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Research article

Developing students' cognitive skills in MMS classes

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Abstract: Modern engineers face the challenges of complexity, uncertainty and ambiguity as three fundamental aspects of post-industrial technology. Hence, meta-subjective cognitive skills, critical thinking and creativity become no less important than professional knowledge acquired in vocational training. The better conditions for the development of these skills can be found if a contextual approach in teaching/learning is incorporated into the engineering curriculum. The article discusses the strategies for involving students in active learning activities while studying Mechanism and Machine Science (MMS) and developing students' cognitive competencies and metacognitive skills. Following the contextual approach, one can find that the simulation of mechanisms and the use of virtual labs form a powerful methodology to help learners better understand theory concepts. They provide students with a means of deeper numerical analysis and stimulate independent learning activity. Simulation and modeling of MMS products contribute greatly in students' comprehension of kinematics and dynamics of mechanisms. Another milestone of contextual approach is a creative problem-based learning that has been shown to be effective in education. However, creative problem-based learning is not in a focus of MMS courses yet. Brainstorming, TRIZ (theory of inventive problem solving, it sometimes occasionally goes by the English acronym TIPS), Synectics, and other creative problem-solving methods can be adapted for the active MMS learning. The article suggests the adaptation of SCAMPER, a method for solving several problems concerning structural analysis, kinematics, and gear trains.

Keywords: MMS, students, cognitive skills, creative thinking, problem-based learning, SCAMPER, heuristic method, problem solving

1. Introduction

The goals and objectives of engineering training are now undergoing a significant transformation. Meta-subjective cognitive skills, critical thinking and creativity become no less important than professional knowledge acquired in vocational training. In the 21st century, engineers face the challenges of complexity, uncertainty and ambiguity as three fundamental aspects of post-industrial technology [1]. This should give engineering education a new focus on student creativity and innovation. A new challenge needs an appropriate response. A. Rugarsia et al. note that the volume of information that engineers are called upon to know is increasing far more rapidly than the ability of engineering curricula to cover it. The solution proposed is that the focus in engineering education must shift away from the simple presentation of knowledge and toward the integration of knowledge and the development of critical skills needed to make appropriate use of it [2]. Active role of a learner becomes very important, so cognitive engagement is cited as a critical component of an educational experience [3]. To increase cognitive engagement, students must move from shallow cognitive processing to meaningful cognitive processing [3]. Some researches note that the expectations of industry, academia and faculty are shared by students themselves: “current expectations of engineering students are not only that they have the ability to learn, to achieve and to create but also to have the ability to be self-starters, critical and creative thinkers” [4].

2. Contextual approach in teaching/learning MMS

By reviewing the competency models of an engineer elaborated during the past 15 years, M. Frank presents sixteen cognitive competencies that are actually a set of cognitive skills [5]. M. Frank addressed to education of system engineers mainly, but it seems, today almost every engineering job can be considered as a system one because of many relations with society, people and other branches of engineering. Engineering pedagogy should be supported by the methods and approaches from cognitive psychology in fostering these skills in engineers.

M. Greene & P. Papalambros attempted to map cognitive competencies to the concepts from cognitive psychology. Some of these correlations are listed in Table 1 [6].

Table 1. Cognitive competencies of engineers vs. cognitive processes required for generating these behaviors.

Frank’s cognitive competencies	Cognitive psychology related concepts
Understand the whole system and see the big picture.	Information integration; mental model formation; generalization
Understand interconnections.	Induction; classification; similarity; integration.
Think creatively.	Creativity.
Understand systems without getting stuck on details.	Abstraction; subsumption.
Understand the implications of proposed change.	Hypothetical thinking.
Understand analogies and parallelism between systems.	Analogical thinking.
Ask good (the right) questions.	Critical thinking.

Every psychological concept gets description via a system of indicators and operators. Thus, S.

Daly et al. emphasize that cognitive aspects of creativity can be measured by the indicators such as generating ideas, digging deeper into ideas, openness and courage to explore ideas, listening to one's inner voice; see Figure 1 [7]. In turn, these indicators are mapped to operators. For example, digging deeper into ideas reveals itself through analyzing, synthesizing, reorganizing or redefining, evaluating, seeing relationships, and desiring to resolve ambiguity/bringing order to disorder [7].

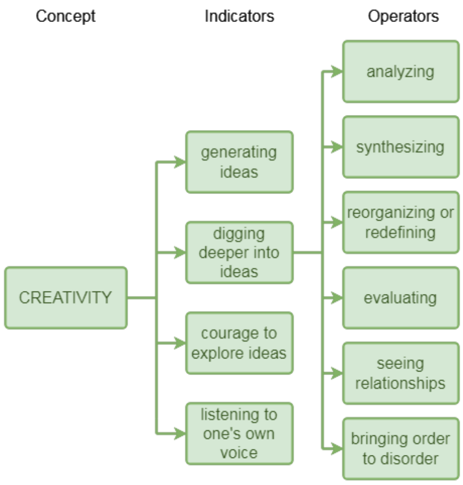

Figure 1. Psychological concept of creativity.

Here we will focus on the course of Machine and Mechanism Science (MMS) in order to identify some ways of developing meta-subjective cognitive skills necessary students for active learning and future creative professional work.

One way to overcome the traditional role of student as a passive receiver of content is involving him/her into the learning activity based upon virtual labs [8,9]. This pedagogy realizes a switch from analytical approach to contextual approach in teaching subjects. M. Lumsdaine & E. Lumsdaine give arguments for contextual approach in [10]. To have the idea about the difference between these approaches, we list only a few features in Table 2 [10].

Table 2. Two ways of teaching subjects.

Analytical approach	Contextual approach
Students must know the fundamentals.	Students must know the fundamentals.
Minimal computer use.	Extensive computer use.
Problems are fully defined.	Problems are open-ended.
Students spend much time substituting in equations (plug-and-chug).	Students spend much time in critical thinking and in asking "what if" questions.
Only one "correct" solution expected.	Multiple solutions/alternatives expected.
Pure analysis-no design content.	Application to design is central.
Ask good (the right) questions	Critical thinking

Following the contextual approach, we find that the simulation of mechanisms is a powerful methodology to help learners better understand theory concepts. It provides them with a means of deeper numerical analysis, and stimulates independent learning activity. Simulation and modeling of MMS products contribute greatly in students' comprehension of kinematics and dynamics of mechanisms. In their recent paper M. Ceccarelli & M. Cocconcelli present an historical analysis of developments for the creation and usage of models of mechanisms in academic teaching fields, including demonstrating the didactic potential of CAD models to analyze different kinematic behaviors of mechanisms [11].

MATLAB with its graphical extension Simulink is widely used both in industry and academia, it is well suited for solving the problem of dimensional synthesis or kinematical and dynamical analysis for a planar or spatial mechanism in study courses [12,13]. Other commercially available software such as ADAMS, general-purpose multibody dynamics program, or LINKAGE, program for prototyping of mechanical linkages, can be used in teaching design of mechanisms.

From a didactic point of view it is important to let the learners feel the designing as an open-ended process: how any change in the input (configuration, number of links, types of kinematical pairs, loads) will affect the final structure of the mechanism and its parameters. Open-ended problems methodology needs appropriate methods and software tools to provide students with an instrument that is ready-to-use, user-friendly, and easy-to-change when applied for different mechanisms. The method of vector closed contours considers a mechanism as a combination of planar or spatial elementary vector modules, depending on the set of linear and angular arguments [14]. On the base of structural scheme, students develop the parametric formula for the mechanism's vector model and use specialized KDAM software for numerical analysis [15,16]. KDAM provides a means of easy-to-use investigation of a mechanism at the first stages of design and the optimization of its key parameters (dimensions, pressure angles, reduced loads, masses, reactions in joints, etc.). This software finds use in the dimensional, kinematical and dynamical synthesis of the typical mechanisms, studied in MMS courses, including crank and slider, quick return, cams, gear trains and others.

3. MMS class within a problem-based learning paradigm

Problem-based learning (PBL) and project learning have been proved to be effective in facilitating students' development of higher order learning and skills [17–20]. PBL has become increasingly popular in K-12 and higher education worldwide since it was first introduced in medical education in the late 1960s [21]. However, even in the 21st century it has not gained significant popularity in engineering curricula due to the large time-scale needed to solve complex engineering problems and the difficulties associated with assessment of its impact on students [22]. There is even some criticism of the benefits of widespread adoption of this method. J. Perrenet et al. claim that PBL has certain limitations, which make it less suitable as an overall strategy for engineering education [23].

Mechanism and Machine Science (MMS) as a study course has much in common with problem-based learning, since it also can be considered as a problem-centered teaching method. Any piece of theory should be illustrated with examples, and many problems come from past or modern industry. So, solving problems in regular course of MMS should also hold promise for cultivating students' creativity. This is especially important for training students for MMS competitions – Olympiads [23,24]. Very often a contest problem has not overcomplicated solution, but participant should be an experienced thinker and creative person to identify this way of solution and follow it to success.

TRIZ and Synectics are creative problem-solving methods that can be adapted for engineering design courses. These and other methods use algorithms based on principles, techniques, and operators. Some of them are intuitive, some analytical, but they all are heuristic. The common milestones of problem solving are: define the problem, analyze causes, generate ideas, weigh up ideas, make a decision, determine next steps to implement the solution, evaluate whether the problem was solved or not.

The aim of this article is to demonstrate the applicability of some heuristic techniques for creative solving MMS problems. In this respect, the phase of idea generating is especially interesting. It can be organized with SCAMPER, the brainstorming methods using a set of directed idea-spurring questions. The questions inspire changes in thinking process and give rise to a new vision of the problem.

The changes that SCAMPER stands for are: S – Substitute; C – Combine; A – Adapt; M – Magnify/Modify; P – Put to other uses; E – Eliminate; R – Rearrange/Reverse [25]. Here, we will demonstrate the application of heuristic solution methods for MMS problems. These methods, which correlate with the elements of the SCAMPER spectrum, have proved to be effective for use in the MMS study course.

We are lucky with MMS that one can find plenty of open-ended creative problems that permit more than one reasonable solution. In some MMS topics the SCAMPER technology helps to arrange the way of solution by following a special flowchart. Structural analysis provides a good example of this. This is one of the first topics that illustrates mechanisms, variability and awakens students' creativity and energy. One can follow SCAMPER (not necessarily in the order S-C-A-M-P-E-R) as the recommended steps to get used to asking and answering certain questions. Figure 2 and Figure 3 illustrate the procedure of replacing higher kinematical pair (j_2) with lower pairs (j_1) using the technology associated with SCAMPER. This, in fact, E-C-M-R-A-S-P sequence is recommended to student for making structural analysis of any coplanar linkage containing j_2 pairs. A similar technique can be used for other topics, i.e., dimensional synthesis of linkages.

The authors would like to stress that the heuristic methods should not be considered as the replacement of any kind of solid theoretical knowledge. The role and importance of the methods like SCAMPER are to give students the opportunities of greater involvement and control over their learning.

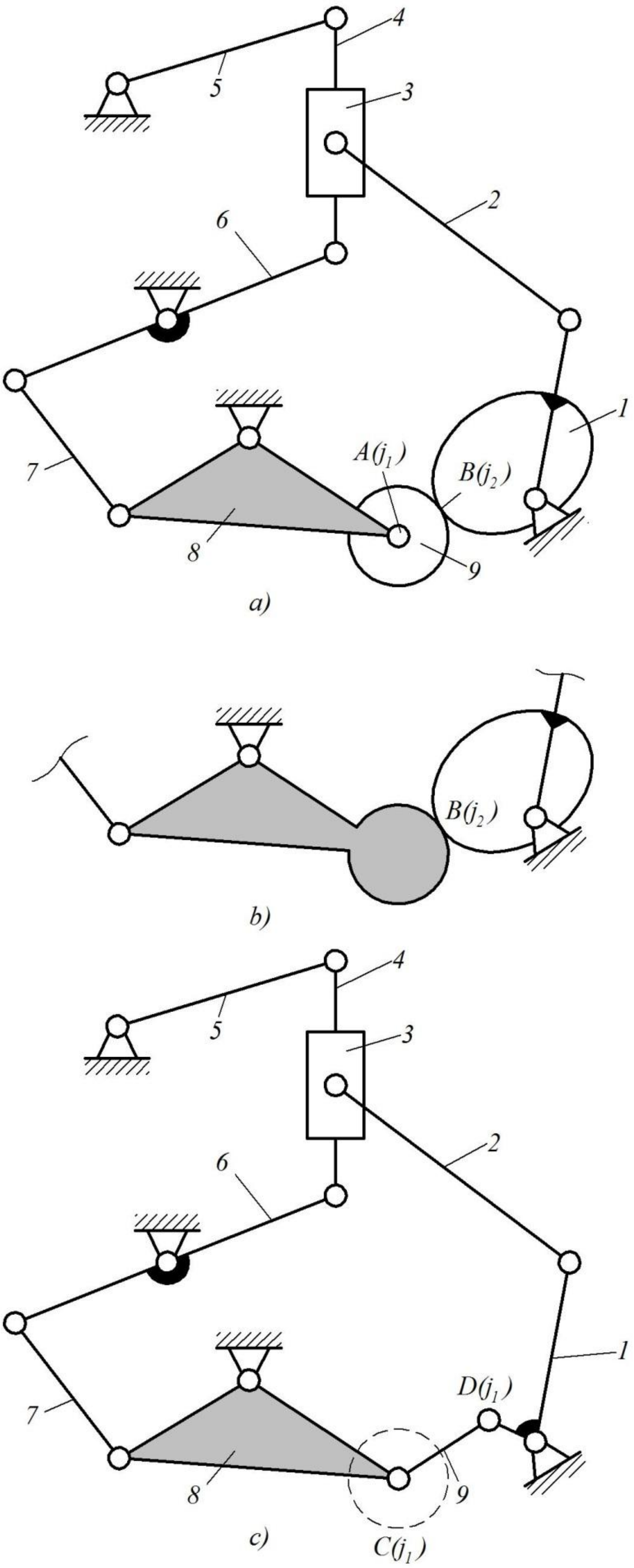

Figure 2. Procedure of replacing j_2 with j_1 in a coplanar linkage.

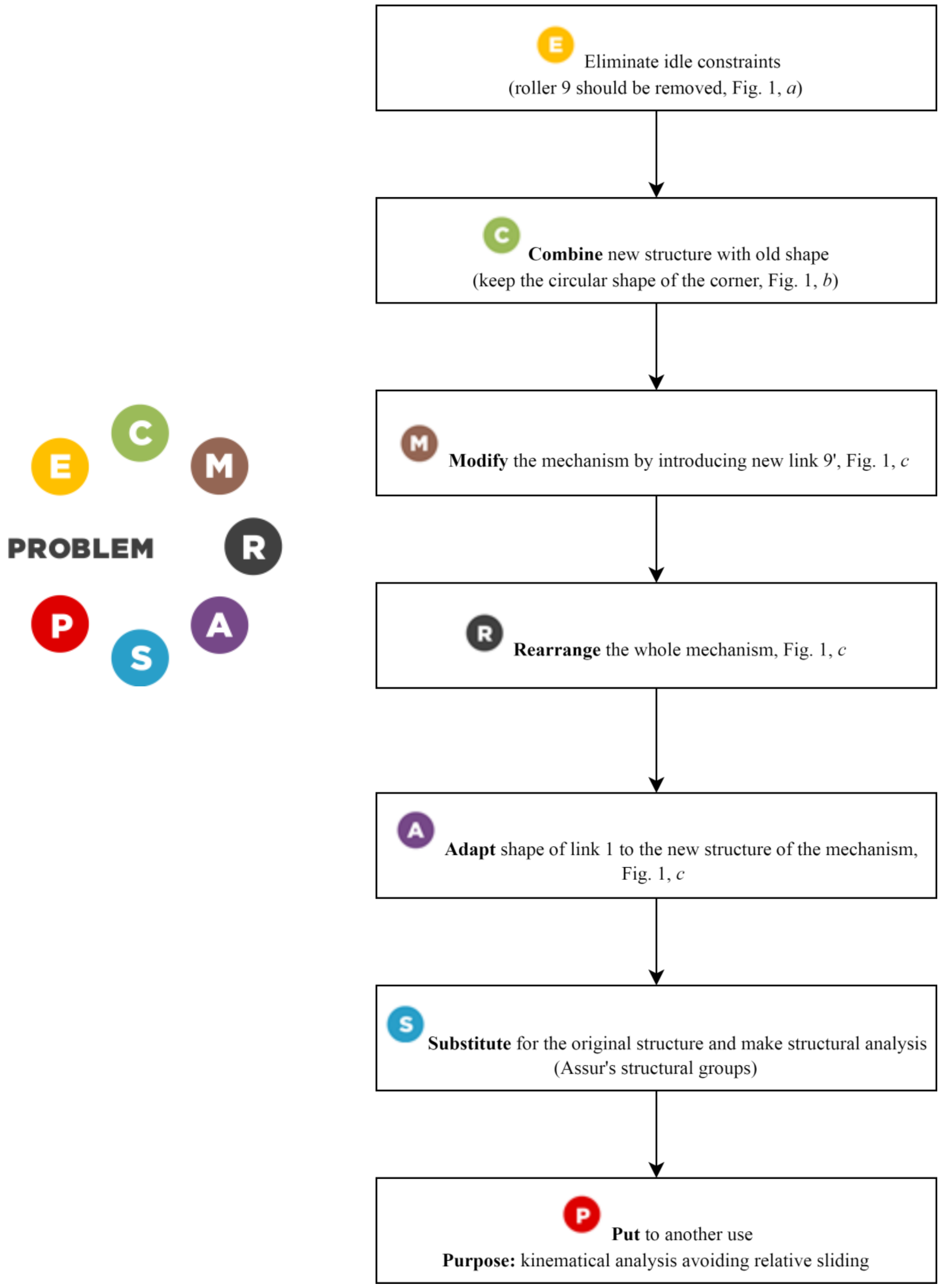

Figure 3. Replacing j_2 with j_1, technology associated with SCAMPER flowchart.

The elements of SCAMPER technology also can be found in more specific issues like contest problems of MMS student competitions (Olympiads). The contest problems do not imply a straightforward solution and can contain uncertainty, so they often do not have a solution that can be reached following a certain sequence of steps, as in Figure 3. Nevertheless, students experienced with SCAMPER use elements of this technique and find solutions more easily. Three examples are given below.

1. ***Substitute***: replacing a parameter (variable) that cannot be easily found by a more convenient option. The application of the method of ***Substitute*** can save effort and time and simplify solution, as

shown for the following problem.

One simple example of ***Substitute*** can be demonstrated with a problem of the extrema of a transmission angle in the quadrilateral mechanism. Indeed, instead of examining the transmission angle itself, one can consider side O_2A of triangle O_2AB and get the relation between transmission angle γ and crank angle φ_1; see Figure 4*a*. The angle was substituted with the length, which can be easily differentiated to get maximum and minimum values of O_2A (and, hence, corresponding values of angle γ); see Figure 4*b*, 4*c*.

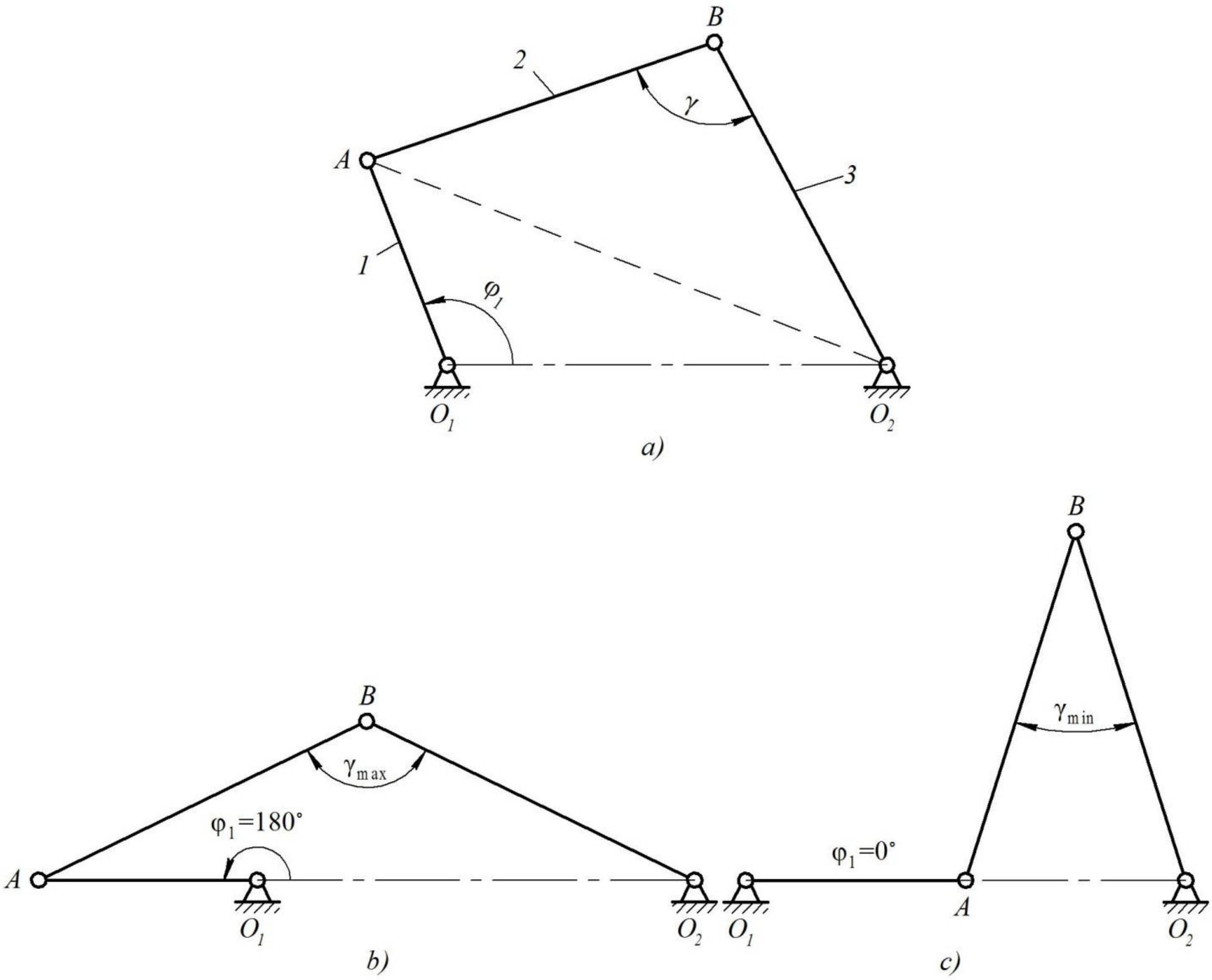

Figure 4. The application of *Substitute* for the transmission angle.

Now consider a more complicated **problem:** the geared linkage has the dimensions of $l_{OA} = 0.05\,m,\ l_{AB} = 0.20\,m,\ l_{BC} = 0.25\,m,\ l_{OC} = 0.20\,m$ (Figure 5, *a*). The gear wheel z_2 is the part of the connecting rod *AB*, while the wheel z_4 rotates about a fixed axis passing through the center of the hinge *C*. The numbers of teeth are: $z_2 = 25$, $z_4 = 35$. Crank *OA* rotates uniformly with an angular velocity of $\omega_1 = 70$ rad/s.

For the special position where angle $\varphi_2$takes the minimum value (i.e., $\varphi_2 = \varphi_{2_{min}}$), ***find*** (*i*) value of angle φ_1, (*ii*) value of angle $\varphi_{2_{min}}$, (*iii*) angular speed of gear wheel z_4.

It can be easily seen that *OABC* is a crank and rocker mechanism, so functions $\varphi_2 = \varphi_2(\varphi_1)$ and $\varphi_2 = \varphi_2(t)$ are continuous ones. Thus, for the position in question $\frac{d\varphi_2}{dt} = \omega_2 = 0$.

However, this means that link 2 instantaneously translates, and all its points move with the same velocity. In particular, $V_B = V_A$, and from this it follows that

$$\omega_3 = \frac{V_B}{l_{BC}} = \frac{V_A}{l_{BC}} = \frac{\omega_1 l_{OA}}{l_{BC}} = 14\ s^{-1}.$$

Gears z_2 and z_4 form an epicyclic gear chain with handle *BC*. Then, angular speed of gear z_4 is found by the formula Willis's method:

$$\frac{\omega_2-\omega_3}{\omega_4-\omega_3} = -\frac{z_4}{z_2} = i_{24}^{BC}, \qquad \omega_4 = \omega_3 + \frac{\omega_2-\omega_3}{i_{24}^{BC}}.$$

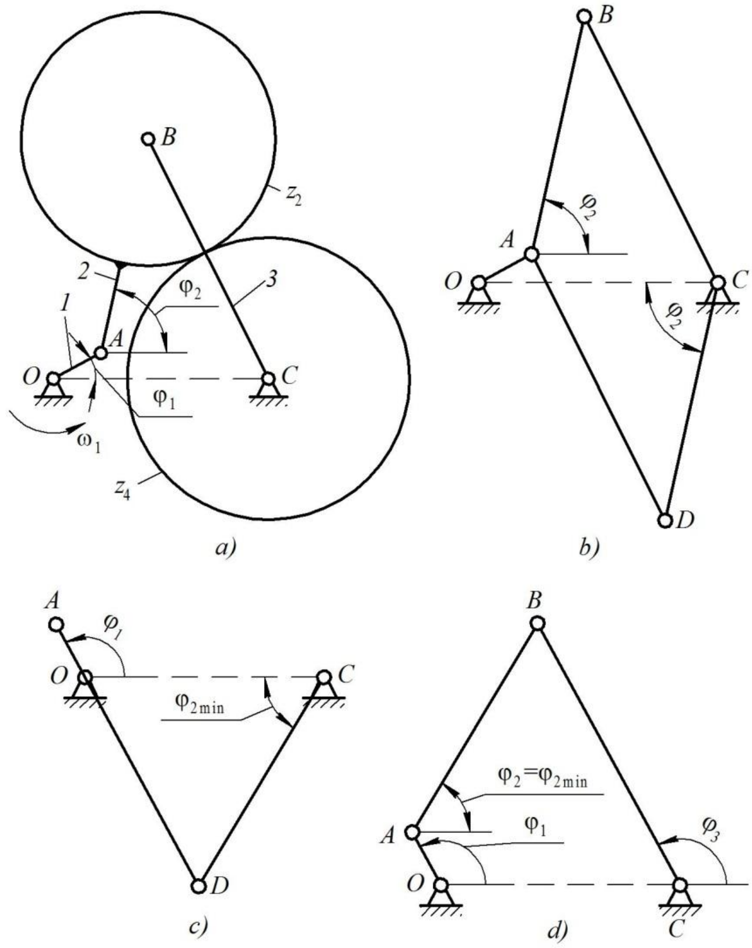

Figure 5. The application of *Substitute* for the geared linkage.

Now, about value of angle $\varphi_{2_{min}}$, it is difficult to find it in the original linkage. The simplification is possible with the method of ***Substitute***: We introduce an imaginary linkage *OADC* provided that $l_{CD} = l_{AB}, l_{AD} = l_{BC}$. For this new linkage it is easily seen that $\varphi_2 = \varphi_{2_{min}}$ when $OD = OD_{min} = l_{AD} - l_{OA} = 0.20\ m$ (Figure 5*b*).

Because of data given, it happens that $OD_{min} = l_{OC} = l_{CD}$, so triangle *OCD* is the equilateral one, and all the desired angles are found immediately (Figure 5*c*):

$$\varphi_2 = \varphi_{2_{min}} = 60°;\ \varphi_1 = \varphi_3 = 120°.$$

Figure 3, *d* illustrates the position of the four bar linkage that corresponds to the value of $\varphi_{2_{min}}$.

It is obvious that angular speeds of rocker (ω_3) and crank (ω_1) are of the same instantaneous direction. Hence using the above formula we finally get

$$\omega_4 = 14 + \frac{0-14}{-35/25} = 24\ s^{-1}.$$

2. ***Modify***: Can you change the item in some way? Can you start your solution with something not completely known?

Very often the solution of a coplanar MMS problem is found from the vector polygon. In some cases the order of components in a sequence of vectors does matter, and reasonable choice leads to significant simplifications. Sometimes the initial chain of the polygon is unknown in magnitude, but solution can be obtained by combining this chain with others.

Kinematical analysis provides good examples for the application of the method of ***Modify***. Consider the following problem. In a coplanar mechanism (Figure 6) links 1 and 2 are connected by rod 2 and pin-in-the-slot unit at *E*. The data given are: $\omega_1 = 2\,{}^{rad}/_{s}$, $O_1A = O_1E = ED = BD = 100\ mm$, O_2D=150 mm.

It asks for angular speed ω_4 at the position given in Figure 4.

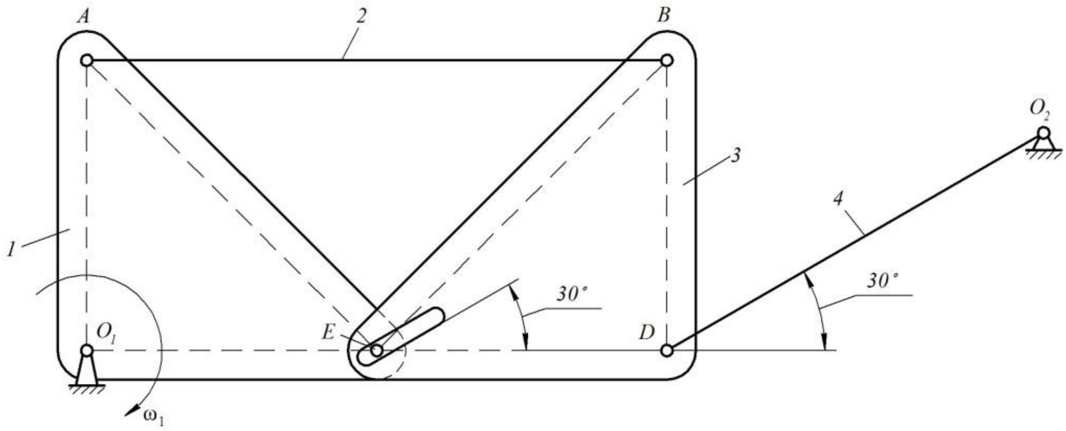

Figure 6. The application of *Modify* for planar kinematics.

There are two possible geometrical methods of solution: instant centers and vector polygon. Here, we will use the second one.

The expressions for velocities of point B with respect to points A and D:

$\vec{V}_B = \vec{V}_A + \vec{V}_{BA} = \vec{V}_D + \vec{V}_{BD}$, where $\vec{V}_A \perp O_1A$; $\vec{V}_{BA} \perp AB$; $\vec{V}_D \perp O_2D$; $\vec{V}_{BD} \perp BD$.

Since this equation contains only one value, known completely (V_A), it is not possible to find solution immediately. However, one can make a guess: vector polygon starts with $\vec{V}_D$ *that is laid off to an arbitrary scale* (Figure 7). We also lay off $V_A = V_E$ as rays from the same origin, taking their directions into account.

Finding velocity of point *E* makes the solution closed:

$$\vec{V}_{E_1} = \vec{V}_{E_3D_3} + \vec{V}_{E_1E_3}, \ \frac{V_{E_3D_3}}{V_{BD}} = \frac{ED}{BD} = 1.$$

The tip points I, II and III serve as the reference points in the velocity diagram. By drawing one line through every of them, according to the equations above, one can close the polygon (Figure 7). The readings in the picture are

$V_A \to x;\ V_E \to x; V_{BA} \to a;\ V_{BD} = V_{E_3D_3} \to b; V_D \to d;\ V_{E_1E_3} \to c.$

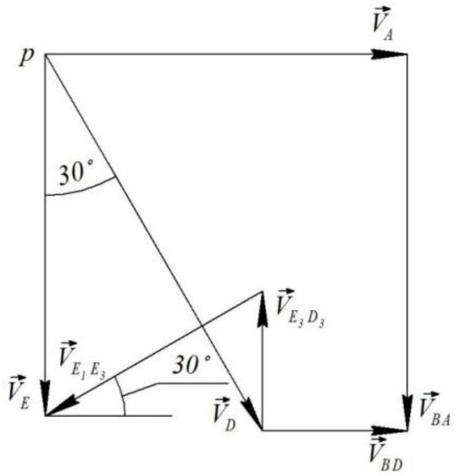

Figure 7. Velocity polygon.

From the polygon we have

$$\begin{cases} d\sin 30° = x - b \\ d\cos 30° = x + b - c\sin 30°. \\ d\sin 30° = c\cos 30° \end{cases}$$

The answer $d = 1.2x$, or $V_D = 1.2(\omega_1 \cdot O_1A) = 240\ mm/s$, and $\omega_4 = \frac{V_D}{O_2D} = 1.6\ s^{-1}$.

3. ***Eliminate, reduce***: What unnecessary issues can you eliminate? Focus on question strictly. Avoid actions that are not required and that are not absolutely necessary.

Many MMS problems are complicated for both reasoning and computation. Sometimes it seems that few values are missing in the data given. What to do, how to solve it? Students can become frustrated and upset or even fall into a stupor. One can remedy the situation by focusing only on relevant piece of the big puzzle, letting irrelevant information float away freely.

Often kinematical analysis of a gear box demands the answer for angular speed of every gear wheel. Yet, in the problem below the question is reduced to another that is less general one.

Problem. The input shaft *A* in the gear box (Figure 8) makes $N_A = 1440\ rpm$. The gear ratio is $i_{AB} = \frac{\omega_A}{\omega_B} = -40$, and the number of teeth $z_4 = z_5$.

Find N_{5H}, the relative velocity of gear z_5 with respect to handle *H*.

From the beginning one should focus closely on the key word: *relative velocity*, the angular velocity of gear 5 as seen from the handle H. It is

$$\omega_{5H} = \omega_5 - \omega_H.$$

The formula (Willis) method for gears 4 and 5 provides

$$\frac{\omega_4 - \omega_H}{\omega_5 - \omega_H} = -\frac{z_5}{z_4}, \text{ but } z_5 = z_4, \text{ and } \omega_4 = \omega_1 \text{ for the mechanism.}$$

Hence $\omega_1 - \omega_H = \omega_5 - \omega_H = \omega_{5H}$.

Now only gear ratio remains unused, the ratio of input and output gear velocities:

$$i_{AB} = \frac{\omega_1}{\omega_H} = -40,\ \ \omega_H = -\frac{\omega_1}{40}.$$

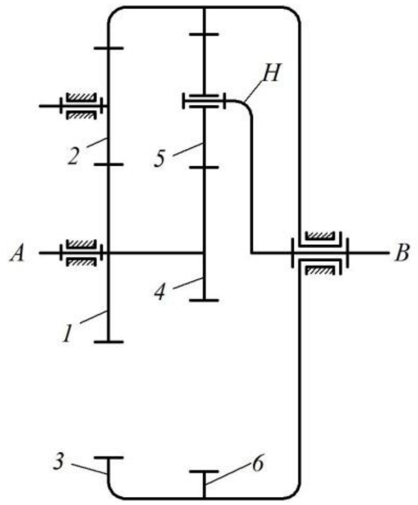

Figure 8. The application of *Eliminate* for epicyclic gear train.

Using the above equations it happens that relative velocity is equal to

$\omega_{5H} = \omega_1(1+\frac{1}{40})$, or $N_{5H} = N_1\left(1+\frac{1}{40}\right) = 1440\cdot\frac{41}{40} = 1476$ rpm.

It can be noted that the solution was pretty simple, because we were focused on the important points only. Also, we needed a clear idea about relative speed and the relevant expression for it.

Other applications of SCAMPER technique can be found in MMS problems. There are only few next possible ones: Rearrange – for closure of a force polygon in a smart way; Adapt – for velocity analysis of the links making translational kinematic pair; Modify – for velocity analysis of 3-d-class Assur's group (by introducing Assur's points) etc.

A brief illustration of **Rearrange**: Solving force equation for Assur's group (see Figure 9*a*) one encounters a difficulty of adding known term to an unknown one, as below.

$$\vec{F}_2^{in} + \vec{P}_2 + \vec{R}_{12}^{\tau} + \ ? \ + \vec{F}_3^{in} + \vec{P}_3 + \vec{R}_{03}^{\tau} + ? = 0$$

Rearranging the order brings a solution, where two unknown terms take the successive positions and meet each other in the diagram, Figure 7*b*.

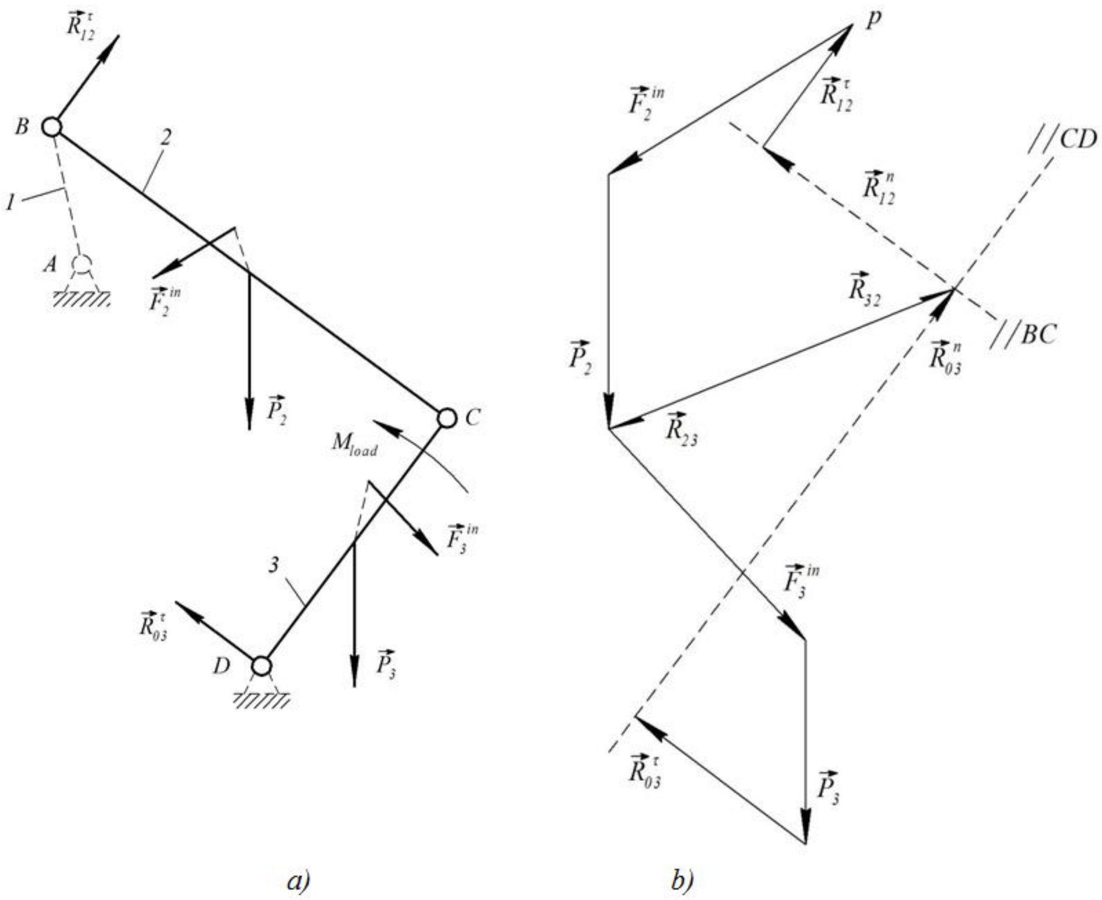

Figure 9. The application of Rearrange for force diagram.

The SCAMPER method was used as a sample in order to think about heuristic techniques in creative solving of MMS problems, so it is highly likely the specific MMS heuristic method has indirect mapping with SCAMPER components.

4. Conclusions

Engineering faces many challenges and controversies, the number of which has increased significantly in recent decades. To be successful in the profession a student should gain cognitive competencies and metacognitive skills during studying in university. Engineering curriculum can provide the development of these personal qualities, including creative and critical thinking, if special types of activities are incorporated in study subjects. In engineering pedagogy a switch from pure analytical approach to contextual approach can be realized in two modes: intensive use of computers in learning process, and creative problem-based learning. MMS as one of core engineering sciences provides many opportunities for both. Virtual labs as learning methodologies and tools are increasingly being used by MMS educators. However, it seems that problem-based learning is not in the focus of discussion. TRIZ, Synectics and other creative problem-solving methods can be adapted for MMS courses. This article shows the adaptation of the SCAMPER method for solving several problems concerning structural analysis, kinematics and gear trains. Authors hope that the creative problem-based learning, regardless of the specific platform on which it is implemented, will make a significant contribution to the cognitive development of future mechanical engineers.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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