Intendend Learning Outcomes for SW Tool TOY :

Knowledge and Understanding : understanding of the concept of shape efficiency.
Skills and Abilities : ability to select efficient material-shape combinations.
Values and Attitudes : awareness of howmaterials and shape interact.

Background

This project was planned within the Student Grant Competition of the UWB in Pilsen (SGS). The above examples were solved by students of the Department of Machine Design at the Faculty of Mechanical Engineering within the subject Extended Fundamentals of Design (RZK) using the above-described SW calculators.

The teaching of the whole Summer semester 2021 took place online, due to the COVID-19 pandemic. Online tuition was an advantage when the students solved the exercises by themselves. Another advantage due to the pandemic situation was almost 100% participation in every online lecture and exercise. Thanks to the "lockdown", students were less distracted by other activities, which was reflected in their higher study activity than can be observed in "normal" times.

By a subjective estimate, it can be said that the distribution of knowledge and diligence of the students of the subject RZK copied the normal distribution of the Gaussian curve. From pedagogical practice it is possible to observe that the team of students is influenced by one or several students, whose characteristics differ significantly from the rest of the team. This is true both in a positive sense and, unfortunately, in a negative sense. In this group of students, however, this influence was positive. There were several students who achieved excellent results, both in terms of knowledge and diligence. This statement is proved by the results described above (achieving the lowest weight with the highest number of attempts to select the dimensions of the profile).

After creating the SW tool TOY, we asked ourselves the following questions:

1) Are the students able to use SW after short introduction?

2) Have the students achieved suitable solution during 45 min term?

Add 1) Yes, all students were able to use SW during remote MS Teams session.

Add2) Mostly yes, except for one student, all of them met minimum weight requirement.

From collected data and evaluation it was found that almost all students were successful with these SW tool and found proper solution to the assignment quite easily and quickly. This indicates SW tool as suitable and easy to use for this kind of solutions.

CONCLUSION

The aim of SW was to teach students how change of individual parameters affects a final design and how big of an influence individual parameters really have. SW tool TOY is based on the theory of prof. Ashby. It uses numerical solver and is capable to provide partial or full profile optimization. SW can evaluate limitations due to loss of stability of profiles (so-called Limits imposed by local buckling) which basic formulas cannot do.

Based on the results of students, it can be stated that the aim of the project has been met. Thanks to SW tool TOY, the students mastered the problem of the dependence between the material properties and the shape of the profile of the part loaded by bending.

FINAL NOTE

Presented SW tool TOY is free experimental educational application, provided "as is" without any warranty. Authors has no liability for any kind of damage or loss caused by the application, its use or using application output anyway.

SW tool is free to download at:
www.home.zcu.cz/~mazini/

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