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Application of selection techniques of optimal planning and evaluation of a system layout in virtual environment

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Abstract:

Aim: The paper presents the application of optimum choice decision-making technique – the Analytical Hierarchical Process (AHP), for system layout planning in virtual environment taking into account specific objectives and planning constraints.

Design / Research methods: The Virtual Factory presents the factory in the form of computer virtual reality. This facilitates on-site design, planning and evaluation of production processes in real time. The virtual environment is a tool by which one can plan and evaluate management of a plant in detail. In the paper evaluation of the optimal decision option is conducted with regard to the changes made in production hall zone, followed by the sensitivity analysis of the decision-making process. A case study of the use of an Analytical Hierarchical Process as a technique for selecting the optimal option for planning and evaluation of a system in a virtual environment is presented.

Conclusions / findings: The results allow understanding the merits and drawbacks of the AHP method implementation for the given aim. Companies need an individual approach to the layout planning. Spatial planning of a plant requires all processes to be linked to the entire life cycle of the enterprise. The optimal option is chosen according to the vision of the company, the established individual criteria and constraints that can change at every stage of the development of the company.

Originality / value of the article: In practice nowadays, companies are often faced with the need to change the layout of an existing production hall, design and optimize the layout of an expanding plant due to the need to increase production capacity or to reorganize production. Consequently, the use of the optimum choice methods for layout planning is crucial to find rational solutions and to take decisions quickly in the digitally generated environment. The paper presents the case study of AHP with the use of virtual factory planning.

Keywords*: Virtual Factory, virtual reality, layout spatial planning.*
JEL codes: D24, L23, M11

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1. Introduction

Virtual Factory allows presenting a factory in virtual and augmented reality. It becomes handy in planning processes in factories and plants, especially for efficient optimisation of the spatial layout of the elements of the factory. Companies need an individual approach to their spatial layout planning. The final choice of an optimal variant arises according to the vision of the company and the established individual criteria and constraints that can change at every stage of the company's development. Analytical Hierarchical Process (AHP) method is presented in the paper as a method for optimisation of planning, allowing a quick assessment of a spatial layout of a production plant in virtual reality.

Adopting appropriate planning stages for each plant as an individual functional facility allows choosing a preferred decision option. Using a system approach in planning, as promoted in the paper, allows for a comprehensive reassessment of the plant as a homogeneous system consisting of interrelated parts. Systems approach calls for interrelating processes between elements and taking into account the interactions between them in the production planning. (Sterman 2000, Senge 2006) Decisions concerning each element of the system (e.g. machinery, equipment, transport) must take into account its impact on the efficiency of the whole system. Creating a spatial layout requires the simultaneous integration of temporal and spatial elements of the system. Spatial integration causes the creation of individual libraries for each system, the creation of different variants for organizing and integrating product flows (materials, semi-finished products, end products).

Explaining interactions between processes, identifying interdependences between machinery and equipment, are the first conditions for analysing existing and developing new plant systems. It is the systems approach that requires a comprehensive consideration of system in the planning process. This approach leads to a comprehensive search for criteria and constraints in the plant's redevelopment process and allows determining the conditions for choosing the optimal re-planning variant.

Planning the layout of a plant is a multi-stage operation, having a major impact on the final spatial distribution of technical systems, transport systems as well as handling and storage areas. Such a task is implement jointly by design and planning teams as well as production implementation teams. The task of changing the layout of a plant due to technological or logistical transition of a production process can be realized according to different options. These options differ with regard to: creative spatial planning, costs of logistics planning, costs of material flow control, costs of storage of raw materials, materials, semi-finished products and finished goods. Optimal choice of a plant layout leads to efficient production processes. A large number of possible variants of the layout require computerized elaboration of various options in order to choose the most advantageous resource efficient variant. In order to shorten the time to create a layout with the use of system approach the optimum variant selection techniques are utilised. (Ciszak & Żurek 2002).

The aim of the paper is to present a case study of the use of AHP as a technique for selecting the optimal variant for planning and evaluation of a system in a virtual environment. The hypothesis is that AHP is a useful and advisable method for above-mentioned goal. In the next section AHP method is presented as a method facilitating optimal choices regarding a plant spatial layout planning. Then the results summarise the application of the method. In the discussion of results the merits and drawbacks of the method implementation for the given aim are discussed.

2. Structured decision-making

Decision-making is an integral part of the conscious functioning not only in economic life, but also in every activity. Starting with the day plan, choosing the products for a household, up to advanced investment projects or strategies. The decision-making process is a complex sequence of actions, which based on the analysis of literature, can be presented as following:

1) An identification of a problem that requires a decision.
2) A formulation of the purpose of the action (an intention of the decision maker with respect to the identified problem).
3) An identification of the decision-making options.
4) An identification of the consequences of selecting the options (their positive or negative impacts on the problem and its environment).
5) Choosing the best option (the decision most advantageous for the decision maker).
6) The sensitivity analysis of the decision taken (a study to determine how much the conditions in which a decision has been made can be changed so that it still remains an optimal decision).

In this paper the fifth stage of the above process is analysed, namely choosing the optimal decision option. Each decision option is a possible decision that can be made by the decision maker and that is fulfilling the goals and constraints set by the decision maker. From a set of all these possible decisions (which are also called permissible decisions), a rational decision maker should choose the one that should bring him the most benefits or minimize the adverse effects of the necessary actions.

The assessment of each decision option should, however, cover all the consequences of its choice. Sometimes the positive results of managerial decisions are also accompanied by negative consequences. An obvious example is the choice of a cheaper product (cost minimization) at the expense of its inferior quality and vice versa by choosing the highest quality available (maximizing the quality criterion) we are forced to accept the high price of such a product.

Decision problems of this kind are called multi-criteria problems. For the purpose of solving them and to determine the ways of choosing the optimal option, many methods have been developed in the field of decision-making over the last several decades. In general, they are called "multi-criteria decision support" methods or in short "multi-criteria" methods. Among them a vector linear programming, target programming, scalar programming (using the notion of utility function) and discrete methods (Promethee, ELECTRE, stochastic domination) are well known. One of the more commonly used methods is the Analytical Hierarchical Process (AHP) developed by Thomas Saaty. This method can be used in individual and group decision-making processes. The hierarchical structure of the method implies the three levels of the decision maker's actions. Firstly, a goal is set. Secondly, the assessment criteria are developed. Finally, the level of the goal achievement is measured in the light of the assessment criteria. In this way the optimal option is chosen.

3. Analytical Hierarchical Process method

The essence of the AHP method is to make comparisons of all decision options against all evaluation criteria. These comparisons are made using special evaluation tables for each of the criteria based on a specific rating scale.

The paper presents the possibilities of using the AHP method to make decisions for the optimal option for planning and evaluating the layout in a virtual environment. AHP is a method, which applies a general hierarchical approach to making complex decisions involving multiple criteria. Modelling with the AHP is used when there is an unknown functional relationship between many criteria, described in the form of hierarchies of factors to allow identification of the most appropriate option in the planning of the plant reconstruction system. A predetermined hierarchy of factors allows structuring the stages of choosing the best solution from many options.

Various options displaying spatial distribution of system elements (e.g. machines, products) are presented in the analysed case study as physical layouts. The layouts result in different levels of safety, quality or risk for the production environment. The AHP method is particularly useful if it is not possible to determine the functional dependence between the decision problem elements for an optimal variant. (Tułecki & Król 2007).

The paper presents the possibility of using the AHP method as a tool for modern design methods of selecting the best layout option in production plants. Planning with the AHP method can be found in the following literature positions.

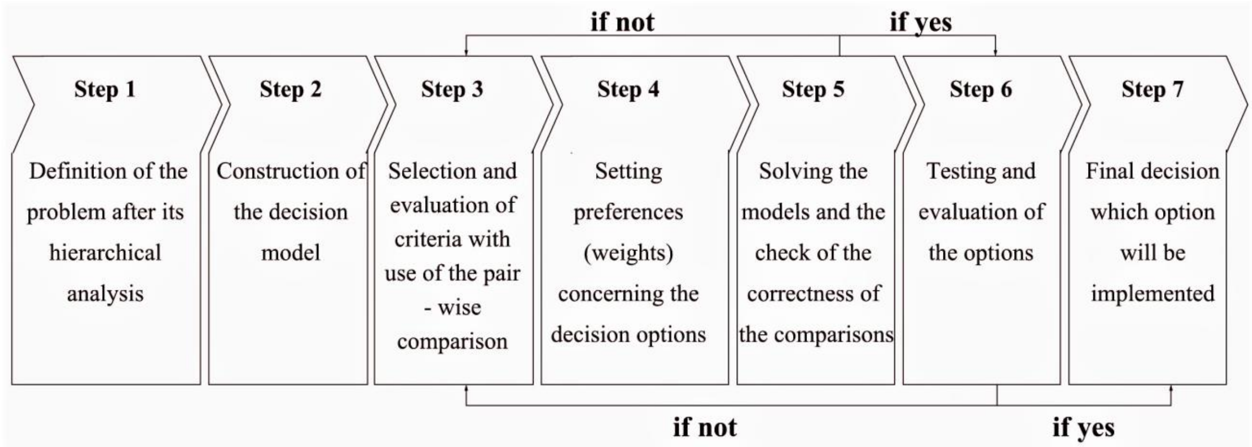
Yang and Kuo (2003) introduced an integrated methodology, called the AHP data development analysis to rank facility layout patterns, which used the AHP method to generate performance measures of the quality criteria, and finally the data development analysis was used to solve the layout performance problems, while analyzing quantitative and qualitative data simultaneously. The methodology was further developed by Hadi-Vencheh & Mohamadghasemi (2013) linking AHP with the simple nonlinear programming models to create a computer-aided layout-planning tool.

Jiang et al. (2014) proposed two planning methods, namely planning information and planning analytic hierarchy process, to solve the multiple attribute decision-making models. During the planning process, criteria and constrains are evaluated in real time to provide immediate evaluation and feedback on decision-making.

Addor and Santos (2015) presented their criteria and indicators (metrics) for evaluating the quality of Building Information Modelling Room layouts with the use of AHP method. Fourteen different layouts were tested for validation of the results on metrics and criteria related to physical layouts.

Planning layouts with the AHP method allows to group selected criteria to find the relationship between them and thus identify the most suitable option in planning the reconstruction of plant layout. For this aim it is necessary to define the sequence of actions that will lead to the effective planning. Within such a process the selected factors influencing the decision options and their relationship are analysed. Figure 1 presents the subsequent steps of running the AHP method.

Figure 1. AHP process



Source: own elaboration, based on Hadi-Vencheh & Mohamadghasemi (2013).

As it can be seen it is possible to iterate the steps until the desired outcome is achieved.

4. Application of the AHP method to the case study

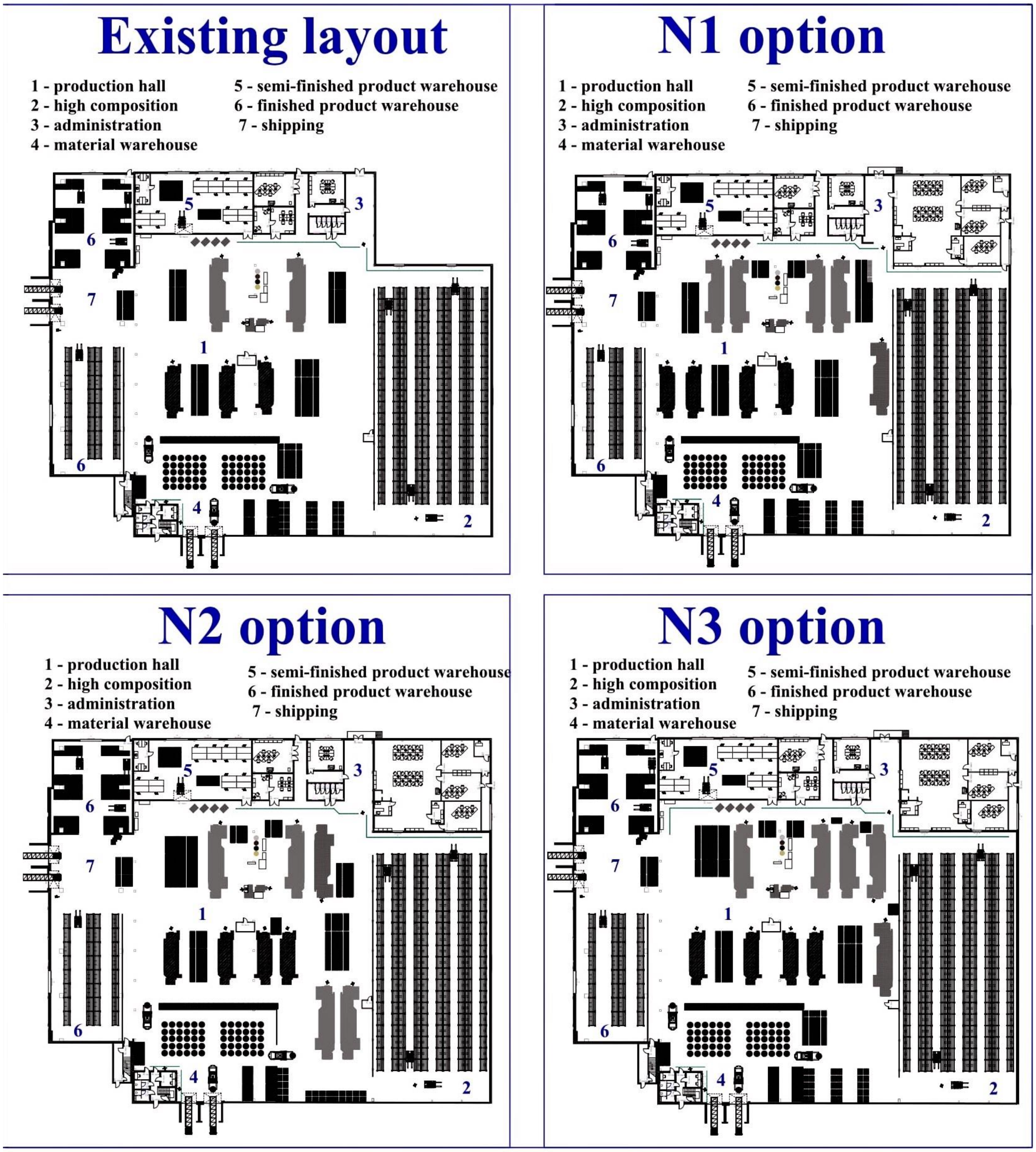
The analysed case study concerns a decision situation in a production company (a printing house). The decision concerns a change of the existing layout of the factory production space for the better one, more appropriate and effective one, which optimises the current production processes. It is assumed that the producer can choose only one of the proposed layout options and that he or she is inclined to use the following three criteria in the decision making process: minimization of the costs of the layout restructuring, minimization of the layout change realisation time and maximisation of efficiency of the layout in the production process.

The usefulness of AHP algorithm will be observed with regard to the mentioned decision situation. The situation was analysed below following the AHP methodological steps.

The first step is the hierarchical analysis of the problem. It involves a detailed description of the problem, definition of the optimisation functions and their constrains, setting the purpose for corrective action(s) and determination of expectations concerning their outcomes. In our case study the common goal was defined as the selection of optimal option of the factory layout in the virtual environment.

The second step is to construct a decision model in mathematical and / or graphic form, taking into account any constraints on decision-making. The paper presents the existing layout of the plant and three proposed conceptual options to choose from (see Figure 2). The actions were directed on the one hand to the expansion of administrative facilities and, on the other hand, to the increase of production capacity by installing four additional machines in the production hall. As shown in Figure 2 reconstruction of the administrative block is planned to the right of the production site. This change is introduced in all three options, while the installation of four machines differs in all options. The challenge is to limit the displacement of the installed machines, because dismantling and transferring them to another place increases the cost of re-planning due to their solid foundation. Therefore, on the basis of the specified criteria and constraints, the three decision options were developed, which optimise the current production processes. Next, with the AHP method, the consequences of choosing the options were identified. will be selected for optimizing current production processes and will be the best. The three options are depicted in figure 2.

Figure 2. Layouts' options



Source: own elaboration.

The third step allows evaluating the criteria by pair-wise comparison (to what extent one is more important than the other) on the basis of creating a list of selected criteria to assess the different decision options. The criteria include: minimization of the costs of the layout restructuring, minimization of the layout change realisation time and maximisation of efficiency of the layout in the production process.

Each tested criterion should be compared with the others to obtain numerical weights. Relations between the different criteria are made in a 9-grade scale:

1 - both criteria are equally valid (relevant),

3 - the first criterion is slightly more important than the second one,

5 - the first criterion is clearly more important than the second one,

7 - the first criterion is definitely more important than the second one,

9 - the first criterion is absolutely more important than the second one.

Even numbers from 2 to 8 may indicate intermediate scores. This stage terminates with the construction of a presented matrix of pair-wise comparison of decision criteria, as presented in table 1.

Table 1. Weighting the importance of the criteria

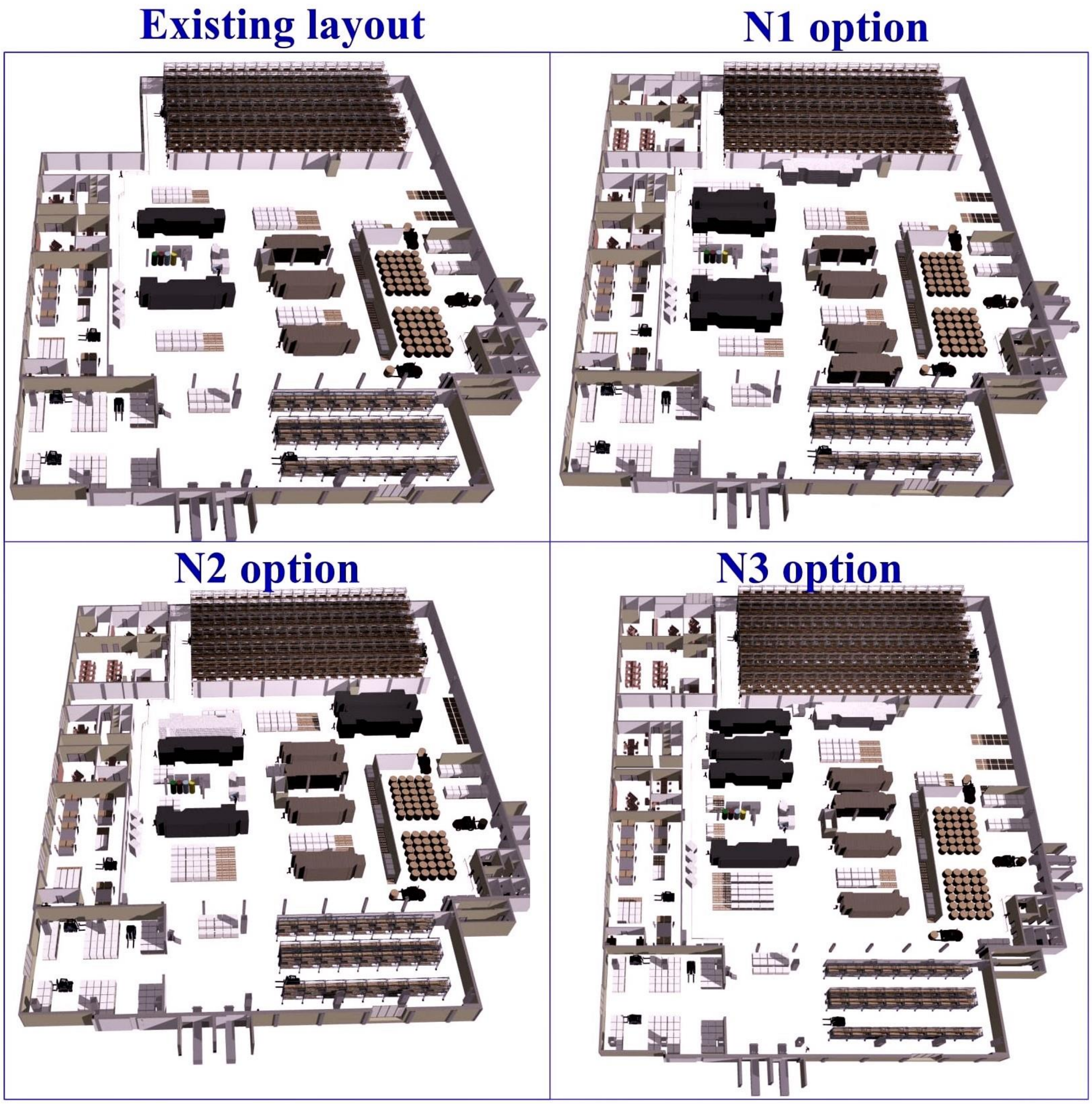
Assessment criteria for the layout options	Cost of the layout restructuring	Layout change realisation time	Efficiency of the layout in the production process
Cost of the layout restructuring (min.)	1	7	3
Layout change realisation time (min.)	1/7	1	1/5
Efficiency of the layout in the production process (max.)	1/3	5	1
Total	1,476	13,000	4,200

Source: own elaboration.

Analysis of the weights show that the layout change realisation time is the most important criterion. It is followed by efficiency of the layout from the point of view of the production process and finally the cost of the layout restructuring (re-planning).

The fourth step is to determine the mutual preference (weight) with respect to the decision options. Within this stage the consequences of choosing the options (their positive or negative impacts on the problem and its environment) are identified. This leads to choosing the optimal option, which is the decision most advantageous from the decision maker's point of view. The weight coefficients are calculated. The same method pair-wise comparison and the same scale as above is used in order to assess the decision options. The virtual reality visualization of the chosen options were performed and they were assessed as 3D model of a virtual factory, see Figure 3.

Figure 3. 3D layouts' options



Source: own elaboration.

Based on the 3D options, preferences (weights) have been given to the decision options in each of the criteria. The preferences of options with regard to each of the criteria are shown in table 2.

Table 2. Preferences of options with regard to each of the criteria

Assessment of criterion: cost of the layout restructuring (min.)	N1 option	N2 option	N3 option
N1 option	1	5	1/3
N2 option	1/5	1	3
N3 option	3	1/3	1
Total	4,200	6,333	4,333

Assessment of criterion: layout change realisation time (min.)	N1 option	N2 option	N3 option
N1 option	1	1/3	7
N2 option	3	1	5
N3 option	1/7	1/5	1
Total	4,143	1,533	13,000

Assessment of criterion: efficiency of the layout in the production process (max.)	N1 option	N2 option	N3 option
N1 option	1	1/5	3
N2 option	5	1	7
N3 option	1/3	1/7	1
Total	6,333	1,343	11,000

Source: own elaboration.

The obtained ratings are normalized by calculating the share of a given criterion in the total value calculated by adding the values in the columns for each layout option. Then, for the normalized assessments, the arithmetic averages are calculated, which will create the scale vector for the individual matrixes.

The fifth step links the model solution with the check of the correctness of the comparisons. If the results are incorrect, for example, a misconceptions of the importance of the criteria occurred, a decision-maker should return to the third stage of the process, namely to the selection and evaluation of the criteria by pair-wise comparison. The error will be signalled by the noncompliance indicator CR, when its value will be greater than 0,1.

Each decision option analysed is considered as a possible decision. The evaluation of each option was calculated by adding their scores for each criterion multiplied by the criterion weights, as presented in table 3. (Al-Harbi 2001; Saaty 2008).

Table 3. Priority matrix

Assessment criteria for the layout options	Cost of the layout restructuring	Layout change realisation time	Efficiency of the layout in the production process	Average
Cost of the layout restructuring (min.)	0,677	0,538	0,714	0,643
Layout change realisation time (min.)	0,097	0,077	0,048	0,074
Efficiency of the layout in the production process (max.)	0,226	0,385	0,238	0,283

Assessment of criterion: cost of the layout restructuring (min.)	N1 option	N2 option	N3 option	Average
N1 option	0,238	0,789	0,077	0,368
N2 option	0,048	0,158	0,692	0,299
N3 option	0,714	0,053	0,231	0,333

Assessment of criterion: layout change realisation time (min.)	N1 option	N2 option	N3 option	Average
N1 option	0,241	0,217	0,538	0,332
N2 option	0,724	0,652	0,385	0,587
N3 option	0,034	0,130	0,077	0,081

Assessment of criterion: efficiency of the layout in the production process (max.)	N1 option	N2 option	N3 option	Average
N1 option	0,158	0,149	0,273	0,193
N2 option	0,789	0,745	0,636	0,724

N3 option	0,053	0,106	0,091	0,083

Source: own elaboration

Based on the above calculations (see table 3) the final results for the different layout options and their hierarchy are presented in table 4.

Table 4. Hierarchy of the analysed layout options obtained with the AHP method

Results / Hierarchy of the options	
N2 option	0,44
N1 option	0,32
N3 option	0,24

Source: own elaboration.

As it can be seen from Table 4 the best is the N2 option, followed by the N1 option and the N3 option.

The sixth step of the AHP process involves evaluating and testing the individual solutions with respect to the analysed option. If the results are incorrect, one should return to the third step, namely the selection and evaluation of the criteria by pair-wise comparison.

Finally, within the seventh step, the final decision is taken – the best option, which has the highest priority from the decision maker's point of view, is chosen and its implementation can commence. (Tułecki & Król 2007; Al-Harbi 2001).

5. Discussion of the results

The AHP method is used in various sectors for various decision making processes. The hypothesis that AHP is a useful and advisable method for selecting the optimal option for planning and evaluation of a system in a virtual environment was proven right.

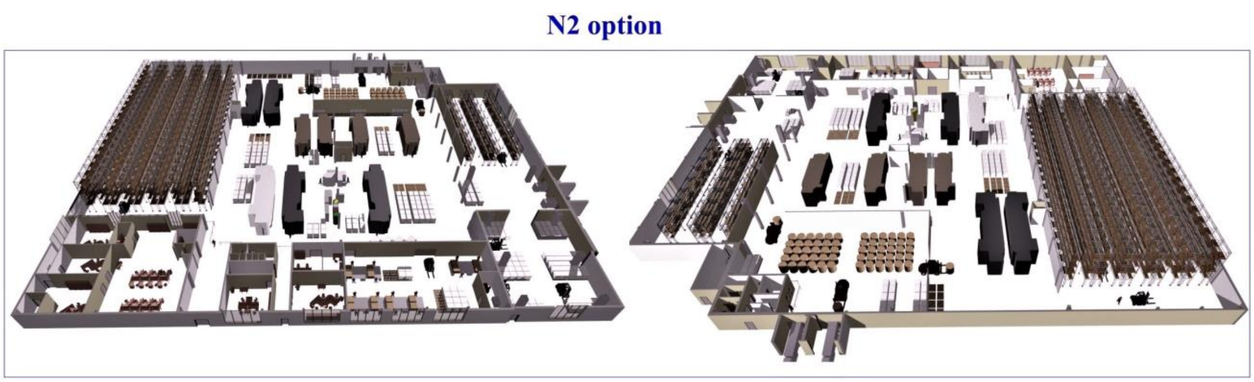
The merits of the AHP method include its easy understanding and application, analysis from the point of view of various criteria synthesised to the single number, possibility of serving as a solid framework for the participatory decision making with multiple actors and stakeholders. At the same time the subjectivity of the views in the criteria weighting and in the options assessment in view of the defined criteria, can be regarded as drawback, hindering the selection of ultimately optimal solution.

Making decisions about layout planning in a virtual environment is an intrinsic part of every production plant. The advantage of the AHP method is that it can be implemented by both individual and group decision makers. This approach is proven useful when creating virtual factory layouts individually by the designer or within the design team.

In the paper, the issues related to determining decision options and planning the optimum factory layout were analysed. In the remainder of this paper, the fifth stage of the defined AHP process is discussed, which deals with the quality check of the process - the solution of the model and the control of correctness of comparisons.

In the AHP method, the higher an option is evaluated the more probable it is that it will be finally selected. The obtained results of the study allowed us to conclude that in relation to the criteria weighing and comparing the variants the most advantageous (optimal) solution is the N2 option (see figure 4), whereas the most valued criterion was the efficiency of the layout in the production process.

Figure 4. Visualisation of the optimal option



Source: own elaboration.

In the N1 option and the N3 option the machines are cumulated in one place, what results in a cumulated load on the floor of the production hall in one place and increases the complexity of the machines installation. In the N1 option there is also a gathering of machines close to the shipping way. The layout change realisation time criterion is realised best in the N1 option, then in the N2 option and finally the N3 option has the longest installation time due to the fact that the machines are installed next to each other. Despite of the fact that the restructuring (re-planning) costs are higher in the N2 option compared to the N1 and the N3 options, this criterion was assigned the lowest importance by the decision maker and therefore as a result the N2 option is perceived the best. However, the second best option – the N1 option will also be a very good choice in this situation, if the narrow transition to the shipping area would not be an issue for the decision maker.

6. Conclusions

This paper describes and applies the decision-making method, which can be used to select an optimal layout variant out of the planned options. The choice of such a variant requires an understanding of the relationships between qualitative and quantitative factors. It is very important to define the criteria and limitations for the planned changes.

Using the AHP method, it is possible for the designer to take the decision individually or together with the design team regarding the optimum layout, which satisfies the expected criteria. The analysis presented in this paper demonstrates that the AHP method can provide designers with a decision support tool useful for various areas of product manufacturing, accounting for individual approach in each plant. The availability of the method and the relative easiness in obtaining results make it possible for the decision maker(s) to combine multiple variants simultaneously and to check them immediately. At the same time, visualization of systems plays an important role, allowing the decision maker(s) to see the bottlenecks and the current state of a three dimensional environment. Taking into account the combination of the designer's experience and the AHP method, one can quickly get the optimal variant according to the desired criteria.

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