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Fuzzy AHP as a tool for prioritization of key performance indicators

Sergei Kaganski[a,]*, Jüri Majak[a] and Kristo Karjust[a]

[a]*Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086, Estonia*

* Corresponding author. Tel.:+372 53445034. E-mail aadress: sergei.kaganski@outlook.com

Abstract

Performance measurement, as a new procedure for monitoring enterprise life and actions, was introduced first in the manufacturing industries. Recently, due to the growing competition between companies, different frameworks, systems, and methods were proposed for small and medium enterprises. The key performance indicators (KPI) are known as a powerful tool, which would provide valuable information regarding bottlenecks and weak spots in companies.
In the current study, the fuzzy analytical hierarchy process (AHP) based on SMARTER criteria and 13 KPIs, has been developed and weights for the SMARTER criteria were calculated. The priority ranks of KPIs were obtained.

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Keywords: key performance indicators; fuzzy analytical hierarchy process (fuzzy AHP); SMARTER criteria.

1. Introduction

Changes in global economy (globalization, fall of oil prices, restrictions from EU and Russian Federation on economic level with implementation of new technologies in manufacture field) made companies to realize that in order to stay alive in harsh dynamic environment with fierce competition and heavy price pressures, they need to focus on their business strategy, which has made a shift from production or cost-oriented approach to more strategic [1-4]. As a result, the organizations deal with a number of key performance indicators (KPIs) covering different areas [5]. Each indicator describes a particular activity/characteristic of the company only. That's why the package of successful indicators is required by managers. However, due to the number of different metrics and their impact on enterprise's health in total, the management has been faced with difficulties in selection of the right metrics. Another restriction of usage of the package of KPIs is that it cannot be utilized in a simple way to improve targets due to the fact, that each independent indicator needs to be faced to some benchmark value without concerning the remaining aspects of the company's activities, which are not related to that metric [6]. It is worth to mention, that KPIs, which have changed the situation and are followed in one company, couldn't work and turn the situation in another, due to the different fields of action, production capabilities, availability of implementing new technologies, different IT solutions and etc. It's necessary to recognize, that reviewing and analysing of wrongly chosen metrics can have a crucial impact on company-the uncovered problems would still continue to damage processes despite the fact that "rightly chosen" indicators are in "green" fields.

On the one hand, the KPIs can have a negative impact on the creativity by establishing restrictions and constraints when dealing with different issues. On the other hand, they can drive management in the right direction by decreasing the unnecessary information and reducing the time.
The objective of this paper is to introduce the Fuzzy AHP (an approach for evaluation the relative importance between attributes by means of pairwise comparison) and the opportunity to rank metrics based on SMARTER criteria (a method for setting objectives, similar to SMART but uses additional two criteria). Traditional form of AHP that uses 9 point scale does not provide good results by dealing with the uncertainty, which can reduce the reliability of the evaluation. The Fuzzy AHP needs to be implemented to eliminate this limitation [7, 8, 9]. In addition, a group of 10 experts was

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invited to participate in the evaluation of criteria vs goal and criteria vs sub-criteria by using triangular fuzzy numbers. The final ranks and weights for each research subject were introduced and evaluated.

2. SMARTER goal settings

In any company, goals are leading enterprise's effort, supporting and optimizing resources, helping in moving straight ahead to their visions. In other words, the goal setting is one of the main processes that should be addressed by management [10]. However, by setting objectives, which are complicated, there is a risk that they could be too difficult to achieve. Furthermore, KPIs, which reflect enterprises goals, should be based on criteria which make them suitable for further studies [5]. In [11] G.T.Doran has proposed SMART way of setting objectives. Although, many organizations have applied SMARTER model considering the fact, that two additional criteria are good reminder to managers that they are staying on top of the process [11].

Specific - Goals should be detailed and as specific as possible. Loose, not clear or uncertain goals are not desirable. When goals are specific, it is easier to take necessary steps to achieve targets.

Measurable - Each target, process or KPI should be measurable. The measure itself could be quantitative or qualitative, but measurement should meet standards and requirements.

Achievable – Objectives should be set at right level. They need to be ambitious and realistic, however, making them too simple won't be motivating and on the other hand, each KPI should have the standard value that should be achieved.

Relevant (if sometimes it's linked with agreed then it's similar to achievable) – every colleague in a team or as individual, need to understand and compare how the objective is relevant to their role and main course of the team. Furthermore, KPIs should provide insight into the performance of the company in obtaining its strategy. In case, when KPI is not measuring a team's or enterprise's goal or doesn't affect the organizations' performance, it's useless.

Time-specific (or time-sensitive) – Work or tasks should have time frames. The deadlines for completing the objectives would provide possibilities to monitor and analyse the progress. In addition, its better understand metric, when everyone knows the time frames in which it should be measured and realized.

Explainable or *Evaluated* – Very often, KPIs have been measured without understanding the reason of measuring. Managers need to ensure, that everyone, who is involved in process, is aware of goals and tasks. Worth to mention that KPIs should evaluate performance and progress of what is measured (is it performance of a team or of a process)

Relative or *Reviewed* – KPIs should be relative and they still could be implemented even company and volumes are growing [5, 11, 13].

3. AHP and fuzzy AHP approach

The analytical hierarchy process (AHP) is a powerful decision-making methodology, which was developed by Saaty in 1980s to simplify the decision making process [13]. It includes qualitative and quantitative techniques and provides the possibility to decompose complicated problems into sub-problems, which simplify the comparison of alternatives [5, 14, 17]. It can also be used to evaluate the environmental performance of each life cycle phase [12]. Although, the nine-point scale simplifies the choice of criteria and provides information regarding dominance of each element over others [18, 19], there is the one weak spot, which occurs during the setup of comparisons matrixes-the information unpredictability cannot be simply explicit by a discrete scale [15]. When the number of characteristics is rising in a hierarchy, more matchings between attributes need to be applied. Furthermore, the experts are not able to represent properly their background knowledge regarding the actual problems [16]. As result, the judgements are becoming unreliable and subjective. However, to deal with the impreciseness of experts' judgements the fuzzy set theory has been selected. The theory was developed by Zadeh and has become widely used in pair-wise comparison [20]. The Fuzzy AHP approach is represented by triangular fuzzy numbers (TFN). The numbers can be identified as triple M = (l, m, u), where its membership function is defined in [21] as

$$\mu_M(x) = \begin{cases} \frac{x}{m-l} - \frac{l}{m-l}, x \in [l,m], \\ \frac{x}{m-u} - \frac{u}{m-u}, x \in [m,u], \\ 0, \quad otherwise. \end{cases} \tag{1}$$

In (1) l, m and u stand for the lower, medium and upper values of M, respectively ($l \leq m \leq u$). In special case where all three numbers are equal ($l = m = u$), then we are dealing with no-fuzzy numbers. The main operations for two triangular numbers were described by Kaufmann in [22] as

$$M_1 (+) M_2 = (l_1 + l_2, m_{1+} m_2, u_{1+} u_2) \tag{2}$$

$$M_1 (x) M_2 \approx (l_1 l_2, m_1 m_2, u_1 u_2) \tag{3}$$

$$M^{-1} \approx (1/l_1, 1/m_1, 1/u_1) \tag{4}$$

In table 1 the triangular fuzzy scale implemented in the current study has been introduced.

Table 1. The scale of fuzzy AHP pair-wise comparison

The relative importance of the two sub-elements	Fuzzy triangular	Reciprocal fuzzy
Equally important	1 1 1	1, 1, 1
intermediate value between 1 and 3	1 2 3	1/3, 1/2, 1
Slightly important	2 3 4	1/4, 1/3, 1/2
intermediate value between 3 and 5	3 4 5	1/5, 1/4, 1/3
Important	4 5 6	1/6, 1/5, 1/4
intermediate value between 5 and 7	5 6 7	1/7, 1/6, 1/5
Strongly important	6 7 8	1/8, 1/7, 1/6
intermediate value between 7and	7 8 9	1/9, 1/8, 1/7
Extremely important	9 9 9	1/9, 1/9, 1/9

For example, let us assume that the criterion i has been ranked by expert as strongly important in comparison with criterion j.

In latter case, based on values given in table 1, the criterion i will be evaluated with fuzzy number M = (6, 7, 8). Alternatively, in the case where criterion j appears less important than criterion i, the pairwise comparison between criteria j and i could be represented by the reciprocal fuzzy number M = (1/8, 1/7, 1/6).

4. Case study

4.1 Introduction

The aim of the case study is to assign priority/rank indexes to metrics, which in its own turn should help managers to simplify the choice of metrics that should be followed at first place in company. Furthermore, it's not only the simplification of a process but also prioritization of tasks. It is worth mentioning, that the success of proposed steps for acquiring ranks for KPI's is in direct relation to the selection of expert group.
The whole process of acquiring priority indexes for KPIs can be divided by next steps:

1. Developing of hierarchy tree based on goal, criteria (SMARTER goal settings) and sub-criteria (13 KPIs);
2. Preparation of matrices for data collection (pair-wise comparison);
3. Data collection from expert group;
4. Consistency check of matrix (fuzzyfication of the data);
5. Calculation of criteria (SMARTER goal settings) and sub-criteria (13 KPIs) weights;
6. Prioritization of sub-criteria (KPIs).

4.2 Development of hierarchy tree

The Fuzzy AHP hierarchy has been built based on SMARTER criteria with combination of main goal of the research and 13 KPIs (Table 2), which were evaluated by group of experts. In [23] the outlier's detection methods were employed (Tukey's, Adjusted Boxplot, Standard deviation method, Z score and Modified Z score) and optimization of KPI-s was performed (13 KPI from initial 41 were selected). The goal, which was established for this approach, is the acquiring of sustainable KPIs for improvement of productivity, effectiveness and finding out optimal parameters to check and monitor with production monitoring system. In the Fig. 1 the hierarchy tree has been illustrated.

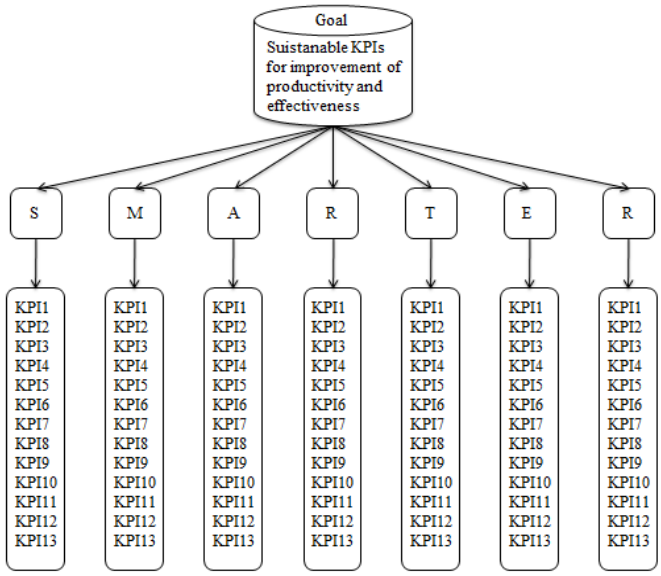

Fig. 1. The hierarchy tree for pair-wise comparison.

During first step, the comparison on first level between SMARTER criteria and main goal was established. On the second level, the pair-wise comparison between sub-criteria (KPIs), with taking into account each SMARTER goal setting, was performed l (Fig. 1).

Table 2. KPI's selected for current study

KPI abbreviation	Definition
KPI1	Inventory turnover
KPI2	% of additional freight costs
KPI3	Product quality/quality ratio
KPI4	FPY (firs pass yield)/Throughput yield
KPI5	DPU (defects per unit)
KPI6	Employee's efficiency
KPI7	changes implementation time
KPI8	Actual production Time
KPI9	OEE (Overall Equipment effectiveness)
KPI10	NEE (Net Equipment effectiveness)
KPI11	OTD (On time delivery)
KPI12	Tact time
KPI13	Unit/Line Reliability

4.3 Pair-wise comparison and consistency test

The pair-wise comparison was done by the expert group of 10 members, who have experience in field of production and process optimization more than 5 years. The hierarchy tree subject is to establish pair-wise comparison between goal-criteria, criteria-sub-criteria. After pair-wise comparison the corresponding matrices have been composed. In order to ensure the quality and trust ability of collected data, the consistency check was performed. During this case study, the deffuzification method for converting of triangular fuzzy numbers to crisp numbers was used. The defuzzification has been performed according to the following formula ([24])

$$M_{crisp} = (4m + l + u) / 6, \quad (5)$$

where M_{crisp} is the crisp number, m is a medium bound, l and u stand for the lower and upper bounds of triangular fuzzy number, respectively.

Table 3. Example of defuzzified numbers vs fuzzy triangular numbers

	Specific	
Criteria	Fuzzy triangular numbers	Defuzzified numbers
Specific	1, 1, 1	1
Measurable	2, 3, 4	3
Achievable	1/4, 1/3, 1/5	0,3472
Relevant	2, 3, 4	3
Timely	1, 1, 1	1
Explainable	1, 1, 1	1
Relative	1/6, 1/5, 1/4	0.202778

In next step, the consistency check methodology proposed by Saaty in [25] can be applied for each matrix. The consistency ratio (CR) can be calculated as ([25])

$$CI = (\lambda_{max} - n)/(n-1)\,, \tag{6}$$

$$CR = \frac{CI}{RI}\,, \tag{7}$$

where, λ_{max} is the largest eigenvalue of a matrix, n is the dimension of the matrix and RI is a random index, that depends on n (Table 4).

Table 4. RI according to Golden and Wang [26]

n	3	4	5	6	7	8	9	10	11	12	13
RI	0.58	0.89	1.12	1.24	1.33	1.40	1.45	1.49	1.51	1.54	1.56

The value of the RI is acceptable, if it will not exceed 0.1. Otherwise, the experts should redo the whole process. If the crisp matrix is consistent then the resulting fuzzy matrix is also consistent [27].

4.4 Calculation of weights and KPI ranking

The weights are required for prioritization of metrics. In conformity with weights the ranks would be assigned to criteria and sub-criteria. According Buckley [28], the geometric mean $\tilde{r}$ of fuzzy comparison values for each criterion can be calculated according to next equation:

$$\tilde{r} = \left(\prod_{j=1}^{n} \tilde{d}_{ij}\right)^{\frac{1}{n}}, i = 1, 2, \dots, n\,, \tag{8}$$

where $\tilde{d}_{ij}$ is an average fuzzy triangular number, n is the dimension of the matrix.
The fuzzy weight $\widetilde{w}_i$ of criteria or sub-criteria can be obtained by multiplication of each $\tilde{r}$ with the reverse vector:

$$\widetilde{w}_i = \widetilde{r}_i \times (\widetilde{r}_1 + \widetilde{r}_2 + \dots + \widetilde{r}_n)^{-1} = (lw_i, mw_{i,}, uw_i). \tag{9}$$

In addition, the two more steps are required before starting calculation of fuzzy weights: the sum of each $\tilde{r}$ should be calculated and the reverse sum of vector with placing values in increasing sequence should be performed.
Worth to mention, that $\widetilde{w}_i$ is still triangular fuzzy number and need to be defuzzified according to Chou and Chang "Centre of area" method [29]

$$M_i = \frac{lw_i + mw_{i,} + uw_i}{3}\,. \tag{10}$$

Finally, the M_i can be normalized by applying next equation:

$$M_i = \frac{M_i}{\sum_{i=1}^{n} M_i}\,. \tag{11}$$

4.5 Numerical results

In Fig. 2 the comparison between SMARTER criteria and goal of the study performed by one of the experts is depicted.

	Goal																				
	Specific			Measureable			Available			Realistic			Timely			Explainable			Relative		
S	1	1	1	0.17	0.2	0.3	0.17	0.2	0.3	0.17	0.2	0.25	0.17	0.2	0.3	1	1	1	1	1	1
M	4	5	6	1	1	1	0.17	0.2	0.3	2	3	4	1	1	1	4	5	6	4	5	6
A	4	5	6	4	5	6	1	1	1	1	1	1	1	1	1	1	1	1	2	3	4
R	4	5	6	0.3	0.33	0.5	1	1	1	1	1	1	1	1	1	2	3	4	2	3	4
T	4	5	6	1	1	1	1	1	1	0.33	0.5	1	1	1	1	0.33	0.5	1	1	1	1
E	1	1	1	0.17	0.2	0.3	1	1	1	0.3	0.33	0.5	1	2	3	1	1	1	1	1	1
R	1	1	1	0.17	0.2	0.3	0.3	0.33	0.5	0.3	0.33	0.5	1	1	1	1	1	1	1	1	1

Fig.2. The fuzzy comparison matrix at first level by one of the experts.

The average consistency ratio CR at first level has been introduced in table 5. The average value CR=0.133 obtained is slightly higher than permissible value 0.1 However, considering that we are dealing with average mean and the calculated ratio is allocated near to 0.1, we can draw conclusion of consistency of matrices.

Table 5. Consistency ratio for comparison at first level

Goal: KPIs for improvement of productivity and effectiveness							
Criteria	Specific	Measurable	Achievable	Relevant	Timely	Explainable	Relative
CR				0.133			

The average consistency ratio CR at second level (comparison between sub-criteria to criteria) has been introduced in table 6. The average value for "Measurable vs KPIs" has been calculated as CR=0.154>0.1. However, it is around 85% which can be considered as acceptable result. The "Timely vs KPIs" CR=0.104>0.1 has also been accepted.

Table 6. The average consistency ratio for comparison at second level

	Criteria						
	Specific	Measurable	Achievable	Relevant	Timely	Explainable	Relative
CR sub-criteria vs criteria	0.857	0.154	0.067	0.095	0.104	0.064	0.044

In table 7 the normalized weights on criteria and sub-criteria levels with assigned ranks are introduced. To acquire the final weights for KPIs, they were summarized by SMARTER criteria weights. Final results are given in table 8.

Table 7. The normalized weights of sub-criteria and ranks

Criteria	Normalized weight	Rank
Specific	0.117933191	5
Measurable	0.189824875	2
Achievable	0.137347325	4
Relevant	0.226618511	1
Timely	0.102053705	6
Explainable	0.169461049	3
Relative	0.056761343	7

Table 8. The weights and ranks for KPIs

KPI n	Name	Specific	Measureable	Achievable	Relevant	Timely	Explainable	Relative	Total	Rank
KPI1	Inventory turnover	0.00803	0.01303	0.02151	0.01604	0.01157	0.02875	0.00647	0.10540	4
KPI2	% of additional freight costs	0.00285	0.00789	0.01061	0.00395	0.00377	0.00650	0.00249	0.03805	13
KPI3	Product quality/quality ratio	0.01969	0.02452	0.01021	0.01742	0.00715	0.02496	0.00568	0.10963	2
KPI4	FYP (first pass yield)/Throughput yield	0.01185	0.01122	0.00787	0.01279	0.00803	0.00730	0.00287	0.06194	10
KPI5	DPU (defects per unit)	0.01150	0.02160	0.01243	0.01264	0.00597	0.01953	0.00393	0.08760	5
KPI6	Employee efficiency	0.00664	0.00996	0.00565	0.01537	0.00561	0.01585	0.00433	0.06340	8
KPI7	Changes implementation time	0.01343	0.01669	0.00685	0.00658	0.00640	0.01084	0.00288	0.06368	7
KPI8	Actual production time	0.01403	0.02582	0.01474	0.03128	0.01454	0.01811	0.00787	0.12639	1
KPI9	OEE (Overall Equipment effectiveness)	0.00852	0.01148	0.00674	0.01768	0.00580	0.00915	0.00309	0.06247	9
KPI10	NEE (Net Equipment effectiveness)	0.00520	0.00707	0.00544	0.01584	0.00434	0.00640	0.00322	0.04750	12
KPI11	OTD (On time delivery)	0.00971	0.01983	0.01674	0.02932	0.01278	0.01242	0.00636	0.10716	3
KPI12	Takt time	0.00318	0.01436	0.00934	0.02612	0.01103	0.00461	0.00334	0.07197	6
KPI13	Unit/Line Reliability	0.00332	0.00635	0.00920	0.02160	0.00507	0.00506	0.00422	0.05482	11

According to results obtained, the metrics should meet the next goal setting criteria: indicators should be relevant, measurable and explainable. Considering the ranks, assigned to metrics, managers should pay attention to the following KPIs: Actual production time, product quality/quality ratio, OTD (on time delivery). However, it doesn't mean, that OEE, FPY and other metrics shouldn't be considered as "non-important" metrics.

5. Conclusion and future study

The proposed Fuzzy AHP for prioritization of metrics from point of company's goal and SMARTER goal settings should help to better understand the nature of metrics and also simplify the choice of them.

Based on proposed approach and numerical results obtained in the case study, the TOP3 metrics (Actual production time, product quality/quality ratio, on time delivery) from package of 13 KPIs were selected. However, it doesn't mean, that other metrics have not impact on company. The proposed package should be taken into account as one useful tool. The final results are in connection to the input data-the package of metrics and can vary due to it. Also the main goal that has been used in comparison on first level can have an impact on the final ranks.

The suggested concept should be tested at real company to better understand its weak and strong sides. The acquired results should help managers to better understand the impact, which metrics could have at their enterprises. Data collection and whole EAM model testing on different companies are foreseen as next tasks. The optimization and improvement processes of EAM and KPI selection model should take part continuously. To summarize:

- Data collection from different SMEs;
- Optimization and improvement of EAM as continuous process and integration to the production monitoring system [30, 31].

The KPI selection model introduced provide powerful tool for analysing in management's hands, which would serve as main stone in decision-making process. In addition, the proposed model helps to reduce time for analysis of the company, make processes more understandable and transparent.

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