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A QUANTITATIVE STUDY OF IDEATION, VISUALISATION AND GRAPHICAL SKILLS IN ENGINEERING DESIGN

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1 Introduction

Ideation is that part of the engineering design process in which ideas for potential solutions are generated. It follows the problem enformulation stage, and precedes the evaluation/ decision and solution specification/communication stages. In diminishing degrees, it is present in the conceptual-, embodiment- and detail-design phases of solution development. It represents the creative nexus between problem and solution, and so is key to the successful outcome of the design process.

More generally, idea generation (or ideation) is central to problem solving. According to VanGundy [1], the four main problem-solving stages are (1) redefining and analysing problems, (2) generating ideas, (3) evaluating and selecting ideas and (4) implementing ideas. Ideation is an integral part of engineering design because engineers are continually striving to find novel and imaginative ways to solve problems in order to do new things or to do things better (that is, more efficiently and effectively).

But what are some of the influences on ideation, and how may they, and the ideation activity itself, be measured?

2 Objectives

This paper investigates the idea generation stage and factors affecting an individual's idea generating ability. There is a general assumption that ideational characteristics vary between individuals. More detailed and experimentally based knowledge is needed in this area in order to equip design engineers with better problem solving abilities [2].

Sketching and visualization ability are two attributes that are increasingly postulated as being relevant for idea generation [references 3 to 11], and hence important for engineers. Thus, it is of interest to investigate the relationship between sketching, visualization and ideational characteristics of engineers. Various other plausible experiential influences upon ideation were also examined in this investigation.

This investigation seeks to measure the quality of ideation of a number of novice designer subjects engaged in simple conceptual design tasks, according to the fluency, flexibility and practicality of the concepts they generate. An exploration is then undertaken of the possible influence of spatial visualisation ability and graphical sketching skill upon ideation.

3 Methods

3.1 Overview of research methodology

Part of investigating a relationship is being able to measure things first. Shah, Smith and Vargas-Hernandez have, in their research, proposed four separate measures of ideational performance – fluency, novelty, variety, and quality [12], and these were adopted for the purposes of the present study. Sketching ability was quantified using different measures: clarity, line/shading, detail, labelling and 3-D view. Visualization on the other hand, was based on scores obtained from participation in standard Mental Cutting Test exercises.

Novice designers (undergraduate students of mechanical engineering at second and third-year level) were posed two conceptual design tasks having differing degrees of difficulty.

Task A: Device for changing direction of a planar displacement (Bonus Test 3).

The level 200 students were required to generate, in a 5-minute period, as many concepts as possible for converting a vertical linear translation at one point on a device, to a horizontal linear translation at a nearby point (refer to Appendix A for details of the design task). The activity was one of a series of "Bonus Tests" completed by students in their design subject. Students' ideas were assessed in terms of their number ("fluency") and diversity (the proportion of distinctly different concepts, or "flexibility"). An assessment was also made of the practicality of these concepts (that is, the likelihood of their successful implementation), although this was explicitly not one of the criteria set for the designers. Separately, the graphical sketching skill demonstrated by these designers in representing their concepts was also assessed using a number of precise criteria. Separate tests of spatial visualisation skill (using the standard Mental Cutting Test) and various elements of childhood recreational experience (using a questionnaire) were conducted on randomly selected subsets of this cohort. These data were compared using the Spearman rank correlation and Kruskal-Wallis test.

Task B: Three-dimensional motion transfer in VIGV mechanism.

The group of thirty level 300 students was smaller, but the study more intensive. These designers were required to produce concepts for a motion transfer linkage forming part of the variable-angle inlet guide vane (VIGV) mechanism of a two-spool turbo-jet engine. The system to be designed was highly constrained, with space and weight restrictions, and the requirement that it be retro-fitted to replace an existing set of components having inadequate reliability of assembly. Designer ideation was tracked using pictorial Idea Logs, and evaluated using similar metrics to those in the level 200 exercise. Further data on these designers was gathered using extensive post-project interviews.

3.2 Measuring the parameters

There are 3 main parameters needing to be quantified: quality of ideas, visualisation skills and sketching skills. Agreeing with Shah, Smith and Vargas-Hernandez that a single measure cannot justifiably quantify an individual's quality of ideas, the four proposed by them were adopted for this research. A brief discussion of the details of all the parameters to be measured is given below.

3.2.1 Ideation parameters

(a) Fluency – this measures the total number of ideas generated by the students.

(b) Novelty – is a comparison of ideas generated among all students. It judges how special or uncommon an idea is. Its calculation is based on the grouping of concepts into "categories" of similar ideas (for example in Task A, there are categories of solutions using gears, hydraulics, inclined planes, and so forth — a compendium of solution categories is given in Appendix B). The novelty weighting, *w* for each category is one minus that student's proportion of the overall ideas generated for that category:

$$w = 1 - \left(\frac{\text{total number of ideas in category}}{\text{total number of ideas of all designers}} \right).$$

The novelty score, *M*, for each individual will be the sum of the novelty weighting of each category into which their ideas fall, $M = \sum_i w_i$.

(c) Feasibility – measures how well the idea works in principle and whether it meets the initial problem requirements (note that this is essentially the same as 'quality' as in [8]). This measure was only used for the bonus test 3, as feasibility was not an issue to be penalised on at the conceptual stages of the VIGV project. The feasibility, *P*, is defined as:

$$P = \sum_{n=1}^{n} F_n * W_n$$

where *n* is the total number of ideas generated; *F* is the degree of fulfilment of the problem's objective, in this case satisfying both a push and pull motion (a score of '1' is given for violating this functionality and a '2' is given for having achieved this), *W* is scored on how well the device works, i.e. transmits the input force through 90 degrees. (0 – doesn't work; 1 – achieves some or little motion; 2 – motion achieved with identical stroke length).

(d) Variety – measures how one idea is different from another. This compares the ideas generated by an individual student. It is computed as:

$$V = 10 \times \sum S_k b_k$$

where S_k has been given values of 2 and 1 for level k=1 (physical principles), and level k=2, (working principles) respectively; b_k is the number of branches at level k.

3.2.2 Graphical skills parameters

Sketching skills consist of these sub measures:

(a) Detail – the level of detail was included as a means of ruling out any possible ambiguity within the sketch and also indicated the level of thought an individual goes through.

(b) Clarity – this was more to do with the legibility of the sketch.

(c) Labelling – included use of arrows to indicate motion, labelling of components, etc. overall to enhance effectiveness of getting ideas across to the reader.

(d) Line/shading – the creative use of lines or shading to increase legibility of the drawing.

(e) 3-D view – the use of perspectives and mental visualisation is much needed in producing an accurate 3-D isometric sketch. This measured how well the sketch could represent the idea in a 3-D space. Note that this measure applies only to Task B (the VIGV idea logs) and not to Task A (Bonus Test 3). The Bonus Test 3 did not require any 3-D isometric sketches and individuals certainly did not have enough time to draw 3-D sketches.

3.2.3 Spatial visualisation parameters

Visualization ability was based on scores obtained from attempting questions from the Mental Cutting Test (MCT). Two different methods are used to measure the visualization skills:

(a) weighted score: each question has different weighting based on the level of difficulty. The level of difficulty is judge by the number of correct answers. Weighting, *ws* is defined as:

$$ws = 1 - \frac{\text{number of correct answers}}{\text{total number of candidate}}.$$

Individual scores are the sum of the weighting of correct answers made by a student.

(b) unweighted score: visualization score of an individual is just the raw number of correct answers he/she made i.e. score between 1-5, as 5 questions were included in these exercises.

3.2.4 Influences from prior life experience

A simple questionnaire on prior life experiences is administered to most students in the first year of the mechanical engineering course, in a subject called Introduction to Design and Manufacture (IDM). The results of this "IDM getting to know you" questionnaire were anonymously correlated with the various performance measures listed in sections 3.2.1 to 3.2.3, above, in an effort to measure the influence of such prior experiences on ideational characteristics. The students reported their experiences at three levels of intensity ('yes', 'a little' and 'no') for a range of ordinary life activities.

3.3 Statistical analysis tools

In this research project, two non-parametric statistical analysis methods, which are used to analyse ordinal-scaled data, were used. For drawing correlations between the abilities of an individual in Task A (Bonus Test 3), the Spearman rank correlation [12] method is used. This is because in analysing data from Task A, the comparison is between two related sets of data. For drawing correlations between past experience and sketching, visualisation and ideation quality, from the Task A (Bonus Test 3) and the IDM prior experience questionnaire, the Kruskal-Wallis test [13] was employed. This is because the same set of data is separated into three groups and we would like to find out the difference between groups. The groups correspond to the varying levels of experience students had with the questions.

(a) Spearman rank correlation

The hypothesis tested for Spearman rank correlation in general term is:

— H_0: the parameters are independent of each other.

— H_1: the parameters are related.

(b) Kruskal-Wallis Test

This was used for the testing of the null and alternative hypotheses:

— H_0: there is no difference between groups.

— H_1: there is a difference between groups.

3.4 Task B interviews (VIGV)

Questions were designed and conducted by the research team to explore the ideational process used by individuals in Task B (design of VIGV mechanism). The aim of the interview was to gain insight into the thoughts and processes/techniques that individuals engaged in whilst searching for a solution to a complex problem. The intention was to discover any common similarities and patterns between a 'strong ideation' group in terms of their use of creativity tools, methodical/systematic approaches, and general style of creative design activity.

4 Results

The results from statistical measurements of Task A (Bonus Test 3), and the Task B interview (VIGV) and Kruskal-Wallis test on past experiences have been summarised into the following tables. Tables 1 and 2 refer to the group of the three strongest (weakest) performing students in Task B (VIGV project) as measured by their ideation parameter scores.

Table 1. Strong Ideation group for Task B

ID	Novelty	Variety	Fluency	Unweighted MCT score	Overall Sketching Score
3	8.4091 (2)	27 (1)	17 (1)	3 (6.5)	18.5 (4)
5	9.4205 (1)	26 (2)	14 (3)	4 (4.5)	21 (2)
8	7.4773 (3)	23 (3)	15 (2)	2 (8)	13.3 (10)

Table 2. Weak Ideation group for Task B

ID	Novelty	Variety	Fluency	Unweighted MCT score	Overall Sketching Score
1	4.545(8)	12 (8)	6 (7)	4 (4.5)	16.67 (8)
2	3.602 (9)	10 (9.5)	6 (7)	1 (10)	18 (6)
9	2.716 (10)	10 (9.5)	3 (10)	5 (2)	17 (7)

Table 3. Correlation between life-experience questionnaire and various parameters for Task A

Question	Sketching	Variety	Novelty	Fluency	Feasibility	Visualisation
1 – experience with Lego™	(null)	(null)	(null)	(null)	(null)	(null)
2 – assembling models	(null)	(null)	(null)	(null)	Positive	(null)
3 – assembling furniture	(null)	(null)	Weak	(null)	(null)	(null)
4 – making things from hard materials	(null)	(null)	(null)	(null)	(null)	(null)
5 – making things from soft materials	(null)	Negative	(null)	(null)	Negative	(null)
6 – art drawing	(null)	(null)	(null)	(null)	(null)	(null)
7 – technical drawing	(null)	Positive	(null)	(null)	(null)	Positive
8 – riding a bike	(null)	(null)	(null)	(null)	(null)	(null)
9 – crewing a boat	(null)	(null)	(null)	(null)	(null)	(null)

Note: "(null)" = accept null hypothesis of Kruskal-Wallis test
"Positive", "Weak", "Negative" = null hypothesis of Kruskal-Wallis test rejected, some degree of correlation found at 95% confidence level.

All the null hypotheses from the Spearman rank correlation analysis done on Task A (the Bonus Test 3) group were rejected (that is, a positive correlation was detected at the 95% confidence level). In fact, these correlations were all found at better than 99.99% confidence! Such strong positive correlations were detected in relation to:

- the correlation between sketching skills and **variety** of ideas generated;
- the correlation between sketching skills and **novelty** of ideas generated;
- the correlation between sketching skills and **feasibility** of ideas generated;
- the correlation between sketching skills and **fluency** of ideas generated;

- the correlation between visualisation ability and **variety** of ideas generated;
- the correlation between visualisation ability and **novelty** of ideas generated;
- the correlation between visualisation ability and **feasibility** of ideas generated;
- the correlation between visualisation ability and **fluency** of ideas generated;

- the correlation between sketching skills and **visualisation ability**.

In contrast, all the hypotheses done in relation to Task B (for the VIGV group) were accepted (that is, no correlations were found at the 95% confidence level).

5 Discussion

The Spearman rank correlation performed on students engaged in Task A shows that for that group there is a strong correlation at the 99.99% confidence level between students' sketching skills, visualisation skills and quality of ideas generated.

The same analysis done on the idea logs for Task B (VIGV project, 2003) however shows a contradictory result, namelythat sketching skills and visualisation skills are not associated with quality of ideas. The use of weighted or unweighted scores for the MCT did not affect the results obtained. This inability of the Task B data to yield similar correlations to that obtained so clearly for Task A, is probably expalined by two defects:

- Task B had a relatively small sample size (around 20 studentsfrom a class of 60, of whom only 10 were interviewed), whereas Task A used data from the entire class of 180 students; and

- Task B analysis was conducted on a sample that was not the entire class population, but a non-random *selection* of the idea logs from best-performing teams. This selection of data appears to have obfuscated the analysis, by removing the differentiations between high-performing and poor-performing design teams that might have led to clearer correlations between sketching, visualisation and ideation performance. Essentially it provided a comparison only between ideational high performers.

In the attempt to discover something about the influence of past experience on sketching and visualisation ability and ideation, we find only very few selected experiences exhibiting positive correlations (see Table 3). Most of the selected experiences do not have any impact on the three parameters. Kruskal-Wallis analysis shows that experiences of assembling models from kits and assembling objects from parts (e.g. furniture) do influence the feasibility of ideas generated. However, there is no trend in the influence of past experience observed from this analysis, so no general conclusion is drawn here.

It is observed that the strong ideation group from Task B (see table 1) are generally ranked high in novelty, variety and fluency. Comparing within and between the two groups, there are no emerging patterns with the use of ideation processes, background experience, sketching background and ability and visualisation ability. One common feature linking the three students in the strong ideation group, is that they each structured the problem as having different levels (either 2 or 3) of allowable extent of change, ranging from minor alterations to the existing mechanism, to major conceptual re-designs.

In the small sample of students interviewed for Task B (VIGV mechanism design) there was no evidence showing the formal use of structured thinking tools in the idea generation phase. Such tools were only evident at later stages in the design process, when used to evaluate and select the final design.

6 Future implications and final remarks

In drawing conclusions, especially with such a heavy emphasis on statistical methods, it is important to bear in mind that "correlation" and "no correlation" are just statistical generalisations; they do not mean "everybody" or "nobody". For most persons, these results simply mean that being strong in any one ability — whether sketching, visualisation or idea generation — increases the likelihood of being strong in the other two.

This paper presents one basic finding of research that may some day lead to a more complete understanding of the causal relationships between sketching, visualisation and idea generation ability. The next step would be to identify which of these can be inferred from the other two (that is, the question of causality), and what factors affect these three parameters.

In this paper, there is strong evidence of the importance of sketching and visualisation skills in the area of problem solving. This is contrary to the lack of emphasis on such creative skills in the engineering syllabus, and suggests that more focus should be shifted towards the development of these skills. The data collected on students' past experience should be conducted using a more detailed instrument, for example specific details of the relevant experience should be noted as opposed to the vague response in the IDM questionnaire.

A separate experiment could be conducted on the use of creative problem solving (CPS) techniques in problem solving. An example would entail three groups of students solving the same problem but two are constrained to using different CPS techniques and one without the use of any formal technique. According to Dixon, gaining conscious awareness and study of the design and analysis of problem solving, will improve the probability of future success [2].

As an alternative to the interview method used for Task B, one method for conducting effective problem solving experiments on humans, is to present a problem to a subject and get him/her to think out loud during his/her efforts to solve it. Such protocol analysis techniques have been used extensively in probing the creative design process [14–16].

7 Conclusion

This study pertains to the current (2004) cohort of undergraduate designers, and is on-going. There is some evidence to suggest that people with high spatial visualisation ability rely less on sketches as they can see "it" all in their mind's eye. Good sketchers are found in general to produce ideas that are more practically implementable. An interesting relationship is also suggested between ideation and childhood experience with construction toys, however the data set for this correlation is small.

But what is very compelling from this experiment in idea generation, is that there is a strong correlation between spatial visualisation skill and the quality of ideation, and also between graphical sketching skills and ideation. The causal direction of these correlations cannot be deduced from the data collected in this study, and is a target for future research.

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APPENDIX A — TEST PROBLEM FOR IDEATION TASK 'A' (LEVEL-200)

Your name (print) …………………………… ID No: ……………………

Date: ……………………

Figure 1 represents a desired motion. The vertical push-pull motion is the input to a reciprocating device, and the reqiuired output motion is a horizontal push-pull, in phase with the input, and with an identical stroke length. Your objective is to obtain the motion within the smallest possible practicable volume — the smallest size of "black box" relative to the length of the stroke.

With the aid of labelled concept sketches, show at least six (6) distinctly different methods of achieving the required motion (use the back of this sheet).

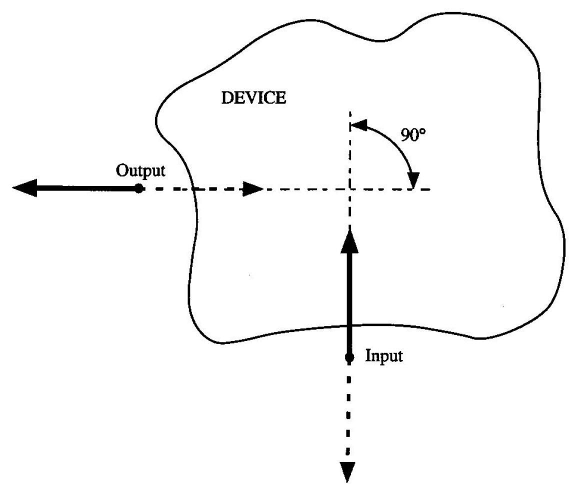

Fig. 1. Desired functional motion

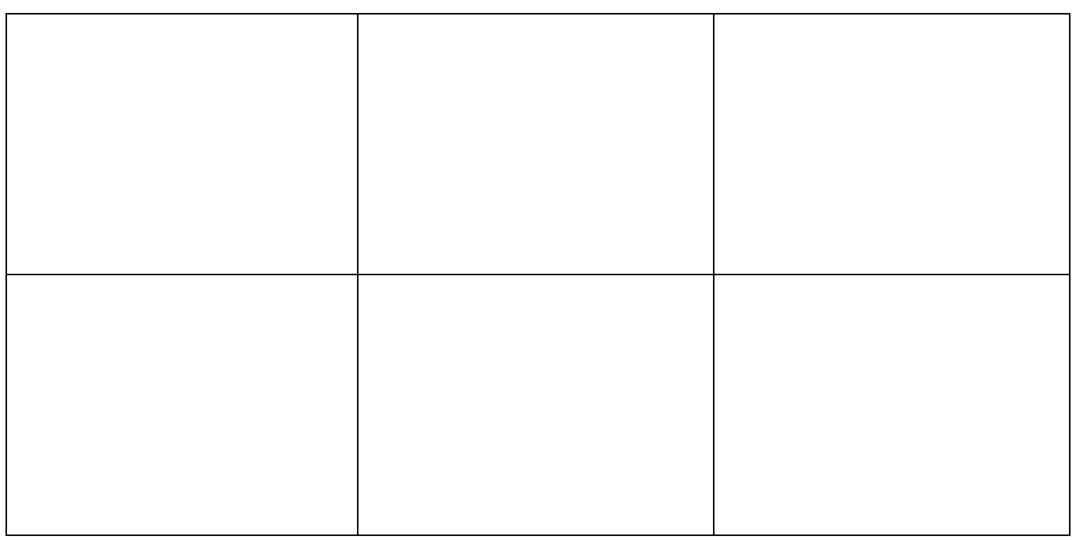

Fig. 2. Student's response sheet (blank)

APPENDIX B — POSSIBLE SOLUTION MECHANISMS FOR IDEATION TASK 'A' (LEVEL-200)

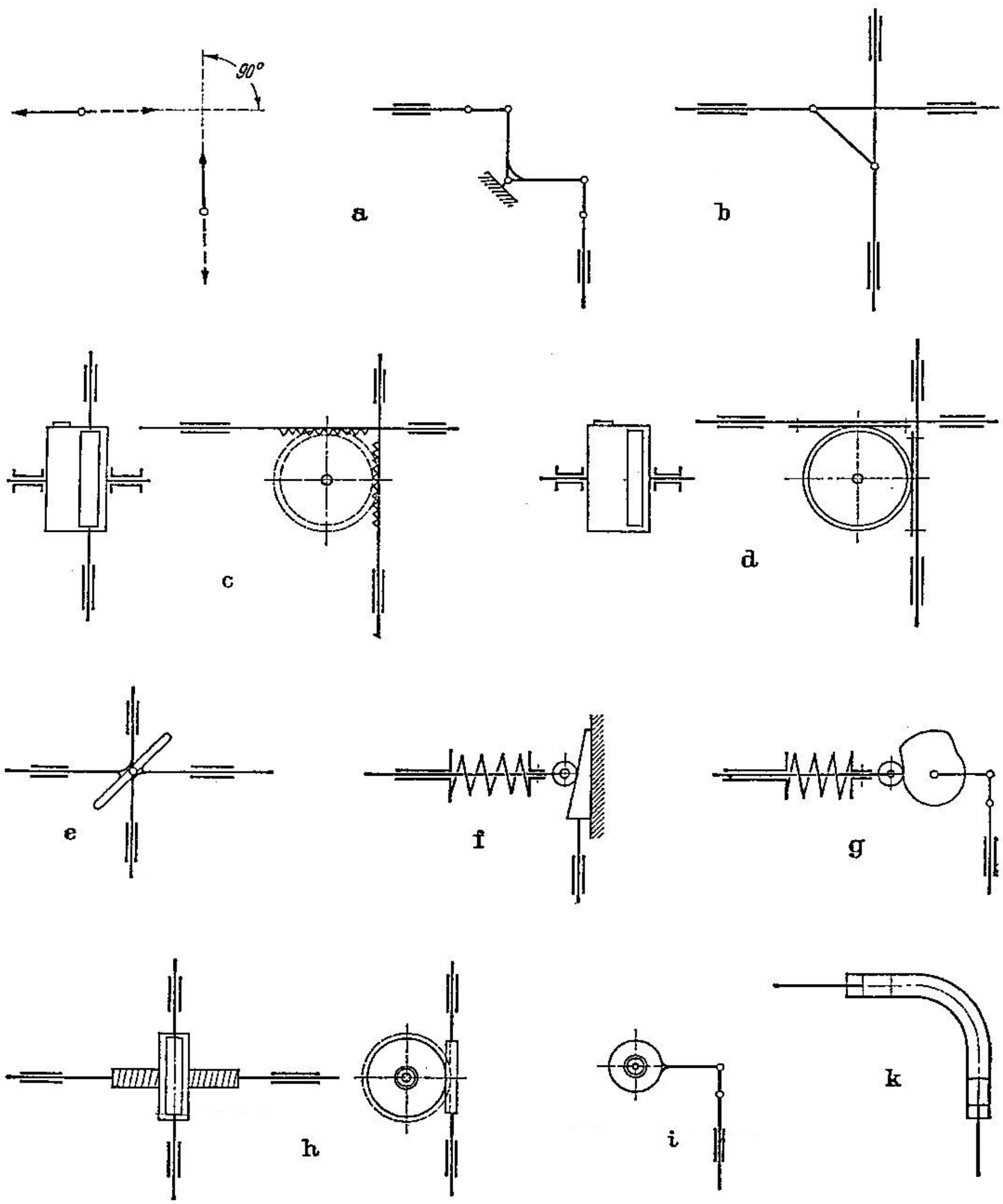

Fig. 3. Ten possible solution concepts