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EVALUATION OF ANALYSIS METHODS FOR THE DESIGN OF FRAME STRUCTURES

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Abstract. *By the use of numerical methods and the rapid development of computer technology in the recent years, a large variety, complexity, refinement and capability of partial models have been achieved. This can be noticed in the evaluation of the reliability of structures, e.g. the increased use of spatial structural systems. For the different fields of civil engineering, well developed partial models already exist. Because these partial models are most often used separately, the general view is not entirely illustrated. Until now, there has been no common methodology for evaluating the efficiency of models; the trust in the prediction of a special engineering model has generally relied on the engineer's experience. In this paper the basics of evaluation of simple models and coupled partial models of frame structures will be discussed using sustainable numerical methods. Furthermore, quality classes (levels) of design tasks will be defined based on their practical relevance. In addition, analysis methods will be systemized. This includes different evaluation methods, criteria, normalization methods as well as weighting possibilities.*

1 INTRODUCTION

The prognosis of function ability, safety and reliability of structures is usually considered by using different partial models with practical couplings. The use of simplified 2D systems was quite common several years ago due to the limited technology regarding structural analysis. If the analysis of 3D systems was necessary, the engineer used simple couplings of different 2D models. This created incompatibilities in the boundary conditions and further investigations were necessary to minimize their effect [1].

By the use of numerical methods and the rapid development of computer technology in the recent years, a large variety, complexity, refinement and capability of partial models have been achieved. This can be noticed in the evaluation of the reliability of structures, e.g. the increased use of spatial structural systems. Nevertheless, several partial models are used in different fields of activities, which are coupled either by their responses or direct sequentially. The realism of reliability statements depend basically on the realism of the modeling of actions, the structure, the material and the coupling conditions as well as on the capability of the calculation methods.

The advanced computational power offered by the digital computers enable the engineer to model complex structural systems and run complicated numerical calculations. Nevertheless, a need for a compatible representation of the applied structural actions is vital to perform a better analysis of the coupled partial models. The extent of the applicability of this statement should be critically analyzed.

For the different fields of civil engineering, well developed partial models already exist but are most often used separately and for this reason the general view is not entirely illustrated. Until now, there has been no common methodology to evaluate the efficiency of the models. The uses of a model and its predictions have been generally based on the engineer's experience.

In this paper the basics of evaluation of simple models and coupled partial models of frame structures will be discussed using sustainable numerical methods. Furthermore, quality classes (levels) of design tasks will be defined based on their practical relevance. In addition, analysis methods will be systemized.

The objective of an evaluation should show the quantitative difference between the various quality classes by using a scalar value filled in Fig. 1. For this reason it is necessary to gather all relevant properties for these models. Subsequently, these criteria (Figures of Merit - FoM) are used in establishing a complex evaluation procedure. Due to the large impact of buildings on their environment it is important to use a complex evaluation procedure. Therefore, the Efficiency Indicator Method (EVM) [2] was used and modified to the Model Efficiency Analysis (MEA). With this holistic evaluation it should be possible to guarantee an effective use of advanced analysis methods for engineers.

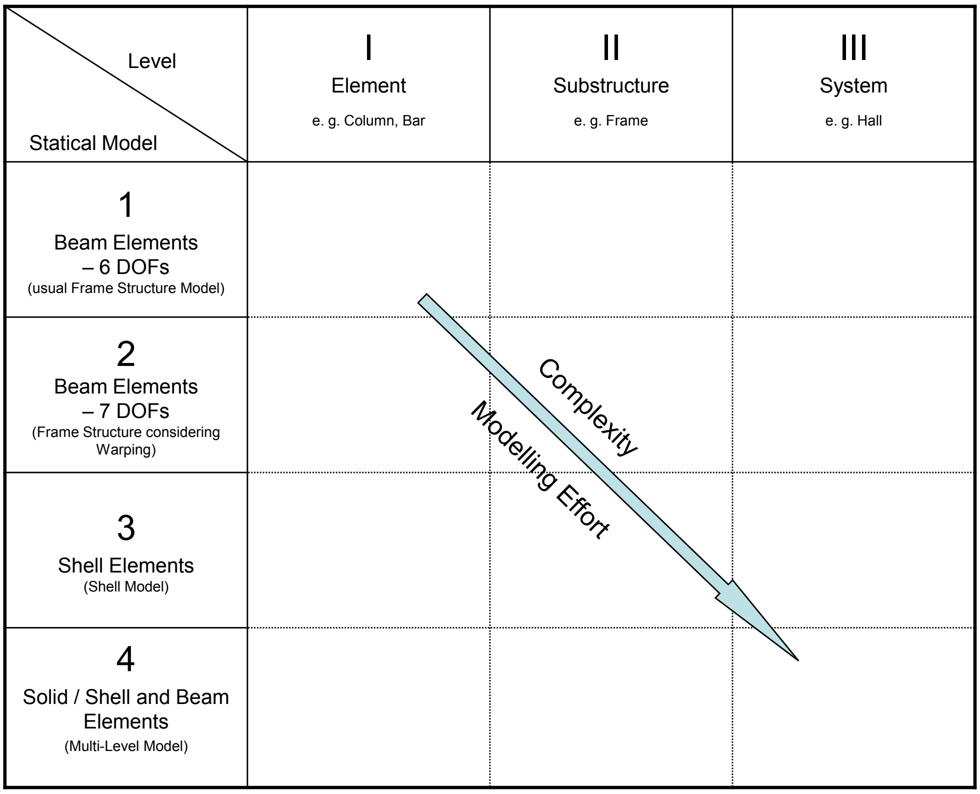

Figure 1: Evaluation Matrix

2 ASSESSMENT METHODS

There are numerous papers on assessment and evaluation methods. Tab. 1 contains an overview of some important methods. These are generally formulated and are applicable in variety of different fields. A more detailed evaluation of the analysis methods in structural engineering is required.

The following is a list of requirements, which are needed in developing the evaluation of analysis methods:

- designed for the assessment of models,
- holisticness,
- flexibility in adjustment to the degree of knowledge,
- clearity and comprehensibility in structure,
- influenced by the user, in order to react to individual requirements and
- creditability and supply of stable results.

Assessment Method	Short Description
Trade-off Analysis [3]	simple comparison of advantages and disadvantages
Technical-Economic Assessment [4]	separate, weighted or unweighted evaluation according to technical and economic significance; results as strengths in diagrammatic form
Value Benefit Analysis [3]	weighted comparison of degree of performance
Ranking [3]	investigation of significance through sweeping statements
Evaluation via Preference Matrix [3]	method is similar to ranking; only a rough weighting
Analytic-Hierarchy-Process (AHP) [5]	investigation of preferences for each criterion by pairwise comparison
Demand-Orientated Weighted Assessment [3]	comparative weighted evaluation based on implicit and explicit requirements by means of absolute consistent evaluation parameter
Objectified Weighted Assessment [3]	evaluation in consideration of sharp, fuzzy and probabilistic, free estimated, evaluation parameter
Cost-Effectiveness-Analysis [6]	evaluation by economical aspects
Cost-Benefit -Analysis [6]	evaluation of overall economic impacts in consequence of microeconomic projects
Relevance Profile [3]	creation by interviewing from customers or users of a technical system; criteria based on linguistic values
Evaluation using Radar Chart [7]	graphical method of displaying multivariate criteria; evaluation by comparing surface areas
Efficiency Indicator Method (EWM) [2]	procedure for a holistic evaluation of buildings

Table 1: Evaluation Methods

A holistic procedure demands to gather all eligible subproblems in the requirements. To compare different models it is important to use criteria, which can be determined with the same level of quality.

Regarding a flexible use of the assessment method, simplifications during the assessment process are possible, if exact issue values are not available. These simplifications should be the same for all models. In this case, it is allowed to use other possibilities to quantify the requirements. Apart from the mathematical determination it is possible to get the evaluation criteria from other sources, e. g. questioning teams of experts or linguistic arguments. However, these values must be prepared in a way that enables comparison. The transformation is realized by quantification, mathematical capture and normalization.

In order to achieve maximum clearness and traceability, it is helpful to create a hierarchical structure. The hierarchical structure must be carefully devised so that it can properly portray the criteria in its several levels. This structure must be thematically organized and the criteria may not be doubly contained.

The evaluator must be able to influence the evaluation result, as the importance of the individual requirements can be different. In this case the evaluator exerts an influence on the results by weighting the criteria.

Lastly, the stability of the results contributes in the increase of credibility. This stability is characterized by the fact that errors and statistic fuzziness do not have a negative impact on the overall result. Thus, a manipulation of results is impossible.

3 MODEL EFFICIENCY ANALYSIS - MEA

3.1 General

Although a multitude of different assessment methods already exist, they all consider cost as one criterion of many. However, by relating cost directly to benefit, a new quality of assessment can be attained in which the sustainability of structures can be assessed. Therefore, the Efficiency Indicator Method (EWM) was developed. The EWM is structured differently than other published assessment methods. This method can be described as follows:

$$\textit{Efficiency} = \frac{Benefit}{Expenditure}$$

The criteria are characterized by two groups, *benefit* and *expenditure*, thus making it possible to make a statement about the efficiency by calculating the quotient. The expenditure combines both the economical and ecological categories using cost and resource consumption, respectively. In the context this corresponds to a sustainability analysis due to the view of the political and social field. Similarly to the expenditure, the benefit contains all conceivable criteria which describe the structure. The quotient - benefit and expenditure - is structured as secondary and tertiary in the primary criteria. With a final correction concerning the requirements of the criteria the catalog is developed. The criteria tree without tertiary criteria is illustrated in Fig. 2.

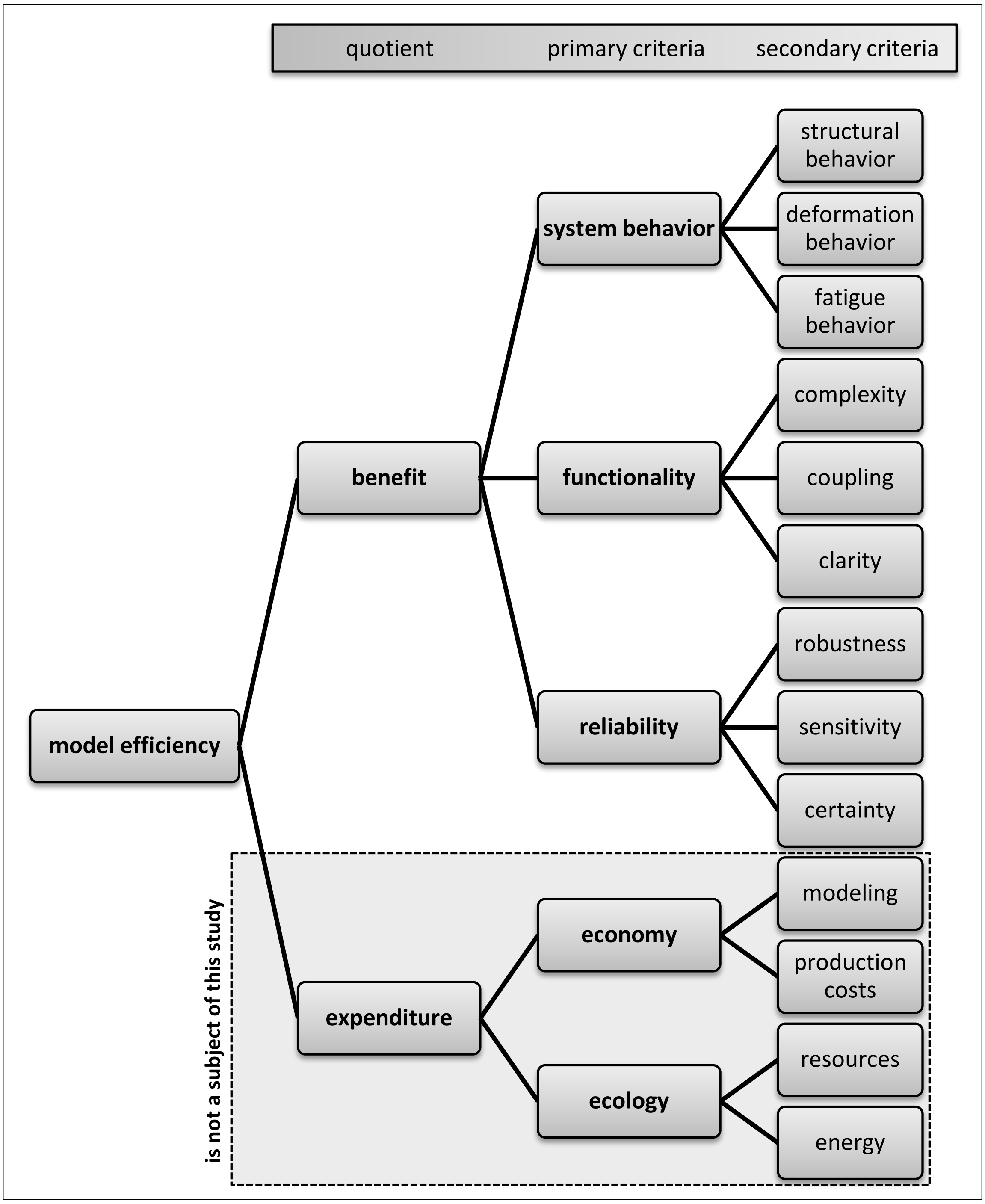

Figure 2: Figures of Merit - Overview

After analysis of previous considerations, it may be noted that the EWM is most suitable for the present assessment problem. Therefore, the EWM was modified to the Model Efficiency Analysis (MEA) for the purpose of a holistic evaluation of analysis methods for the design of frame structures.

Herein the expenditure value is not a subject of investigation, and so the model efficiency is calculated only by the benefit value. In order to fulfill the holisticness of the evaluation method, the calculation of the expenditure value, which consists of the economy and ecology, will be calculated later. The following chapter will include a brief introduction of the MEA.

3.2 Benefit - Figures of Merit

The causes for the separation of benefit and expenditure were given in chapter 4.1, and in addition to the requirements in chapter 3, the following is needed:

- The benefit criteria may not contain expenditure criteria.

The criteria which are arising out of many fields of knowledge are meaningful to structure. Regarding the choice of a criterion, it should be made sure that the observed models can provide also the associated results. The criteria in Tab. 2 may be expanded or modified with respect to the requirement. At this point this is a draft, not the final criteria catalog.

3.3 Expenditure - Figures of Merit

In order to achieve a holistic result, it is necessary to consider the expenditure value of the respective model during the evaluation. The investigations of the research training group 1462 are currently focused on the consideration of the benefit value of the observed models. Based on this convention, the expenditure value is not the subject of the investigations. Therefore, the model efficiency is calculated only by the benefit value. The calculation of the expenditure value, which consists of economy and ecology, will be calculated later in order to realize a holistic evaluation method. Further investigations concerning the expenditure criteria are not presently planned.

3.4 Quantification of the Tertiary Criteria

The criteria are divided into the following subspecies according to ascertainability:

- deterministic
- probabilistic and
- linguistic.

The deterministic and probabilistic criteria are quantifiable i.e. they are scalar values. Contrary to these, linguistic criteria, which cannot be described accurately by a mathematical equation. In this case scales from, e.g. 1 to 9, are suitable for the presentation and description of qualitative criteria.

primary criteria	secondary criteria	tertiary criteria
system behavior	structural behavior	bearing reserve eigenvalue buckling load equivalent stress etc.
	deformation behavior	vertical displacement horizontal displacement rotation etc.
	fatigue behavior	fatigue strength response etc.
functionality	complexity	solutions etc.
	coupling	expansions modifiability recirculation handling etc.
	clarity	solution display presentation etc.
reliability	robustness	robustness index etc.
	sensitivity	sensitivity index etc.
	certainty	reliability level failure immunity control etc.

Table 2: Benefit - Figures of Merit

3.5 Normalization of the Tertiary Criteria

The criteria must be transformed to aggregate the individual subfunctions. Therefore, the different scales of the respective measuring data must be converted into a common dimension "value". For this, Churchman/Ackoff/Arnoff [8] describe a very complex and lengthy normalization procedure and thus is not suitable for the MEA. There are other normalization analyses based on different scales, like the ones published by Saaty [5], Belton [9] or Dyer [10].

Saaty normalizes the rank vector by dividing each individual vector element by the sum of all vector elements. This means that the normalized value indicates the percentage of the vector in relation to the alternative. Belton refers each vector element to the maximum value of the respective vector. Thus, the best model obtains a value of "1".

In contrast to that, Dyer qualified the relationship of the vector element to the maximum value by subtracting the minimum value. The normalized value, r_i, according to Dyer is computed as follows:

$$r_i = \frac{x_i - x_{min}}{x_{max} - x_{min}}, \tag{1}$$

with x_{min}, x_{max}, and x_i as minimum, maximum and the value of the criterion x, respectively.

Pötzl modified the procedure according to Eq. (1) and introduced a range in order to exert influence of the variable significance of the single criterion on the final result [11]. He distinguishes between two ranges. For important criteria he permits a range of 10% to 100% and for less influential criteria between 40% and 60%. According to Pötzl, the function is influenced by the scaling, similiarly to a weighting procedure. Eq. (1) shows that the type of distribution of single results is not considered. This approach considers the absolute deviation of the single values, however, the relative deviation is neglected. Tab. 3 clarifies this criticism. In order to show the problem for this normalization method, two criteria are considered; the rotation and the displacement. Both criteria are equally weighted.

model	criterion 1 rotation [mrad]	criterion 2 displacement [mm]	norm. $r_{rot.}$	norm. $r_{displ.}$	mean value $\sum r_i/2$
A	10	51	0	1	0.5
B	20	50	0.5	0.5	0.5
C	30	49	1	0	0.5

Table 3: Normalization according to Eq. (1)

Regarding the mean value of Tab. 3, all models according to Eq. (1) are equally evaluated. Objectively, this result does not correspond to reality. The normalized values differ in the two digit percent area. In comparison to this, the deformations exhibit only minimum differences. From this a related range should be considered.

For this reason Eisert [2] modified Eq. (1) to the following expanded value function which considers a variable range

$$r_i = \frac{\sum x_i - x_{max} - x_{min} + 2 \cdot x_i}{2 \cdot \sum x_i}. \quad (2)$$

The results obtained from solving Eq. (2) using the values from Tab. 3 are shown in Tab. 4:

model	criterion 1 rotation [mrad]	criterion 2 displacement [mm]	norm. $r_{rot.}$	norm. $r_{displ.}$	mean value $\sum r_i/2$
A	10	51	0.33	0.51	0.42
B	20	50	0.50	0.50	0.50
C	30	49	0.66	0.49	0.58

Table 4: Normalization of 3 Models according to Eq. (2)

By looking at the mean values it is clear that model A is preferred over the other models and the rotation confirms this choice.

However, the expanded value function seems to be losing its uniqueness when six models are used for the evaluation instead of three. This critical point is shown in Tab. 5:

model	criterion 1 rotation [mrad]	criterion 2 displacement [mm]	norm. $r_{rot.}$	norm. $r_{displ.}$	mean value $\sum r_i/2$
A	10	51	0.417	0.503	0.46
B	20	50	0.500	0.500	0.50
C	30	49	0.583	0.497	0.54
D	10	51	0.417	0.503	0.46
E	20	50	0.500	0.500	0.50
F	30	49	0.583	0.497	0.54

Table 5: Normalization of 6 Models according to Eq. (2)

The newly introduced models D, E, and F are copies of models A, B, and C. The mean values compared to Tab. 4 do not change by the increase in the number of models. However, the range of the normalized values for the observed models does change. In this case, the uniqueness of the normalized values is not given.

Therefore, equations are applied while considering the percent deviation of the models from each other or from an ideal model if available. If there is no ideal model, the criterion of best model, $x_{i,max}$, obtains a value of “1” and consequently the values of the other models are calculated using [3] [9]

$$r_i = \frac{x_i}{x_{i,max}}. \quad (3)$$

Otherwise, the criterion of the ideal model, x_{max}, obtains the normalized value of "1" and the values of the other models are calculated using

$$r_i = \frac{x_i}{x_{max}}. \tag{4}$$

Tab. 6 shows the advantage of using Eq. (3) as opposed to using Eq. (2). Regarding criterion 1, rotation, the models differ by a range of 30.5%. When using the normalization procedure according to Eq. (2) with these large percentage deviations, there does not appear to be a large difference in normalized values.

In comparison to that the normalization procedure shows the accurate percent deviation between the models. By using Eq. (3) it is possible to increase the number of observed models without an influence on the normalized values.

criterion critical load factor	Δ lf [%]	norm. r_i acc. to Eq. (2)	Δ norm. r_i [%]	norm. r_i acc. to Eq. (3)	Δ norm. r_i [%]
18.95	-7.61	0.5110	-2.10	0.9739	-7.61
19.95	-2.75	0.5180	-0.76	0.9725	-2.75
17.44	-14.97	0.5004	-4.14	0.8503	-14.97
16.59	-19.10	0.4944	-5.28	0.8090	-19.10
14.50	-29.30	0.4797	-8.10	0.7070	-29.30
14.26	-30.50	0.4780	-8.43	0.6950	-30.50
20.01	-2.44	0.5185	-0.67	0.9756	-2.44
20.51	**0.00**	**0.5220**	**0.00**	**1.0000**	**0.00**

Table 6: Normalization according to Eq. (3)

Eq. (3) seems to fit for the criteria, critical load factor, since the model with the maximal critical load factor obtains the normalized value of "1". This means that the best model offers the largest result. If the best model offers the smallest result, then Eq. (3) cannot be used.

Therefore the following equation was developed which allows to normalize the smallest result to the value of "1".

$$r_i = 1 - \left(\frac{x_i}{x_{i,min}} - 1 \right) \; ; x_{i,min} \neq 0 \tag{5}$$

An example would be the criterion of the total deformation, |u|, according to Tab. 7. This equation provides normalized values regardless of the number of models. The percent deviation between the models is also considered.

criterion deformation |u|	Δ |u| [%]	norm. r_i acc. to Eq. (2)	Δ norm. r_i [%]	norm. r_i acc. to Eq. (5)	Δ norm. r_i [%]
12.40	0.16	0.4959	-1.66	0.9980	-0.16
12.90	4.22	0.5009	-0.68	0.9580	-4.22
12.70	2.62	0.4989	-1.07	0.9740	-2.62
13.25	7.04	**0.5043**	**0.00**	0.9300	-7.04
12.43	0.40	0.4962	-1.60	0.9960	-0.40
12.92	4.32	0.5010	-0.66	0.9570	-4.32
12.38	**0.00**	0.4957	-1.70	**1.0000**	**0.00**
12.88	4.01	0.5006	-0.73	0.9600	-4.01

Table 7: Normalization according to Eq. (5)

The introduced normalization equations are a selection of published procedures, which satisfy the evaluation of the observed analysis models. Currently, other procedures are being investigated in order to find a solution for the normalization problem.

3.6 Weighting of the Criteria

The criteria of a technical system are not all equally important. They may vary depending on their specific requirements. Therefore, the criteria must be weighted for their aggregation by use of a importance factor. Due to practical standpoints, the sum of the importance factors of one criteria level should have a value of "1". The importance factor is to be individually determined for each evaluation. The results must satisfy the needs of the user before they may be manipulated.

An example for a modification of the importance factor is to consider the risk potential of different structures. For a structure with a high potential of risk the primary criteria, reliability, has a larger importance factor compared to the primary criteria, functionality.

3.7 Dynamical Weighting

It is of special interest to evaluate the models regarding the extravagant or balanced solutions. In addition to weighting of criteria, a dynamical importance factor is considered in the EWM. It is to be prevented that the averaged models are mostly in the front places.

Therefore, approaches are published in [7] by using radar charts. This type of diagram consider a non-linear influence of the criteria. The criteria are presented in a scaled circle. The resulted surface area is used visually for the evaluation of the structure. This way the criteria do not have a linear influence on the result, which leads to a disproportionate increase in the influence of very well fulfilled criteria. This, in return, promotes extravagant models, however, it has an important disadvantage. For the total result, not only the weighting is important. Although the arbitrary criteria arrangement in the radar chart has an influence on the overall result. In particular this applies to unbalanced models. The following Fig. 3 shows two figures of the same model with different arrangements of the criteria. Due to this different criteria arrangement, the first radar chart area is 25% smaller than the second one. Presently the use of dynamical weighting is verified.

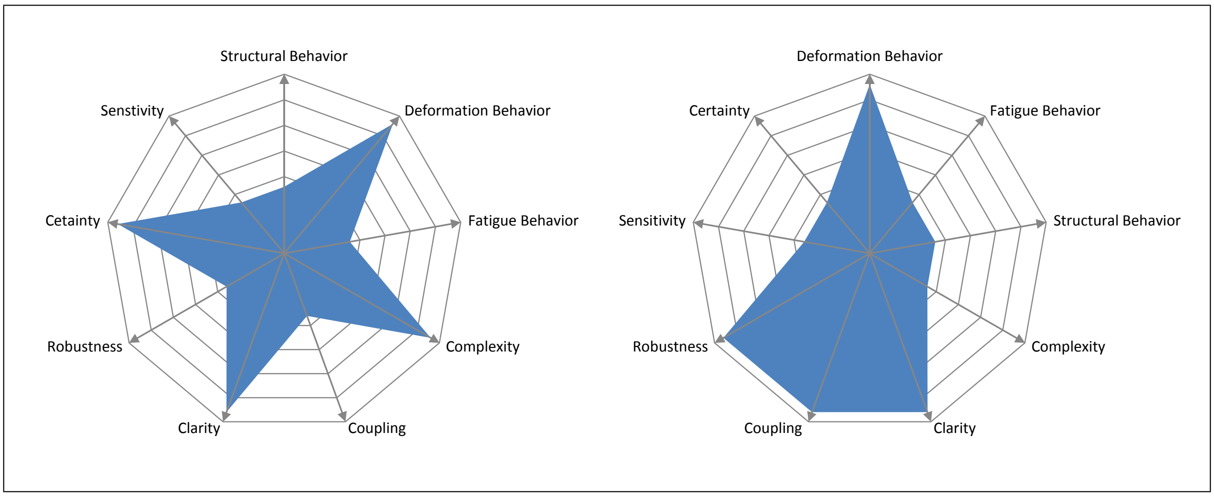

Figure 3: Radar Chart

4 CONCLUSION

This paper shows the evaluation problem of analysis methods especially for the design of frame structures. After analysis of different published assessment methods, it may be noted, that the EWM [2] is most suitable for the observed evaluation problem. Therefore, the EWM was modified to the Model Efficiency Analysis for the purpose of a holistic evaluation. The criteria are characterized by two groups, benefit and expenditure, and it is possible by calculating the quotient (benefit/expenditure) to make a statement about the efficiency of the observed models. Presently, the expenditure value is not a subject of investigation, and so the model efficiency is calculated only by the benefit value. This paper also contains the associated criteria catalog, different normalization methods, as well as weighting possibilities. For a future step the criteria catalog will be completed.

The introduced normalization equations are a selection of published procedures, which fit to the evaluation of the observed analysis models. Currently, other procedures are investigated to find a solution for the normalization problem. Furthermore, the use of the dynamical weighting is verified.

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