Feasibility study tool for semi-rigid joints design of high-rise buildings steel structures

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Abstract. There are many ways to consider the final cost of the high-rise building structures and to define, which of their different variations are the most effective from different points of view. The research of Jaakko Haapio is conducted in Tampere University of Technology, which aims to develop a method that allows determining the manufacturing and installation costs of steel structures already at the tender phase while taking into account their details. This paper is aimed to make the analysis of the Feature-Based Costing Method for skeletal steel structures proposed by Jaakko Haapio. The most appropriate ways to improve the tool and to implement it in the Russian circumstances for high-rise building design are derived. Presented tool can be useful not only for the designers but, also, for the steel structures manufacturing organizations, which can help to utilize BIM technologies in the organization process and controlling on the factory.

1 Introduction

One of the greatest accents in the steel structures researches is the optimization of the design model. It takes into account factors of economics, ecological influence on the environment and safety of the structure. Prediction of the structure's manufacturing costs considers as a complicated operation. The real price of the different design decisions of the building structure depends on its geometrical characteristics, material, manufacturing quality, etc. There are many ways to consider the final cost of the structures and to define, which of their different variations are the most effective from different points of view. The research of Jaakko Haapio is conducted in Tampere University of Technology, which aims to develop a method that allows determining the manufacturing and installation costs of steel structures already at the tender phase while taking into account their details. In order to take into consideration all the features of the joint fabrication process, the macros for the modelling program Tekla can be used at the tender phase. The program is based on the calculation methods developed by Jaakko Haapio in [1], which use time-based cost functions for all the process of steel structures manufacturing, transportation and installation. In the program, also, carbon dioxide emissions of the structure can be easily derived from the Building Information Model (BIM) of the steel structure.

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In the work Jaakko Haapio the economic analysis tool for skeletal steel structures was studied in order to make analysis and to find the most appropriate ways to optimize the design and construction processes. As a result of analysis a method was presented that allows to determine the manufacturing, transportation and installation costs of steel structures already at the tender phase while taking into account their details. This is possible by analysis of the initial building models at the tender phase. The special macros of the modelling program Tekla allows to take into consideration all the features of the joint fabrication process. Preset parameters were studied in the Jaakko Haapio time-based cost functions of all steel structures manufacturing processes at the workshop and during installations are known. The development and testing of these cost functions in Russian circumstances is the subject of the research.

1.1 Feasibility study methods

1.1.1 Feature-Based Costing Method and other cost models

At the preliminary design step the cost and emissions can be calculated by the method presented in [1]. It is based on the Feature-Based Costing Method, where feature is an attribute which affects the costs of the structure during the project.

It involves dividing the manufacturing process into cost centres of a specified floor area and height, equipment suitable for executing the required process (i.e. drilling a hole) and a certain number of workers. These resources have a fixed per minute cost, whether the process is running or not. Some cost components are related only to process time, i.e. electricity consumption of the equipment. They are called variable costs. The time required by the process is the sum of non-productive time, i.e. fixing the profile to the equipment, and process time, i.e. drilling. Total process cost is the sum of the fixed cost multiplied by total time plus the variable cost multiplied by process time. Some processes may also involve non-time related cost components. These are added to time-dependent costs.

The basis of the feature-based costing method was described in the Jaakko Haapio doctoral thesis. The material flow of a skeletal steel assembly shown in Figure 1. The workshop is divided into cost centres, where single work phases are performed. The time spent at each cost centre is converted to costs including equipment, wages, energy, rents etc.

Total cost considers as a sum of the cost derived for each cost center. The generic form of the cost for each cost centre is:

$$C_k = \frac{(\mathrm{T_{Nk}}+\mathrm{T_{Pk}})(\mathrm{c_{Lk}}+\mathrm{c_{Eqk}}+\mathrm{c_{Mk}}+\mathrm{c_{REk}}+\mathrm{c_{Sek}})}{u_{\mathrm{k}}} + T_{\mathrm{Pk}}(c_{Ck} + c_{\mathrm{Enk}}) + C_{Nk} \tag{1}$$

where $\mathrm{C_k}$ = total cost of cost centre k [€]
$\mathrm{T_{Nk}}$ = non-productive time of cost centre k [min]
$\mathrm{T_{Pk}}$ = productive time of cost centre k [min]
$\mathrm{c_{Lk}}$ = unit labour cost of cost centre k [€/min]
$\mathrm{c_{Eqk}}$ = equipment installment unit cost of cost centre k [€/min]
$\mathrm{c_{Mk}}$ = unit cost of equipment maintenance of cost centre k [€/min]
$\mathrm{c_{REk}}$ = unit cost of real estate of cost centre k [€/min]
$\mathrm{c_{Sek}}$ = unit cost of real estate maintenance of cost centre k [€/min]
$\mathrm{c_{Ck}}$ = unit cost of time-related consumables needed in processing of cost centre k [€/min]
$\mathrm{c_{Enk}}$ = unit cost of energy needed in processing of cost centre k [€/min]
$\mathrm{c_{Nk}}$ = total cost of non-time-related consumables used in cost centre k [€]
$\mathrm{u_k}$ = utilisation ratio of cost centre k [decimal, ≤1]

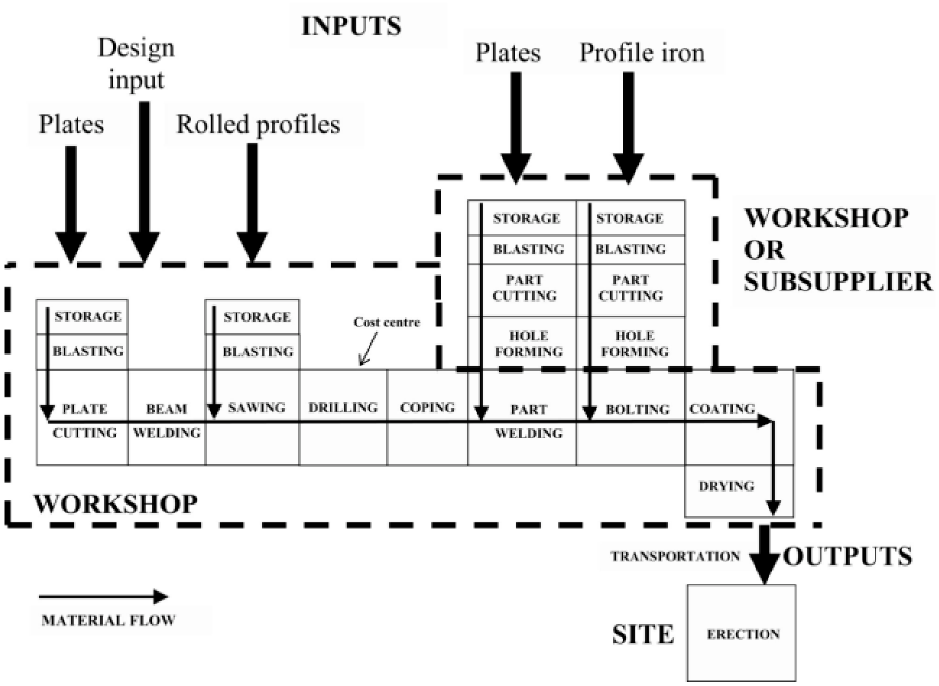

Fig. 1. Manufacturing process flows [1]

1.1.2 Feasibility study methods development in Russia

The issues of steel structures optimization process was considered in the researches of Ya.M. Lichtarnicov [2], I.S. Cholopov [3-5] and others.

The function of cost and labour intensity for the steel structures optimization process is the key function in the research of Ya.M. Lichtarnicov, that was published in 1979 y. From that time price levels, technological operations, labour intensity and other factors have changed a lot. So, today it is extremely important to find a way to deal with dynamically updated database for cost function input data. The research mostly deal with feasibility study of different design variants of space arrangements and only one chapter for the joints.

In the cost analysis method of Ya. M. Lichtarnikov the cost of steel structures estimates based on mass calculation G, that consists of two parts:

G_0 - mass of main parts,

G_s - mass of secondary parts.

Main parts mass can be determined by stress distribution and buckling resistance of the structure. Secondary parts mostly uses by any design consideration and in order to provide adequate behaviour of the structure. The mass of the secondary parts can be taken into account by construction coefficient of mass ψ. So, the formulae for structure mass:

$$G=G_s+G_0=\psi\cdot G_0 \tag{2}$$

The labour intensity can be calculated by multiplying the mass and the coefficients that Ya. M. Lichtarnikov get from the analysis of big database of different structures costs. The coefficient of seriation that can be taken into account in order to provide better accuracy of manufacturing cost calculation.

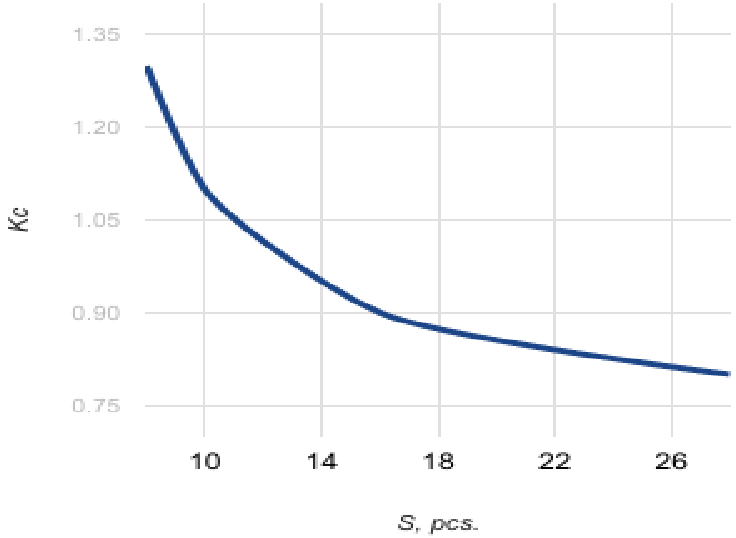

Fig. 2. The coefficient of seriation KC dependence from the quantity of equal parts in the one production run diagram [2]

For each steel grade the reduction and correction coefficients should be included in analysis that can be taken from tables 1-2. [2]

Table 1. The correction coefficient KT for different steel grades.

C38/23	C46/33	C52/40	C60/45	C70/60
1	1.5	1.18	1.22	1.36

For construction of main steel details from different steel grades the reduction coefficient α is used, that has the square root dependence for the labor intensity calculation (Table 2).

Table 2. Average value of reduction coefficient α for the effective steel classes and profiles.

	α	$\sqrt{\alpha}$
Steel type and profile	0.89	0.94
Effective steel class		
Thermally stabilised carbon steel, yield stress 290 MPa, class C44/29	0.83	0.91
Low-alloyed steel, basic bearing structure of general purpose, yield stress 330-400 MPa, class C46/33, C52/40	0.72	0.85
High-impact low-alloyed steel of general purpose, yield stress 450 MPa, class C60/45	0.69	0.82
Low-yield constructions for the structures in the northern regions, yield stress 290-330 MPa, class C44/29-C46/33	0.91	0.95
Economic hot-rolled profile		
Wide-flanged beam	0.97	0.98

The example of correlation between cost of steel structures transportation and the region of construction for columns and gantry girders can be determined from Table 3. [2]

Table 3. The enlarged average values of the transportation costs.

Type of structures	European part of USSR, besides of Komi ASSR, regions and republics of the Northern Caucasus,territories of the Urals	Territories and regions of Northern Caucasus	Ural, Western Syberia, Union republics of the Central Asia	Carelian ASSR, Eastern Syberia	Far East
Columns with mass less than 15 tons	1	1.19	1.19	1.39	4.94
Columns with mass more than 15 tons	1	1.84	1.31	1.53	5.43
Girder from hot-rolled profiles	1	1.71	1.30	1.51	5.28
Girder with the mass less than 3 tons	1	1.68	1.19	1.39	4.94
Girder with the mass 3-5 tons	1	1.86	1.38	1.57	5.10
Girder with the mass 5-15 tons	1	1.66	1.18	1.37	4.86
Girder with the mass more than 15 tons	1	1.78	1.31	1.52	5.37

While dealing with the installation cost it is necessary to include in analysis the steel grade and the location of the site. The correction coefficients for steel grade was presented in table 3. The location of construction site can be taken into considerations by the correction coefficient Kp from table 4. [2] The steel grade correction coefficient for different types of structures is given in table 5. [2] The correlation between the installation costs from the height and the cost of painting for different weights of structures is shown in the tables 5-6. [2]

Table 4. The average values of the coefficient Kp.

	The region of the structural erection	Kp
1	The European part of the USSR, besides of Komi ASSR, regions and republics of the Northern Caucasus, territories of the Ural, the piedmont of the western Urals	1
2	Udmurt ASSR, territories of the Ural, the piedmont of the western Urals, Western Syberia, republics of the Central Asia	1.1
3	Carelian ASSR, Comi ASSR Buryat ASSR, Krasnoyarsk territories and regions of the Eastern Syberia	1.13
4	Far eastern region	1.21
5	Murmansk region	1.27

Table 5. The value of the coefficient Km for different steel grades.

Type of structures	Steel class		
	C38/23	C46/33	More than C46/33
Columns with the weight less than 8 tons and framework less than 3 tons	1	1.07	1.17
Columns with the weight more than 8 tons and framework more than 3 tons	1	1	1.2
Crane beams	1	1.12	1.22

Table 6. The installation costs and the cost of painting for columns.

Constructions	Installation cost for the different heights			Cost of painting
	Less 15 m.	15-25 m.	25-40 m.	
Steel columns with weight: less than 8 t.	1	1.11	1.14	0.42
From 8 t. to 15 t.	1	1.10	1.13	0.28
More than 15 t.	1	1.06	1.07	0.25
Column connections	1	1.06	1.08	0.76
Framework structure	1	1.09	1.12	0.55

There are more different correction coefficients and more detailed cost functions, that can be derived from the research of Ya. M. Lichtarnikov [2]. It may be included in analysis in the future improvement of the method, at least, as coefficient that provide relative functions of different feature dependences, but in that thesis was excluded from calculations.

1.2 Semi-rigid joints definition by Eurocode 3

In Eurocode 3 [6] connections are classified regarding their strength and their stiffness. The stiffness classification is clear from Figure 1. It is shown (see Gomes et al. [7]) however that if plastic rotations are adopted the use of initial stiffness as a unique description parameter is not correct. In other words the initial stiffness of the connection is not enough to classify the connection properties. In this research that method of semi-rigid joints description is enough.

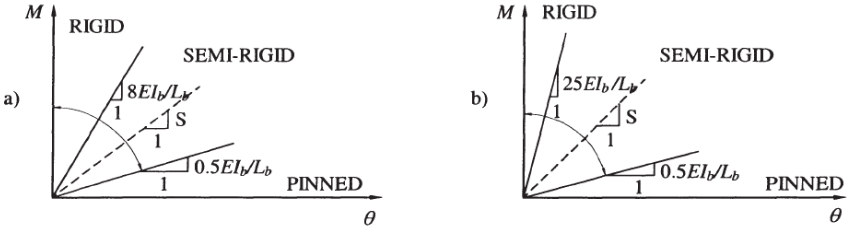

Fig. 3. Classification of beam-to-column connections by stiffness according to the Eurocode 3 - Annex J (revised): a) unbraced frames and b) braced frames. The region studied in the paper is denoted by arrow.

2 Design example

The third numerical example is a three bay, ten storey steel frame designed by Xu and Grierson [8]. Kameshki and Saka [9] as well as Foley and Schinler [10] performed weight optimization on the same example using Genetic Algorithms and evolutionary computation. The frame configuration, dimensions and loading are shown in Fig. 4. The used steel grade is S235, with a modulus of elasticity of 210 000 MPa and yield stress of 235 MPa.

2.1 Design procedure description

Basic times of different manufacturing operations are evaluated according to a fabrication cost model of joints developed at the Laboratory of the Design Optimization and Environment Engineering (LOCIE) of Polytech'Savoie (France). This cost model was first developed by Hamchaoui [11] and incorporated into a computerized module for joint design. Bel Hadj Ali updated the cost model for structural optimization with semi-rigid joints [12,13].

Design is performed considering only members as design variables while beam-to-column connections are specified to be of three type. Column bases are supposed to be rigid. Optimization variables are thus limited to 10 groups of beam members and 10 groups of column members. Beam members at each storey level are to have the same European IPE section while exterior and interior column members are to have the same European HEB section over two stories (Fig. 4).

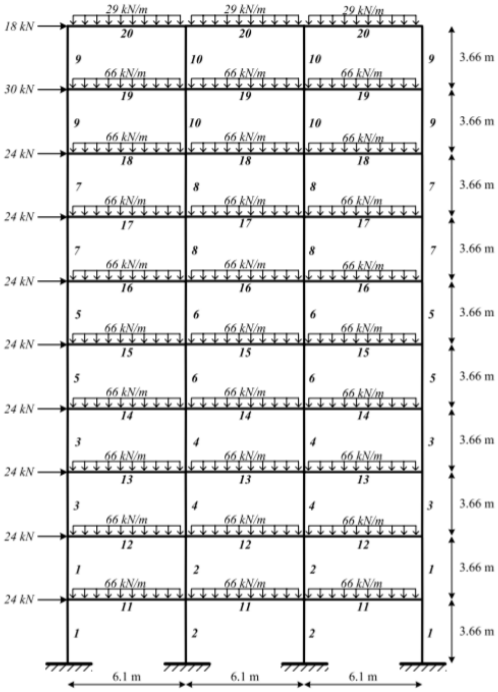

Fig. 4. Three bay, three storey frame

2.2 Results

Optimum designs obtained for frames with rigid and semi-rigid connections are presented in Tables 7, for unbraced and braced frame configurations, respectively.

Table 7. Design results for braced three bay, ten storey steel frame.

Member group	Joint type		
	Rigid	Semi-rigid	Pinned
1	HEB 300	HEB 280	HEB 260
11	IPE330	IPE330	IPE400
Total cost by original tool	82 034	66 290	75 572
Total cost by developed tool	70 970	57 632	61 214

3 Conclusions

Structural optimization has been widely studied over the last decades and extensive work has been done in the case of optimal design of steel frames [14-20]. However, engineers have few tools to approach cost optimization in a systematic manner. Here are som developments that should be made:

1. Dynamic data collection. The cost of hot-rolled steel profiles varies significantly for fairly short periods of time, thus prices monitoring for products, wages, prices for consumables and electricity can be updated by the dynamically replenished database, which will allow to change the specific coefficients of costs.

2. Localization accounting. In large countries, such as Russia, it is critically important where the construction will be arranged, where the structures should be transported. Specific costs will be strikingly different.

3. Possibility of information exchange. The designer can provide BIM models to the manufacturer, in order to plan the production process, calculate the costs, track expenses, plan purchases and reuse of production balances. In return the designer gets access to some of the information gathered by ERP and SAP systems of manufacturer, to conduct the feasibility study. So the plant can automate production planning, and the designer has the opportunity to improve the tool for feasibility studies.

Here are some of assumption made in Jaakko Haapio feasibility study tool [1]:

1. After an investment into a workshop or site facility has been made, many of the related cost factors are fixed, and the costs will run for their life time regardless of the utility rate of these factors.
2. The time used to produce a feature is essential, and a time-based approach for estimating its cost is justifiable.
3. The process consists of productive time and non-productive time. A virtual workshop was established to be able to estimate the non-productive time as well as the cost of real estate.
4. Transportation between cost centres is not considered in this thesis.
5. The aim of the used form of cost calculation is to make use of so-called deep knowledge. By using it the components of the cost function of a cost centre represent the actual, cost-causing processes and the use of statistical factors is minimised.
6. Usually, the designer does not know during the basic design phase which workshop is going to manufacture the structure, and consequently does not know which facilities will be used to manufacture it. The designer must be aware of this uncertainty and might possibly conduct a sensitivity analysis with selected parameters.
7. Typically columns are grouted to the foundations after bolting, but this process is not dealt with here. Stiffening of the frame is effected by rigid joints, steel diagonals, wall structures or a stiffening superstructure such as a concrete tower. The thesis does not deal with secondary structures, such as wall and roof claddings, stairs, handrails, floor slabs or plates, or cold formed profiles.
8. Coating is assumed to be carried out by painting, hot dip galvanising is not dealt with.
9. Columns and braces are hot rolled I-profiles (IPE, HEA, HEB), rectangular hollow sections (RHS), circular hollow sections (CHS), welded I-profiles (WI) or box profiles (WB). Beams are hot rolled or welded I-profiles or welded box beam profiles (WQ).
10. Unit costs and costs of equipment and investments are revised to correspond to the 2009 price level in Finland.

Most of them can be neglected while using above mentioned ways of method development.

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