Fostering Creativity and Innovation in Engineering Design Education: A case study

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***Abstract*—Finding innovative solutions is a key task for nowadays companies. To support the creativity of product designers and to guarantee design success a systematic / methodical design is highly recommended. Therefore, design education for future engineers has to meet these challenges. However, design methodologies are difficult to understand because described on a quite abstract level. Instructors are facing the situation of delivering the design theory in an appropriate and comprehensible manner. The conduction of generally understandable engineering design examples is essential to improve the use of design techniques and to strengthen the confidence and competence of engineering design students in terms of functional thinking and problem solving. This article presents some findings about an efficient use of design methodologies and techniques in the engineering design education at the faculty of Mechanical Engineering and Mechatronics of the Technische Hochschule / Deggendorf. It emphasizes especially the functional representation of a design task and the systematic change of its representation in order to support problem solving capabilities of students. The applied methods are used especially in the conceptual design phase. In the following the focus is on the generation of variants by the variation of relationships between functional representations and the variation of related physical effects. The given example originated from working group sessions with engineering students.**

Keywords—engineering design education; design methodology; creativity and innovation; functional representation and variation

I. Fundamentals of Methodical Design

A. *Conceptual design process*

The methodical design has a long tradition in the field of mechanical engineering and the theory has been outlined in literature and publications (e.g. [4], [5], [7], [8], [9], [10], [11]). According the theory the design process utilizes several stages, beginning with the clarification of the task, followed by a conceptual design phase, characterized by the development of functional and working interrelationships, elements and structures (Fig. 1, left). Finally the process includes the embodiment and detail design phase, which is characterized by building up constructional and system interrelationships and the respective elements and structures (Fig. 1, right). The most important and crucial step within these design process is the concept design stage because the basic functions, ideas, fundamental working and solution principles have to be found and outlined. This phase generally consists of the following steps:

- Realize the essential task by abstraction of the problem
- Define the overall task / function, sub-divide into sub-functions and sub-structures
- Find physical effects and working principles and combine them into principle solutions
- Sketch principle solutions as realizable concepts
- Evaluate concepts and select best solution variant(s)

The challenge within these activities is actually to define the combination and interrelationship between several design models and to combine them in an appropriate way. The possibilities of connecting instances of these entities in order to create solution patterns are almost countless. Every design task respectively requirement of a product relates to one or more functions respectively function structures (Fig. 2). Even the definition of requirements is a difficult task, because the problem formulation obtained by problem abstraction may lead to various possible overall functions. A function or sub-function itself can be related to one or more physical effects, whereby a given physical effect can represent the core effect for one or more functions. The same applies for the relationships between physical effects and solution principles, for instance a solution principle may have relationships to one or more physical effects in order to become a complete working principle.

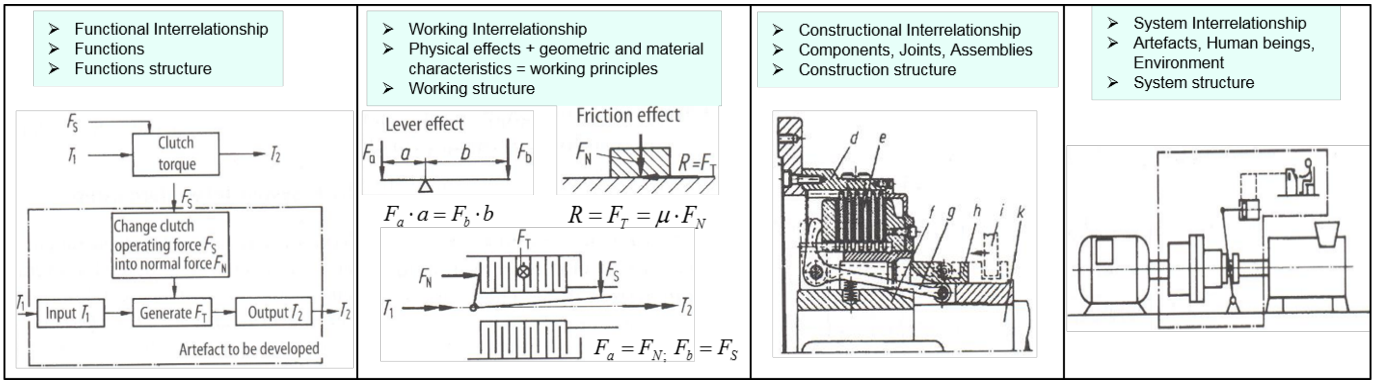

Fig. 1: Interrelationships, elements and structures of a systematic design process [10]

Although this is a difficult design stage to master especially for beginners, the concept design stage opens up the possibility and opportunity to develop design variants in various ways, therefore fosters motivation and creativity ([1], [6]). A systematic approach in order to create design variants for example dispels prejudice to ensure the most wide-ranging possible search for solutions and to look for variants from which the best can be selected. At the beginning of a new design project designers are often influenced, fixed and prejudice and conventions stand in the way of better and more economic but unconventional solutions. The challenge for a designer is on the one hand to find a reasonable number of realizable working principles for a given task and on the other hand to be able to evaluate feasible variants in order to obtain the best solution for a final embodiment and detail design.

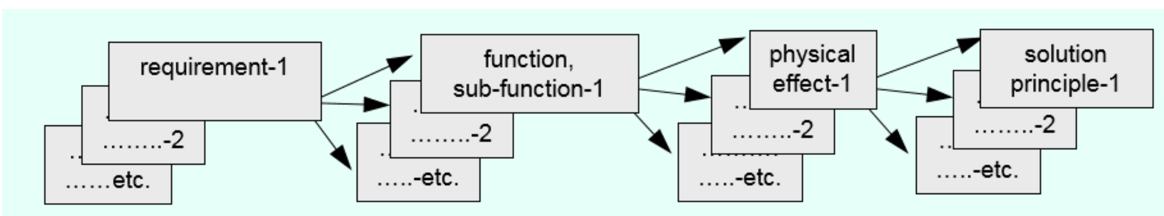

Fig. 2: Interrelationships between design models

B. *Function structures and their variation*

Based on an elaborated specifications list the required functions and essential constraints have to be identified. Then an abstraction and overall problem formulation is aspired by omitting requirements that have no direct bearing on the function and therefore leads to a generalized overall task with inputs and outputs (conversion of energy, material, signal), i.e. a definition of the objective on an abstract plane, without laying down any particular solution. A subsequently established function structure allows a clear definition of existing sub-systems or of those to be newly developed, so that they can be dealt with separately, thus facilitating the subsequent search for solutions. Setting up a function structure means identifying functional, that is physical and/or logical relationships among elements considering the following [7]:

- It should be kept as simple as possible, so as to lead to simple and economical solutions.
- The division into decreasing complexity must be continued until the search for a solution seems promising.
- Sub-functions are often subject to temporal restrictions (chronology).
- It is often useful to define entry functions (EF), output functions (OF) and internal functions (IF)
- It is often useful to start with sub-functions, whose input/output cross the system border.

Taking these guidelines into account the main function has to be decomposed into individual sub-functions and logically arranged by the use of block diagrams. To support the stimulation of creativity and the creation of variants, appropriate methods should be incorporated and applied within this design phase. Recommended techniques are for example the establishment of a morphological matrix ([2], [7], [12]) based on relevant functions and conceived solutions or setting up one or more classification schemes ([2], [6], [7]) for finding solutions for one or more functions. While these techniques consider mainly a static functional structure the dynamic variation of a function structure should also be taken into account when searching for design solutions systematically. A defined sub-function structure serves as a starting point for the creation of further variants (Fig. 3). This can be done by breaking down or combining elements (omit, add, combine, integrate, separate functions), change the order of functions, change the mode of connections and arrangements, i.e. type of switch mode (serial, parallel, cyclic, mixed) and shifts in the system boundary etc. In general it is advisable to aim at the combination of functions for the purpose of obtaining integrated function carriers (combine/integrate) ([3], [7]). In the next chapter the focus is especially on the generation of variants by the variation of relationships between functional representations and related physical effects. The systematic creation of solution concepts is described in detail for a given example.

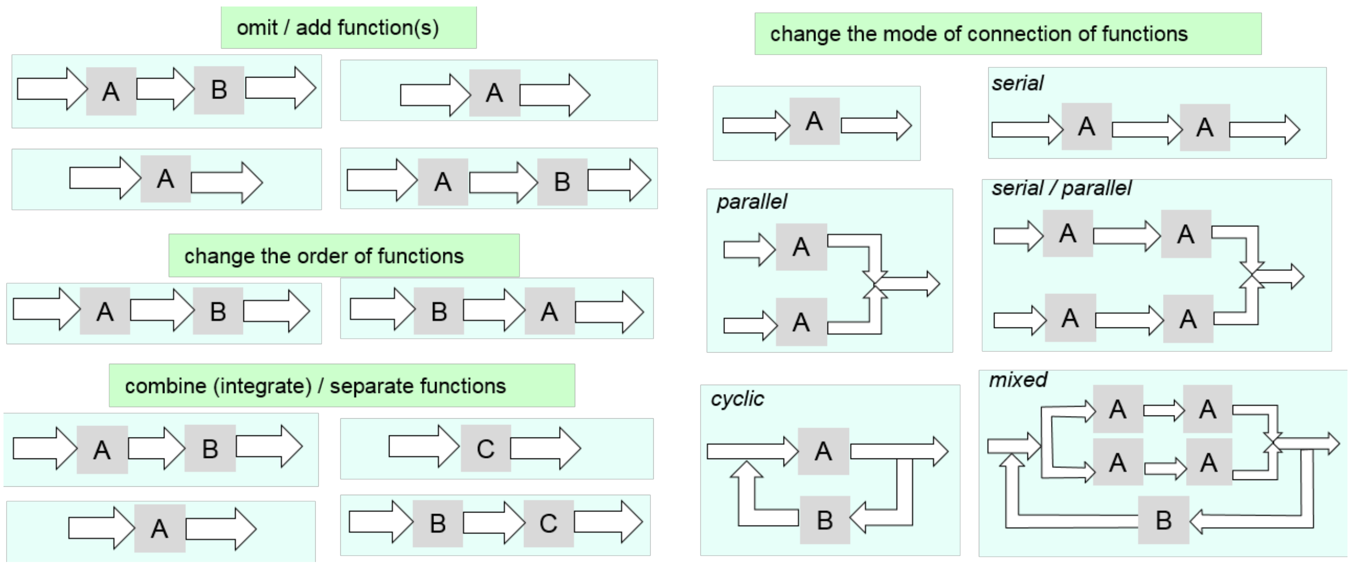

Fig. 3: Options for the variation of function structures [3]

II. CASE STUDY: PUNCHER

A. Function analysis and function structure

In the following the application of the presented approaches is discussed. A puncher for filing away paper serves as an example. When reasoning about new and innovative products, it is good practice to analyze existing solutions, which are available on the market with respect to their functionalities respectively offered functions. Fig. 4 (upper left) shows the specification of the overall function of a puncher, which essentially consists of producing holes according to a standard (see Fig. 4, upper right, ISO 838: Filing holes). The overall function may be represented by a set of possible sub-functions. Some functions are important and essential for the overall functionality (e.g. “Produce holes”), some are usually offered for a convenient use of the device and some may also be omitted (e.g. “Store material”, “Produce anti-force”, “Amplify force”, etc.). Fig. 4 (lower left) shows the representation of the identified functions in a function structure with inputs and outputs in the form of a flow of material and a flow of energy using respective terminology. The main function is a material conversion, having an un-punched paper sheet at the input side and punched paper plus waste paper at the output side. The energy path consists of the manual force at the input side and the usual increase of force for the punching operation. The force multiplication is at least necessary for punching a stack of paper. If the puncher is supposed to return to the initial position after the punching process, the applied force has to be partly used to store energy for the reverse movement. Reaction forces have to be considered for the stability of the device during the operation. In order to generate new types of punchers, a developer could now reason about the adding/omitting/changing-order/combining/separating of functions at this stage, e.g. punching the holes simultaneously or one after another; change the order of operation by applying the operation force at first followed by the punching process, etc.

When having a closer look at existing commercial punchers the function “increase force” is realized commonly by a single one-armed lever, which has effect on two punching pins. The pins are simultaneously pressed down by means of a connecting rod at the one-armed lever which then transfers the multiplied force to the top of the two pins. The vintage puncher shown in Fig. 4 (lower right) illustrates the arrangement of the relevant components. This working principle is basically the prevailing operation mode of nearly all manually operated purchasable punchers. The analysis done so far serves now as a starting point for the exemplified development of alternative concepts and solutions.

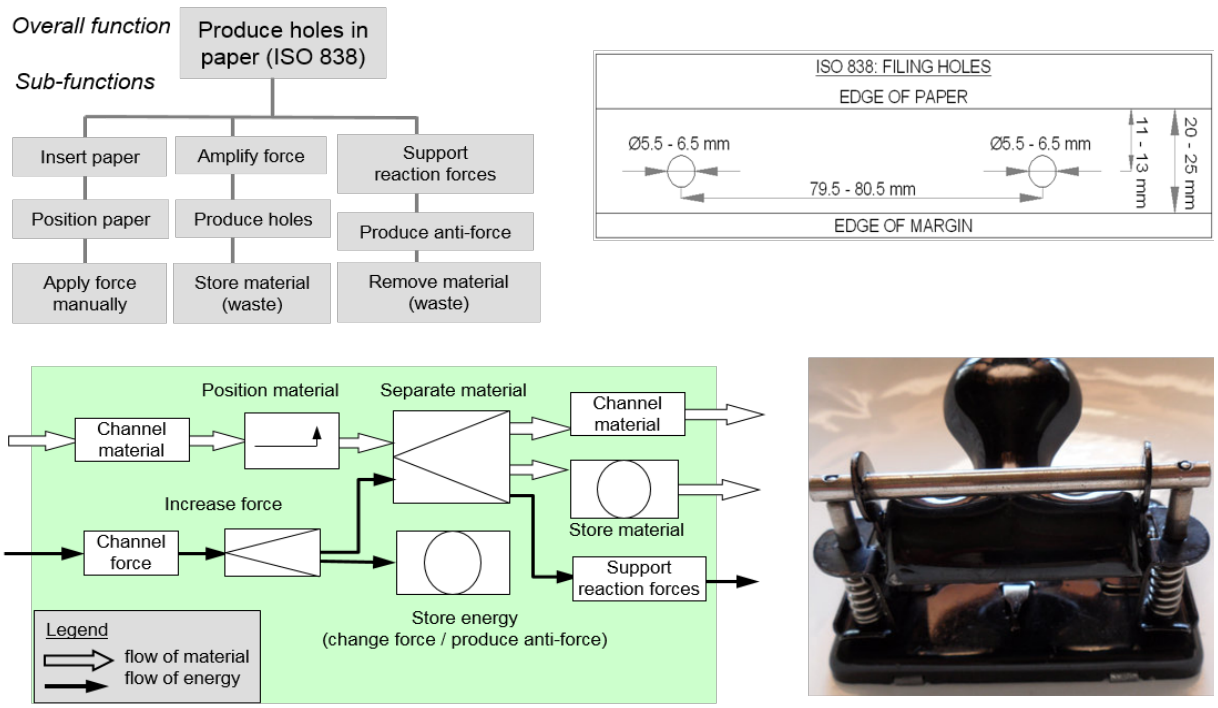

Fig. 4: Puncher: Functions and functional structure

B. *Generation of concepts for a puncher*

Part of the lecture about design methodology are brainstorming sessions and educational workshops with students where product concept developments are trained by making use of systematic approaches and exercises are carried out, e.g. by taking a puncher as an example. The requirements for the development and variation are as follows: The focus is on the basic operation process of a puncher, i.e. the input of manual force by an operator and the transfer of the multiplied forces in order to generate the holes. The paper stack thickness is to be about 5 mm, i.e. the operation path of the punching process is estimated to be about 6 mm in length. The operation force should be applied from above, because this is considered the best option to support reaction forces coming from the pressing process. Furthermore the operation force should mainly be effective in the same plane as the pressing forces are, however in an opposite direction. Otherwise torque and bending moments would be produced, which have negative effects on the handling of the device. Existing solutions and the commonly used operation arrangement, i.e. the one-armed lever which has effect on two punching pins should be avoided. Instead, new types of force multipliers, their combinations their arrangements and directions should be taken into account. The variants should be kept as simple as possible in order to get reasonable, economic and easy to use products, which also can be manufactured. When delivering students tasks like this they truly don't have any idea at first how to solve such a problem. By looking up a solution catalogue containing force increasing effects some vague ideas are developed, e.g. based on single-armed / double-armed /angled lever, knee-lever, wheel pairing, hoist element, wedge, eccentric wheel, cam, etc. Afterwards students were asked, to modify initially found solution concepts by applying variations of physical effects and functional descriptions. The following pictures and concept descriptions represent a selection of ideas which originated from several brainstorming sessions. For reasons of clarity any necessary limits for the lifting motion, components which allow to return to initial positions (springs etc.) and housing or covers are omitted.

Fig. 5 (left) shows a modified punching device by using twice a two-armed lever in order to increase the applied force at each punching pin. The two-armed levers are each connected via a connector rod. The input force is applied by means of a knob, which goes straight down and up and which operates in the plane of the reaction forces caused by the pressing, however in a reverse direction. The input force then is deflected by a two-armed lever with equal arms in length, though just for the purpose of force redirection with an angle of 180° and force transfer to the pins. The block diagram (Fig. 5, upper left) represents the functional structure of the operation mode, i.e. force deflection (two-armed lever "2L"), force increase elements in parallel (two-armed levers "2L").

Fig. 5 (right) shows a modified punching device by using twice a one-armed lever in order to increase the applied force at each punching pin. The input force is applied by means of a knob connected directly to the ends of the levers. The operation force goes straight down and up and is situated in the plane of the reaction forces caused by the pressing, however in a reverse direction. The connector arranged between the knob rod and the lever ends features two long slots to allow an un-resisted rotation of the two levers. The block diagram (Fig. 5, upper right) represents the functional structure of the operation mode, i.e. force increase elements in parallel (one-armed levers “1L”).

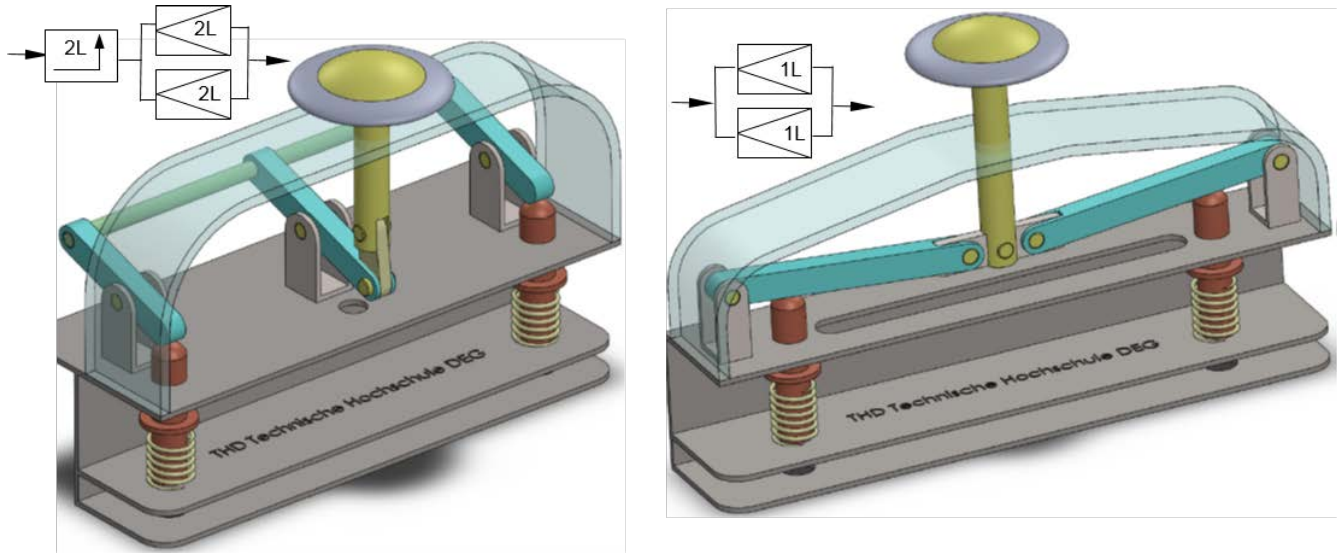

Fig. 5: Puncher concepts: Use of two-armed levers (left) and one-armed levers (right)

Fig. 6 (left) shows yet another modification of a nowadays puncher by using two one-armed levers in order to increase the applied force at each punching pin. The input force is applied by means of a knob, this time connected via a knee-lever directly to the ends of the one-armed levers. The operation force goes again straight down and up and is situated in the plane of the reaction forces caused by the pressing, however in a reverse direction. By using a knee-lever instead of a connector with long slots the un-resisted rotation of the two one-arm levers can easily be realized. Additionally, the knee-lever allows for a huge increase of the operation force when coming close into a horizontal position. The block diagram (Fig. 6, upper left) represents the functional structure of the operation mode, i.e. force increase element (knee-lever “KL”), force increase elements in parallel (one-armed levers “1L”).

Fig. 6 (right) shows another modification of a puncher. It is similar to the version before, but instead of two one-armed levers twice a two-armed lever is employed and the connection is done via a knee-lever. The knee-lever, however, has to be activated from below in an upward direction. Therefore, another two-armed lever has to be used to turn the downward movement of the operation knob into an upward movement of the knee-lever. The block diagram (Fig. 6, upper right) represents the functional structure of the operation mode, i.e. force deflection (two-armed lever “2L”), force increase element (knee-lever “KL”), force increase elements in parallel (two-armed levers “2L”).

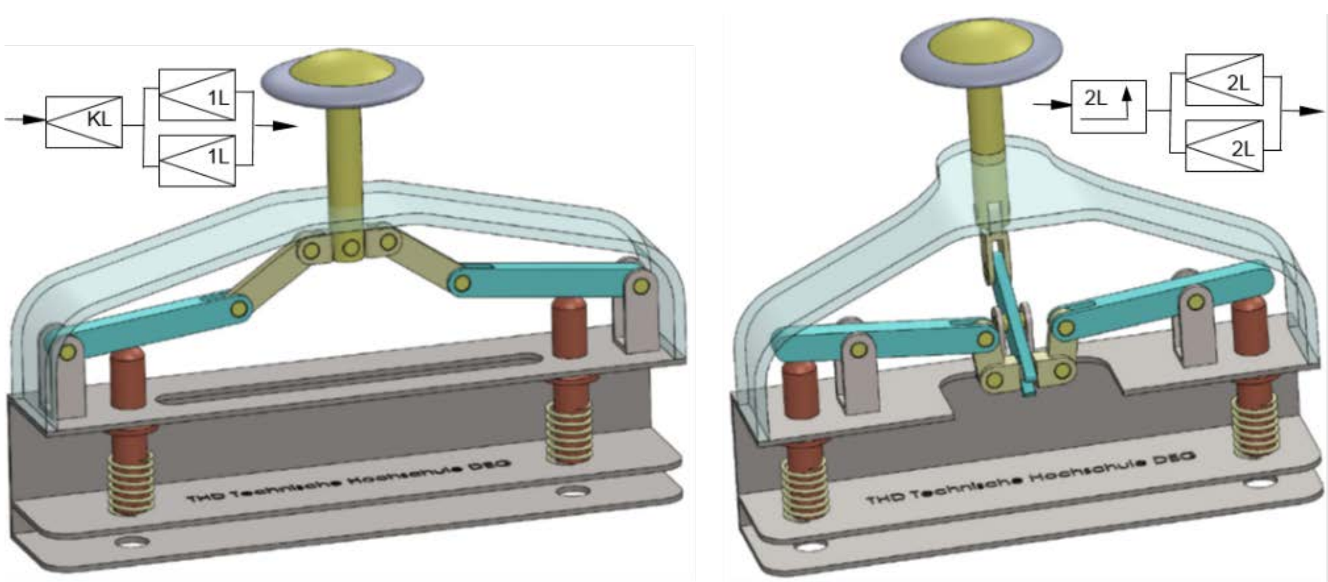

Fig. 6: Puncher concepts: Use of knee-lever/one armed levers (left) and two-armed levers (right)

Fig. 7 (left) shows a puncher version by using a knee-lever at the input side to increase the operation force. The ends of the knee-lever each are connected to angled-levers, which then are effective directly to the ends of the punching pins. The operation force goes straight down and up and again is effective in the plane of the reaction forces caused by the pressing in a reverse direction. The angled-lever could be modified so that it realizes also a force increase instead of just being a component for changing the force direction. The knee-lever at input side allows for a huge increase of the operation force when coming close into a horizontal position. The block diagram (Fig. 7, upper left) represents the functional structure of the operation mode, i.e. force increase element (knee-lever “KL”), force increase elements in parallel (angled-levers “AL”) respectively force deflection (angled-levers “AL”).

Fig. 7 (right) shows a similar puncher version compared to the concept described before, but instead of having two angled-levers connected to the ends of the knee-lever at the input side two eccentric wheels are employed. The eccentric components have a large surface contact with the flat ends of the punching pins. Instead of eccentric wheels, which are easy to manufacture, two cams could also be installed at each ends of the knee-lever. The whole mechanism allows for a huge increase of the input operation force. The block diagram (Fig. 7, upper right) represents the functional structure of the operation mode, i.e. force increase element (knee lever “KL”), force increase elements in parallel (eccentric wheels “EW”).

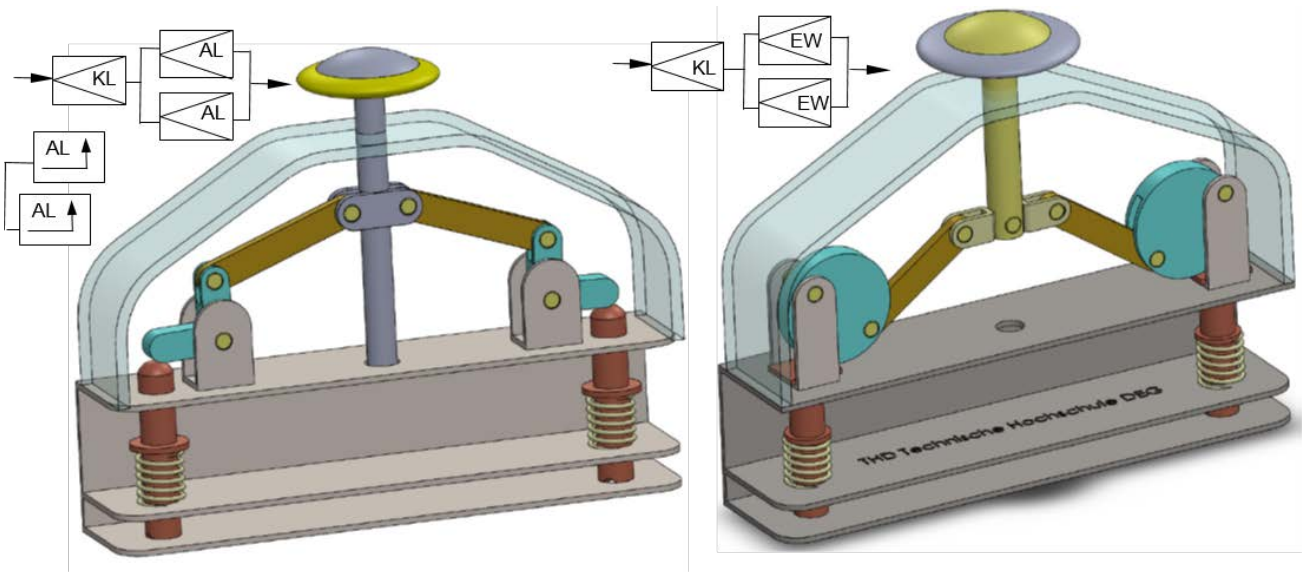

Fig. 7: Puncher concepts: Use of knee-lever/angled-levers (left) and knee-lever/eccentric wheels (right)

Fig. 8 (left) shows quite a similar puncher version compared to the concepts before (see Fig. 7), but instead of having two angled-levers or eccentric wheels connected to the ends of the knee-lever at the input side two wedges respectively tapered elements are employed. The wedges have a large surface contact with the flat ends of the punching pins and are guided by cylinder pins at the inclined upper wedge face. The force increase can be adjusted by the choice of an appropriate angle of the wedge. Again, this whole mechanism allows for a huge increase of the input operation force. The block diagram (Fig. 8, upper left) represents the functional structure of the operation mode, i.e. force increase element (knee lever “KL”), force increase elements in parallel (wedges “WE”).

Fig. 8 (right) shows a puncher alternative which is characterized by quite a different layout and operation mode. Usually, when using a puncher the sub-functions “Apply / Channel / Increase force” has to be carried through before the sub-function “Produce holes / “Separate material” can be applied (see Fig. 4, left). Therefore, sub-functions are often subject to temporal restrictions, i.e. a specific chronology has to be observed. When applying systematically the variation of functional structures, the change of order of functions is also an option (see Fig.3, left). So, the idea was born to change the order of these sub-functions mentioned before. As a consequence for the realization of such a concept the applied force respectively energy has to be stored in a certain way within the system in order to let it be effective later on when the punching process is required. This task represented a real challenge for the participating students. One out of several concepts, which is able to meet the requirements of reversed functions is depicted in Fig. 8 (right). The puncher is build up by three knee-levers, with a central knee-lever at the input side connected with symmetrically arranged two more knee-levers. These two knee-levers at each side are able to compress two springs with integrated striker pins, and which are located exactly above the punching pins. When the input knee-lever is pressed down, the springs within the cylindrical spring housings are maximally tensioned up to the position when the knee-lever reaches its horizontal position. This state represents a bi-stable position, which can easily be left to trigger a punching operation. The activation of the pre-stressed mechanism can be realized by an external signal (button, not shown in Fig. 8, right) or also by the operation knob itself, even in both direction. The block diagram (Fig. 8, upper right) represents the functional structures of the operation mode, i.e. reversed functions by changing the order of "Input force" and "Produce holes".

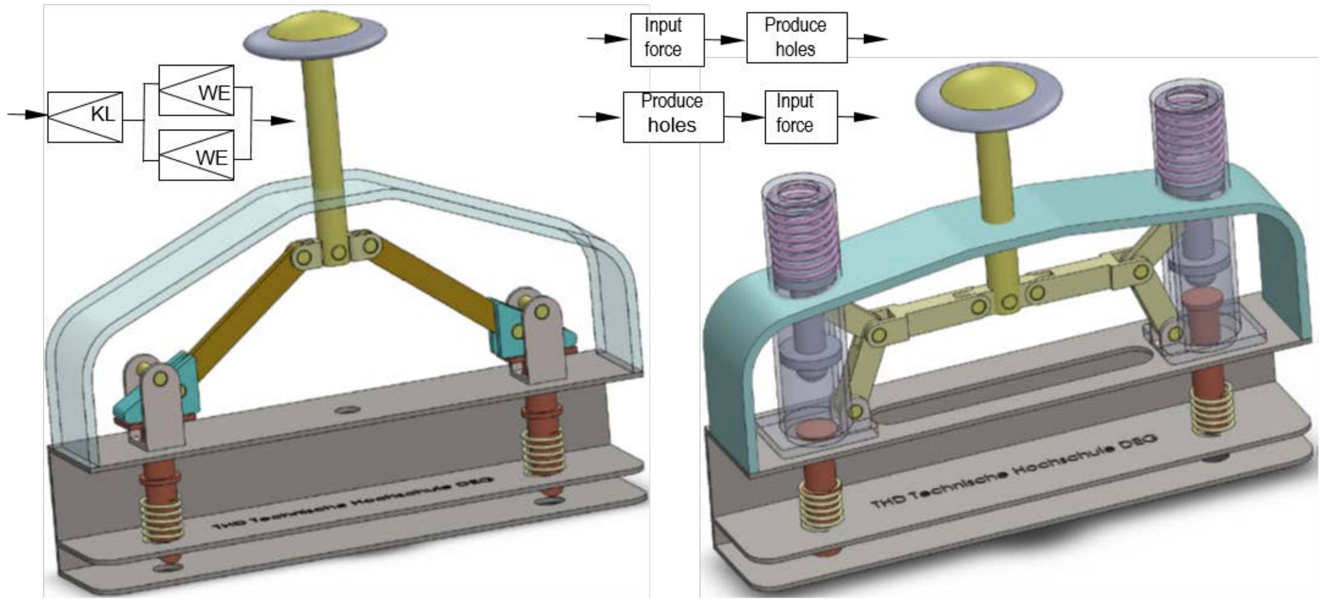

Fig. 8: Puncher concepts: Use of knee-lever/wedges (left) and knee-levers (reversed functions, right)

Fig. 9 illustrates the extreme positions of the described puncher concept. The depicted positions explain how the striker pins are moved quickly downwards to activate the punching pins. The mechanism provides a high impulse when triggered off and therefore could be useful for punching more resistant materials.

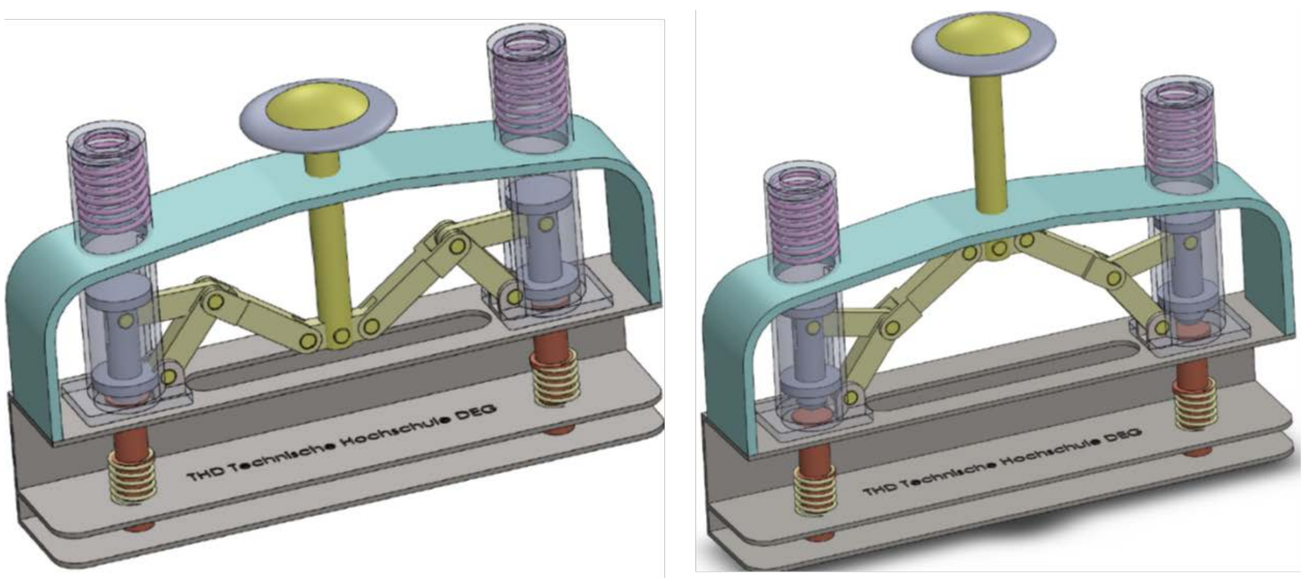

Fig. 9: Puncher concepts: Activating the punching process

III. Outcome and conclusions

One of the main goals in engineering design education is to demonstrate the usefulness of the application of a systematic approach. By means of a puncher an example was presented which demonstrates that applying specific techniques recommended by design methodology is able to enhance the creativity of the designers and eventually lead to a variety of solution concepts. It was pointed out that especially the systematic variation of physical effects and functional structures opens a broad spectrum of different and possible solutions which afterwards have to be evaluated in order to select the most promising ones for a final embodiment design. Therefore, it is useful to be familiar with the establishment of function structures, design catalogues, and to have the knowledge about physical effects and their application. If these techniques are well trained, it will allow the generation of ideas easily and their modification in various directions. Especially in the case of origin design it is good practice to start with techniques on a quite abstract plane. This increases the probability of having several variants from which the best can be selected afterwards. Furthermore, the confidence and competence of students are strengthened by the use of a systematic approach. It helps to foster the motivation and subsequently the creativity which is obviously ceaselessly in flux when inspired continuously. Students experience the nearly automatic production of ideas and are often astonished about the type and number of generated ideas, and variation is surely a source of innovation. For that reason, the conduction of further comprehensible engineering design examples is desirable for training future design engineers and for pointing out the benefits of systematic approaches.

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