Fostering Creativity and Innovations based on Classification Schemes: Case Studies in Engineering Design Education

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Abstract

This article describes case studies with respect to the establishment of so-called classification schemes used in engineering design education within the Faculty of Mechanical Engineering and Mechatronics at the Deggendorf Institute of Technology (DIT), former University of Applied Sciences, Germany. The described techniques aim at providing undergraduate students with examples for systematic product development and fostering and stimulating student's creativity. It serves also as a guideline for conducting engineering design projects embedded within the curriculum of their studies. The described procedures are based on existing design methodology and long term experience of the authors in giving respective design lectures and in conducting engineering projects with students and enterprises as well. Eventually, by taking advantage of the approach, a patent and innovative product is presented.

Keywords
Engineering Design Education; Design Methodology; Classification Scheme; Creativity and Innovation.

1. Introduction
1.1 Systematic Design Process
A systematic/methodical design has a long tradition in Mechanical Engineering. The theory has been worked out and outlined in literature and publications (Pahl and Beitz et al. 2007, Roth 2012, VDI 1993, VDI 1997). According to the literature cited the design process utilizes several stages, beginning with the clarification of the task, followed by a conceptual design phase, an embodiment design phase and ending with detail design (Fig.1, left) which finally results into a mechanical, electromechanical, hydraulic or pneumatic respectively combined structure of the product.

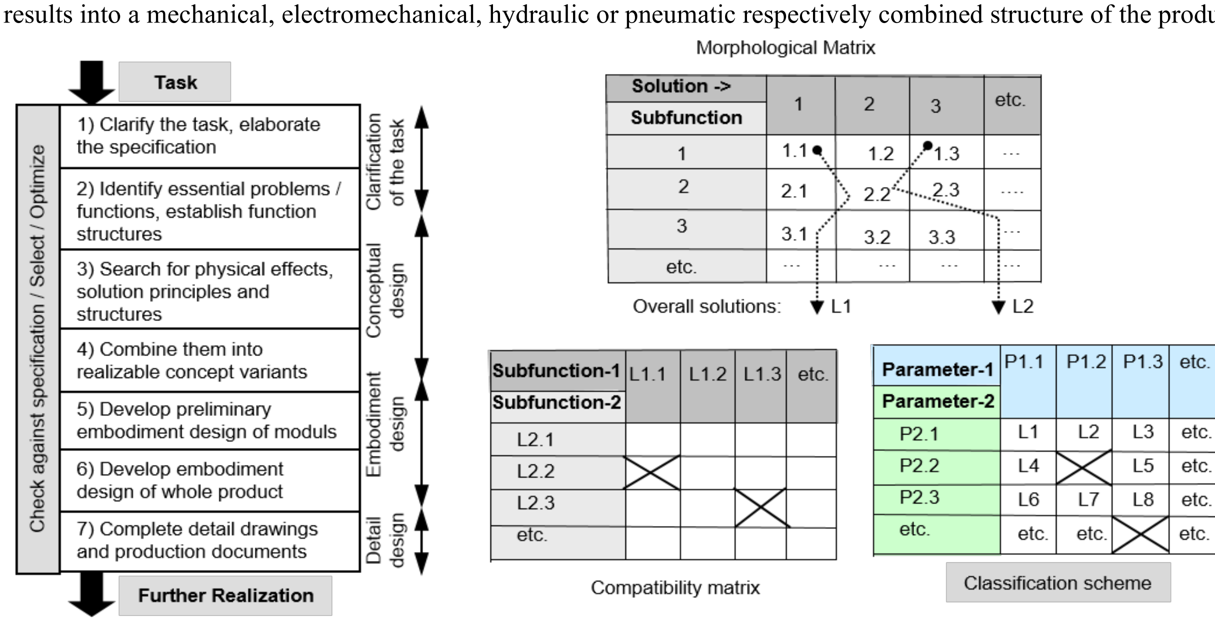

Figure 1. Systematic design process (left) and schemes to depict solutions

It is often useful, to divide problems, tasks and functions into sub-problems, sub-tasks and sub-functions and to solve these individually. Once the solutions for sub-problems, sub-tasks or sub-functions are available, they have to be combined in order to arrive at an overall solution. In order to support the generation of solution variants and to handle the often huge number of possible solutions certain formal schemes are recommended for use in the design process. These are:

Morphological matrix (Fig. 1, above right): This sort of scheme enumerates all solutions for known sub-functions in the rows of the scheme. The combination of solutions for given sub-functions results in an overall solution satisfying the overall task (Zwicky 1997). The main problem with such combinations is ensuring the physical and geometrical compatibility of the solution principles to be combined, that is to narrow down the theoretically possible search field to the practically possible search field.

Compatibility matrix (Fig. 1, below middle): This scheme facilitates the identification of compatible sub-solutions listed in the morphological matrix. Usually sub-functions are chosen according to the order in which they occur in the function structure. The solutions for a certain sub-function is checked against the solutions of another sub-function with respect to compatibility (e.g. type of energy etc.).

Classification scheme (Fig. 1, below right): This scheme is another systematic presentation of information and data within the search for solution design phase. The classification scheme may be referred to a specific sub-function, a group of sub-functions or could also represent overall solutions for the whole product. This article focusses especially on drawing up classification schemes, therefore their structure and application are explained in more detail in the following chapter.

1.2 Classification Scheme

Classification schemes are considered as powerful means to help the design process in a great many ways (Pahl and Beitz et al. 2007, Lindemann 2011). In particular, they can serve as design catalogues during all phases of the search for solutions, and they can also help in the combination of sub-solutions into overall solutions. The choice of classifying criteria or their parameters is of crucial importance. The classifying criteria and characteristics listed in Fig. 2 can be useful when searching systematically for solutions and the variation of solution ideas for technical systems. They refer to types of energy, physical effects, manifestations (Fig. 2, left), as well as the characteristics of the geometry, motions, and the basic material properties (Fig. 2, above right). It should be mentioned that these are recommendations for in general applicable characteristics, any other product criteria could also be applied.

Mechanical	gravitation, inertia, centrifugal force
Hydraulic	hydrostatic, hydrodynamic
Pneumatic	aerostatic, aerodynamic
Electrical	electrostatic, electrodynamic, inductive, capacitive, piezo-electric, transformation, rectification
Magnetic	ferromagnetic, electromagnetic
Optical	reflection, refraction, diffraction, interference, polarisation, infra-red, visible, ultraviolet
Thermal	expansion, bimetal effect, heat storage, heat transfer, heat conduction, heat insulation
Chemical	combustion, oxidation, reduction, dissolution, combination, transformation, electrolysis, exothermic and endothermic reaction
Nuclear	radiation, isotopes, source of energy
Biological	fermentation, putrefaction, decomposition

Surfaces	*Type*	point, line, surface, body
	Shape	curve, circle, ellipse, hyperbola, parabola, triangle, square, rectangle, pentagon, hexagon, octagon, cylinder, cone, rhomb, cube, sphere, symmetrical, asymmetrical
	Position	axial, radial, tangential, vertical, horizontal, parallel, sequential
	Size	small, large, narrow, broad, tall, low
	Number	simple, double, multiple, undivided, divided
Motions	*Type*	stationary, translational, rotational
	Nature	uniform, non-uniform, oscillating, plain or three-dimensional
	Direction	in x/y/z direction and/or about x/y/z axis
	Magnitude	velocity
	Number	one, several, composite movements
Material properties	*State*	solid, liquid, gaseous
	Behaviour	rigid, elastic, plastic, viscous
	Form	solid body, grains, powder, dust

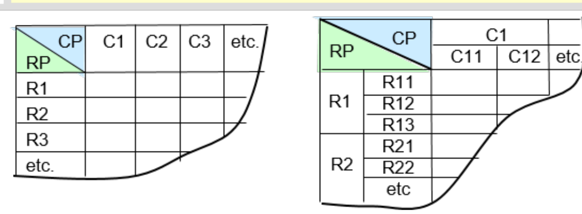

Figure 2. Classifying criteria and scheme structures

With respect to the structuring and arrangement of rows and columns a number of classification schemes have been drawn up, all with a similar basic structure. The usually two-dimensional scheme consists of rows and columns of parameters used as classifying criteria which the designer has to determine. This structure is illustrated in Fig. 2, middle below. When parameters are provided for the rows only, because the columns cannot be arranged in any apparent order, then the column contains only the consecutive numbers (i.e. instead of C1, C2, C3 only the numbers 1, 2, 3 appear). If necessary, the classifying criteria can be extended by a further breakdown of the parameters or characteristics (Fig. 2, below right). Again, if the columns in such a scheme cannot be arranged in any apparent order, then the columns are merely numbered and only the rows are hierarchically structured. The main steps in developing a classification scheme and successively creating further solutions are as follows:

- Apply intuitive methods/brainstorming to produce initial solution ideas
- Analyze known solutions or solution ideas according to their characteristics
- Identify or select appropriate product characteristics
- Draw up the classification scheme
- Enter initial solution proposals in the rows and columns in random order
- Develop further solutions by systematic combination of characteristic (fill white boxes)

2. Case Study 1: Development of a Redirection Facility

2.1 Task Definition and Requirements

The following describes some steps of the systematic design of a device which allows the distribution respectively redirection/deflection of power/torque/force, therefore named redirection facility. This example serves as a design exercise for a systematic engineering design process in the lecture design methodology. The project starts with delivering a requirements list and clarification of the task, according to recommendation for systematic design. Fig. 3 (left) shows part of the specification, which was structured into several headings like “Geometry”, “Kinematics/Forces /Energy”, “Input/output side” and so on. By doing so all relevant aspects of the design are considered. The desired redirection facility (Fig. 3, right) is to be used between an existing electric motor and an existing driven machine, e.g. a fan, pump, mixer etc. This intermediate device shall allow the flexible transfer of power e.g. around a corner and obstacles or even through workshop ceiling or floor openings. The primary use of the device is intended for a 90°-deflection of the electric power which takes place on two parallel planes, whereby the distance of the working planes is not explicitly defined. Power transfer respectively force deflection without angle limits between input and output side of the device is optional. A further requirement is that the electric motor as well as the driven machine are equipped with V-belt pulleys, and the transfer ratio 1:1 has to be realized, other transfer ratios are optional. The device should be equipped with means for a stationary installation.

Main characteristics	Type	Requirements
1. Geometry	W W W	max. height: 300 mm max. width: 400 mm max. depth: 300 mm
2. Kinematics, Forces, Energy	D D D W D D W	Engine output power (E-Motor): P= 22 kW Revolution speed E-motor n= 1420 revolutions / min Transfer ratio i=1:1 Different transfer ratios realizable Environmental temperature: -30°C to +30°C Operation: medium heavy few moving parts
3. Input side / Output side	D D W	by means of V-belts Force redirection 90° (horizontal in vertical) Force redirection without angle limits
4. etc.		etc.

D = Demand, W = Wish

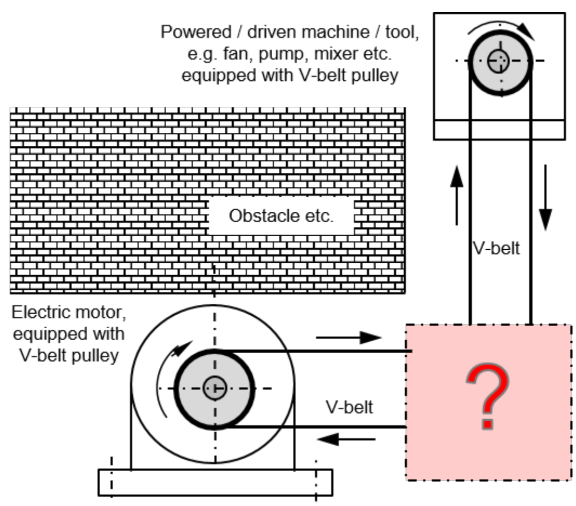

Figure 3. Requirements list (left) and task clarification (right)

2.2 Establishing a Classification Scheme for a Redirection Facility

After having delivered to students the complete requirements list and presented the quite abstract defined task standard brainstorming sessions and/or educational workshops have been conducted. The outcome of these more intuition based methods are usually a few basic ideas. According to experience, in most cases (95%) the variants shown in the Fig. 4 are proposed as solution concepts, that is, a device with a doubled V-belt pulley connected to a shaft along with ball bearings to support reaction forces of the shaft (Fig. 4a), and a device with doubled V-belt pulley which rotates around an axis (Fig. 4b) having the ball bearings inside the pulleys. It is imaginable at this stage that the double V-belt pulley (one single component) of version "a" could obviously be replaced by two separate V-belt pulleys connected to the shaft (Fig. 4c), but this, if applied to version "b" requires connecting elements between them (Fig. 4d), indicated by respective lines, otherwise the power transfer would not work.

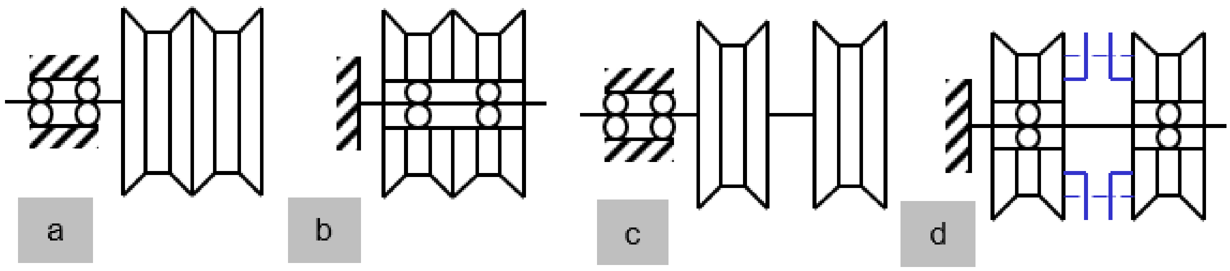

Figure 4: Initial solution concepts for the redirection facility

When these few concepts are analyzed with respect to their basic characteristics, it can be stated, that the essential categorization respectively working principle is based either on a shaft or axis solution. If only one variant would have been created, for example version "a", the application of the technique "Persistent Questioning" might lead to the following: A rotating (dynamic) shaft is used (Fig. 4a), could an axis (static) also be used? This might lead to the axis solution as well (Fig. 4b). If the version "b" would have been initially proposed, the question could be as follows: An axis (static) is used (Fig. 4b), could a rotating (dynamic) shaft also be used? This might lead to the shaft solution as well (Fig. 4a).

Another question applying the technique "Persistent Questioning" might lead to the following: The pulleys are presently located in both cases "a" and "b" at the right hand side, could they change the position to the left hand side, to both sides, to the center, mixed etc.? If the questions can be answered with YES, the position of the pulleys with respect to the locations of the bearings could be a distinctive criterion and an important design characteristic.

At this stage, having found distinctive design characteristics, a systematic representation of possible solutions based on axis/shaft arrangements and various positions of pulleys is recommended to get a comprehensible overview. In this specific design the classifying criteria for the columns were determined to be "Force Transfer" (axis/shaft /combined) and for the rows "Bearing/Fixing" (one-side/two-sided/centered/combined). Therefore, a two-dimensional scheme with the found characteristics has been drawn up. The basic ideas resulting from initial brainstorming sessions were inserted into this scheme, i.e. variants 1.1.1, 1.1.2 and variant 2.1. The subsequent task is to complete the blank fields in the classification scheme according to the identified criteria (Fig. 5). The great benefit of establishing a classification scheme is that it stimulates the search for further solutions in various directions. This leads to a generation of further solution principles by a successive combination of the characterizing parameters, i.e. the step by step completion of blank boxes.

Sometimes more than one solution fit conceptually in a certain box of the scheme as a result of applying methods of systematic variation, that is variation of type, shape, position, size, number (see Fig. 5, versions 1.1.1 and 1.1.2, and also 1.3.1 and 1.3.2) specifically for a certain scheme field. These versions should represent preferably minor changes of the design. Sometimes it is very hard and challenging to get a solution for specific parameter combinations, see e.g. variant 1.3.1 in Fig. 5. When students are asked to tackle the parameter combination in this field, usually they at first are convinced, that this would be impossible to do and there is no solution for this. But after a while a feasible solution and working principle for this box can be found. It just requires a slight change of the axis and can be realized when the axis is transformed into a tube like component which then provides the space for the connecting elements between the pulleys. Mastering design stages like this gives students the feeling that endurance and patience finally leads to success and is worth the effort.

When drawing up classification schemes usually additional solutions are created, which meet in general the requirements, but seem to be quite complex and therefore not appropriate in the first place, possibly over-fulfill the task. Then it is recommended, to analyze those solutions with regard to the special features and functions which are provided and to reason which additional (future) problems can be solved, like "We have a solution, give us the problem". Take for example variant 1.3.1 in Fig. 5, this arrangement allows the power transfer as required, but also enables having the pulleys of the redirection facility located at different sides of a wall.

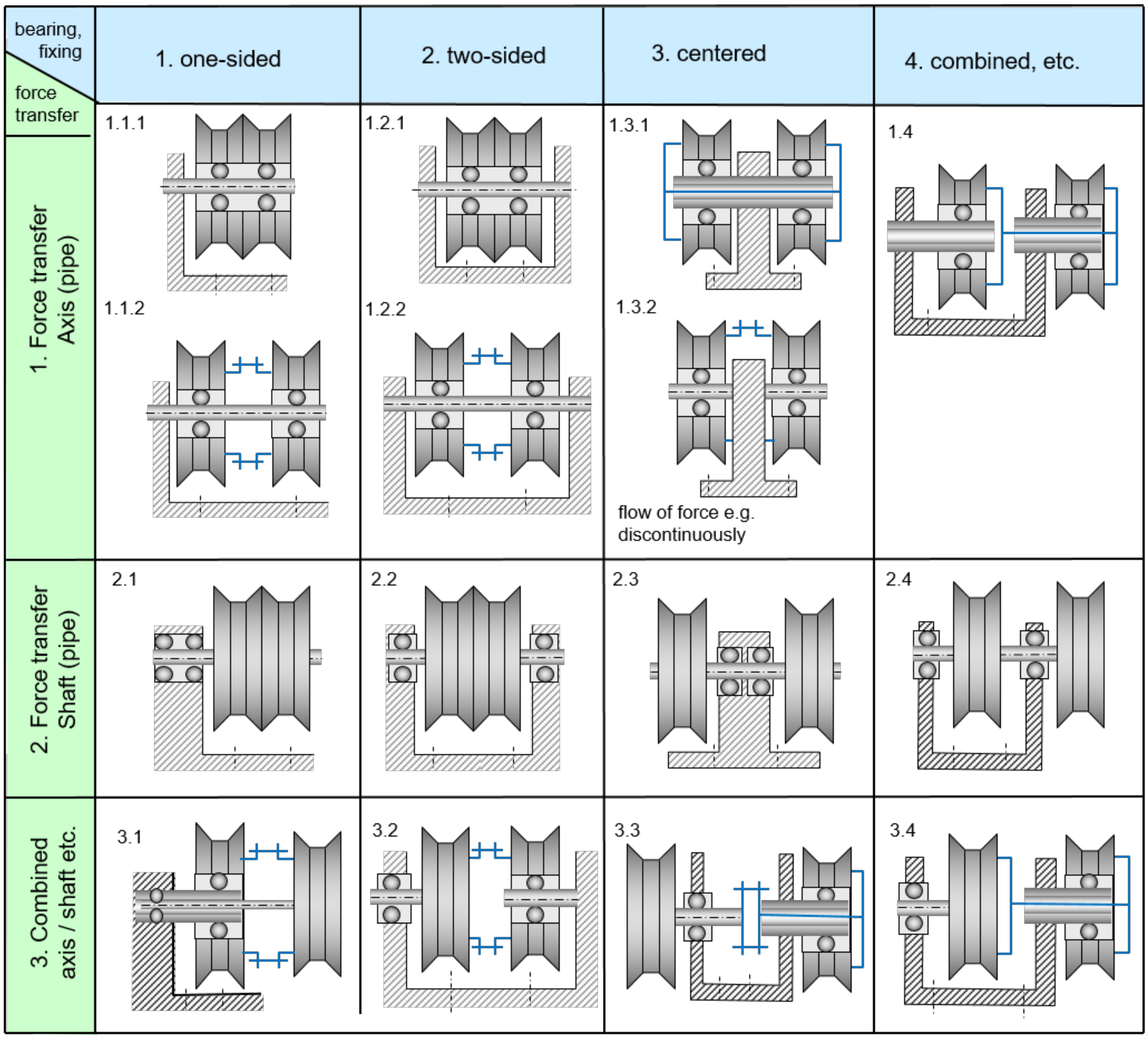

Figure 5. Classification scheme for a redirection facility

As a next step after having completed the classification scheme usually a rough pre-selection among the variants is conducted, which takes into account if it e.g., fulfils demands, is realizable in principle etc. This step reduced the number of variants from 15 to 5, namely 1.1.1, 1.2.1, 2.1, 2.2 and 2.3. These final variants have been investigated at first with respect to the mechanical behavior, stiffness and robustness. With the given load conditions calculations have been carried out in order to determine stresses like bending moments, torsional moments and bearing forces for each of those five arrangements. After having generated these data the final evaluation and selection took place, taking into account the mechanical properties (high stiffness, low stresses), material properties (light weight, few parts), usage properties (any installation position, exchangeable V-belts and pulleys, angle limitations), production properties (simple assembly, production, reusable parts). This evaluation is done in a workshop where every student contributes to the vote and the team output determines the final concept. In general variant 2.3 is chosen for the final detailing process and embodiment design of the redirection facility (Fig. 6).

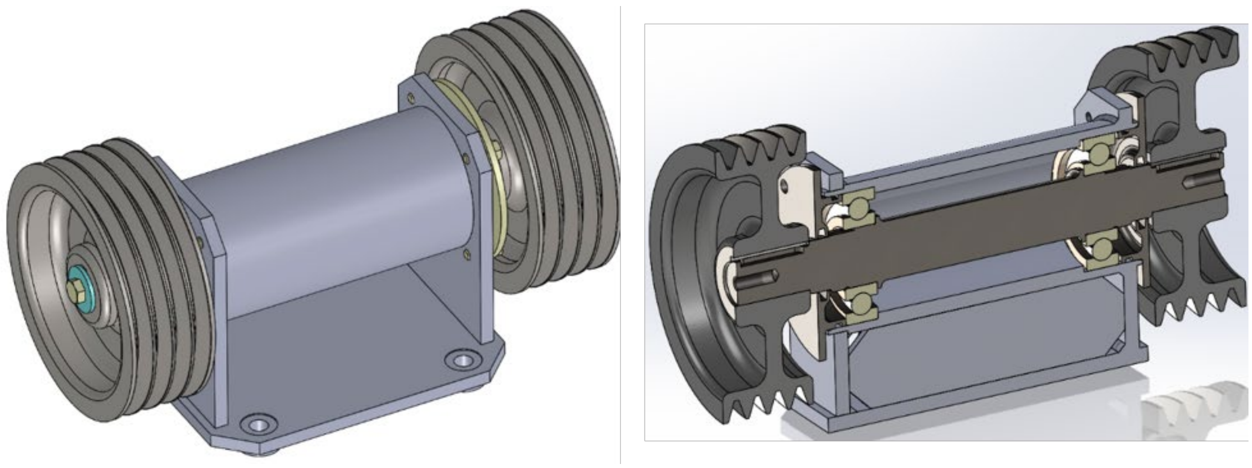

Figure 6. Elaborated assembly of redirection facility (left); section view (right)

3. Case Study 2: Development of a Lifting Facility

3.1 Task Definition and Requirements

Preface: Hain and Rappl 2015/2016 have developed several examples for educational use in engineering design. However, they focused especially on the functional variation options of technical products, that is the variation of the functional structures.

In the following an example, i.e. a lifting device, is described which focusses on the creation of solution variants by a systematic establishment of classification schemes. Fig. 7 (left) shows part of the specification, which was structured into several headings like “Geometry”, “Kinematics/Forces/Energy”, “Input/output side” and so on. The requirements for the intended lifting device are as follows (Fig. 7, right): A heavy weight (4000 N) is supposed to be lifted up from a workshop ground floor (lifting height: 5 mm) in order to move it to another position. Therefore, a force (ca. 200 N) has to be applied in an upward direction, while the operation force is going to be in a downward direction that is to say from above. Supposing that a maximum operation force of about 200 N is applied, the lifting force shall be increased by a multiplying factor up to 20, provided by the mechanism. Additionally, the directions of the operation force and lifting force shall be vertically aligned. The support respectively the housing for the mechanism is not to be considered.

When delivering students tasks like this they truly don’t have any idea at first how to solve such a problem, they even think that this represents a task which is impossible to solve. By looking up a solution catalogue containing single-stage force increasing effects (Fig. 8) and a subsequent initial brainstorming some vague ideas are developed, e.g. based on two-armed lever/one-armed lever/angle-lever, knee-lever variations (horizontal/vertical), wedge, eccentric wheel/cam etc. The prerequisites for the development and variation are as follows: Use different types of force multipliers given in the design catalogue, combine and arrange them in various directions within the available working space. Additional mechanical machine elements like pulleys, pins, chains, belts, bearings, supports, connecting rods etc. might be used to connect force multipliers or also to align the forces in a requested direction. At first the variants should be kept as simple as possible in order to get reasonable, economic and easy to use products. 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. Afterwards students are asked to modify initially found solution concepts by applying variations of physical effects and characteristics in order to produce the required motions of the lifting facility.

Main characteristics	Type	Requirements
1. Geometry	W W W	max. height: 500 mm max. width: 500 mm max. depth: 500 mm
2. Kinematics, Forces, Energy	D D D W D	Lifting force: 4000 N (400 kg) in upward and vertical direction Lifting height: 5 mm Operation force: 200 N in downward and vertical direction few moving parts Frame / support not in scope
3. Input side / Output side	D	Directions of operation force and lifting force aligned
4. Operation etc.	D	Hydraulics / pneumatics not available

D = Demand, W = Wish

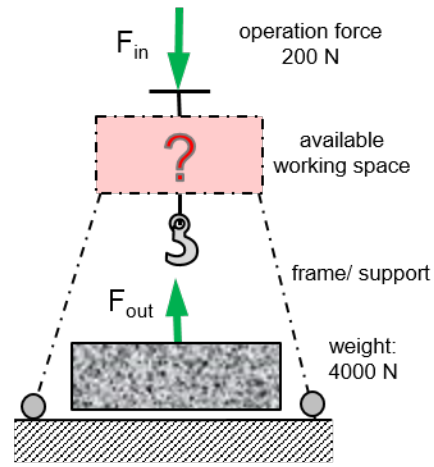

Figure 7. Requirements list (left) and task clarification (right)

The main goal of this step is to analyze solution ideas according to their characteristics and identify certain product characteristics, which later can be used to determine the criteria when drawing up classification schemes. The following design characteristics respectively criteria could be derived from the initial rough sketches (cp. Fig. 2):

- One-stage, two-stage, three-stage (sequential): order/sequence of the one-stage force multiplier
- Horizontal/vertical: arrangement of the one-stage force multiplier
- Symmetric/asymmetric: arrangement of all mechanical elements
- Others, but not used in the schemes shown in the following chapter 2.2

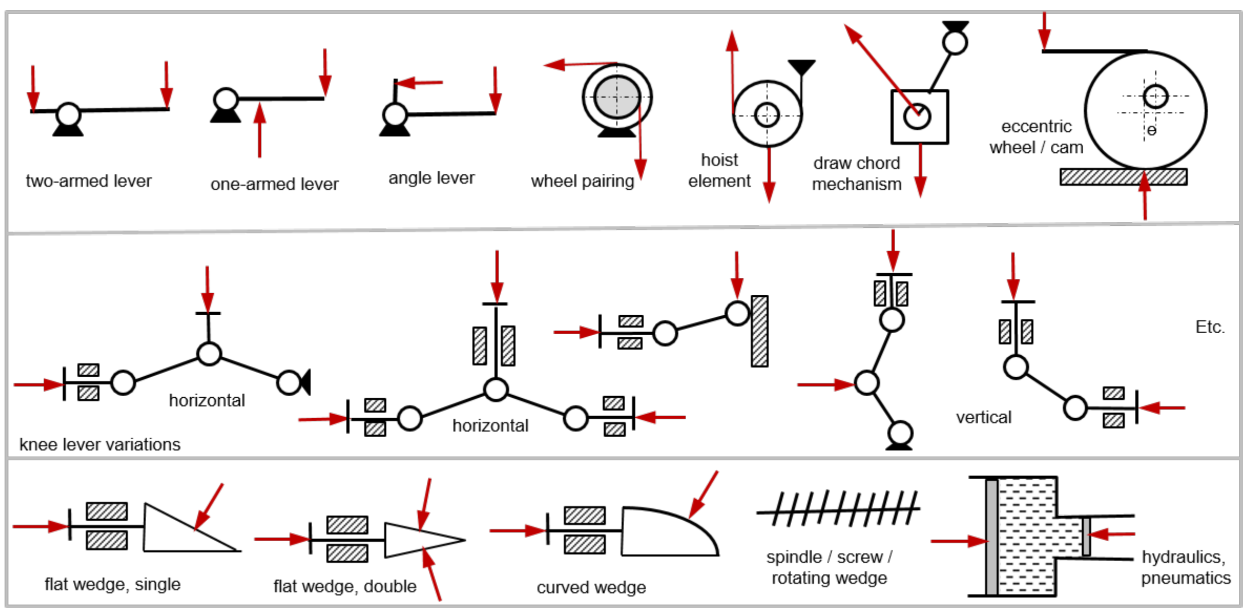

Figure 8. Principle effects of a one-stage force multiplication

2.2 Establishing Classification Schemes for a Lifting Facility

The classification scheme shown in Fig. 9 contains essentially several knee-lever mechanisms. The knee lever can be employed in a "horizontal/vertical" direction, according to the specified criteria of the rows. The column parameters are hierarchically structured with the order/sequence parameters “one-stage/two-stage/etc.” on top level and the parameters “asymmetric/symmetric” on the second level. In the following some features of the entered variants are described:

Version 1.1.1: consists of a one-stage knee lever (horizontal) as input mechanism in combination with a deflection pulley which allows the redirection of the increased input force in order to realize the requested vertical alignment of the input and output force directions. The layout is asymmetric.
Version 1.2.1: consists of the same input mechanism (horizontal) and adds a wheel-pairing (two-stage).
Version 1.1.2: represents a symmetric layout of version 1.1.1
Version 1.2.2: represents a symmetric layout of version 1.2.1
Version 2.1.1: consists of a one-stage knee lever (vertical) in combination with a deflection pulley which allows the redirection of the increased input force in order to realize the requested vertical alignment of the input and output force directions. The layout is asymmetric.
Version 2.2.1: consists of the same input mechanism (vertical) and adds a wheel-pairing (two-stage).
Version 2.1.2: represents a symmetric layout of version 2.1.1
Version 2.2.2: represents a symmetric layout of version 2.2.1

Please note that any other force increase effect and working principle, e.g. all kind of levers, wheel pairing, hoist element, draw chord mechanism, eccentric wheel/cam, all kind of knee levers, wedge and spindle/screw could have been used as the first input mechanism of the lifting facility. Even the premise of using a knee lever as a force increase mechanism at the input position leaves enough room for different arrangements of these mechanisms (cp. Fig. 8). Furthermore, the number of stages when sequencing force multiplier is not limited (3-stage, 4-stage etc.).

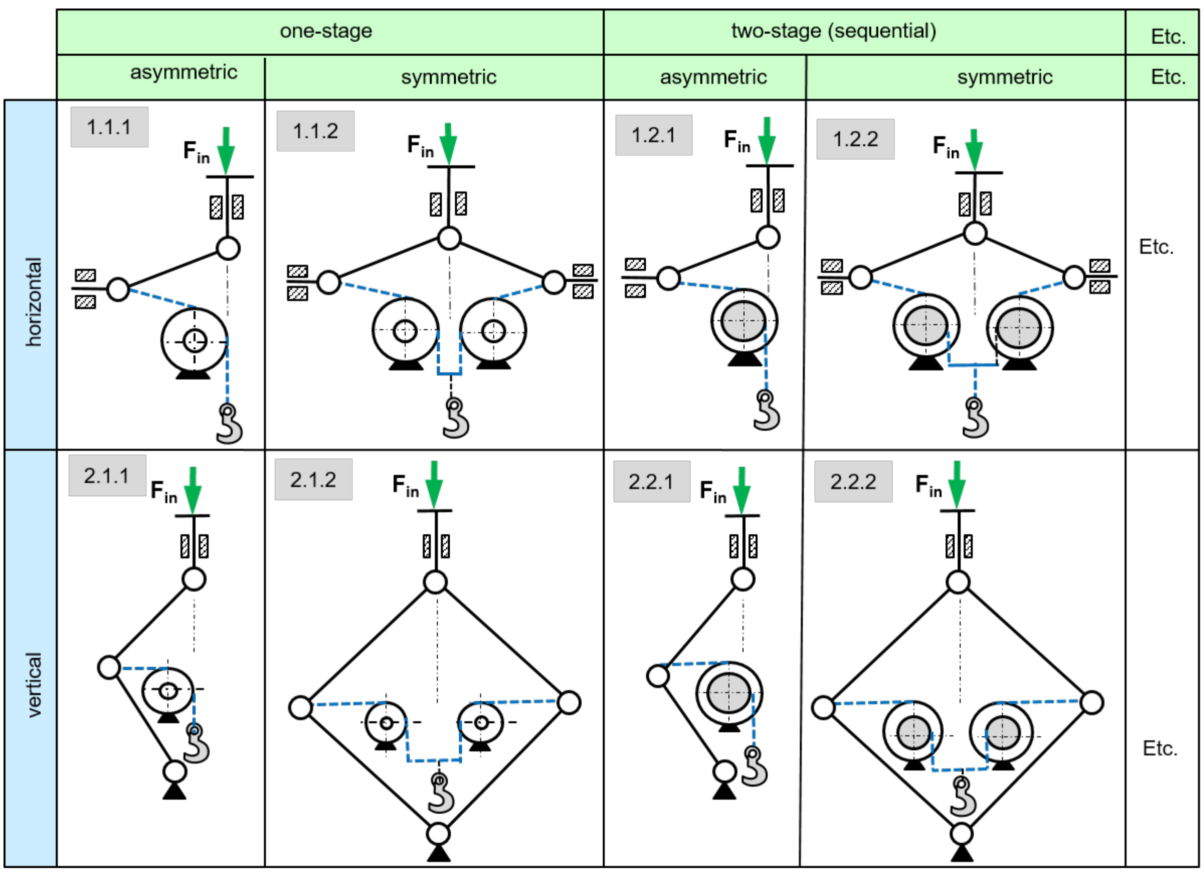

Figure 9. Classification scheme No. 1 for lifting facility

The classification scheme shown in Fig. 10 contains essentially several lever based mechanisms (two-armed lever, one-armed lever, angle lever). The layout can be “asymmetric/symmetric”, according to the specified criteria of the rows. The column parameter represents the order/sequence "one-stage/two-stage/etc." In the following some features of the entered variants are described:

Version 1.1.1: consists of a one-stage two-armed lever as input mechanism in combination with two deflection pulleys which allow the redirection of the increased input force in order to realize the requested vertical alignment of the input and output force directions. The layout is asymmetric.
Version 1.1.2: consists of a one-stage angle lever as input mechanism in combination with one deflection pulley which allows the redirection of the increased input force in order to realize the requested vertical alignment of the input and output force directions. The layout is asymmetric.
Version 1.2.1: consists of an angle lever as input mechanism and adds a wheel-pairing (two-stage). Asymmetric.
Version 1.2.2: consists of a two-armed-lever as input mechanism and adds a one-armed lever (two-stage). Asymmetric.
Version 1.2.2: consists of a one-armed-lever as input mechanism and adds a two-armed lever (two-stage). Asymmetric.
Version 2.1.1: represents a symmetric layout of version 1.1.1
Version 2.1.1mod: represents a modified version of 2.1.1, where a horizontal bar replaces 4 deflection pulleys.
Version 2.1.2: represents a symmetric layout of version 1.1.2
Version 2.2.1: represents a symmetric layout of version 1.2.1
Version 2.2.2: represents a symmetric layout of version 1.2.2
Version 2.2.3: represents a symmetric layout of version 1.2.3

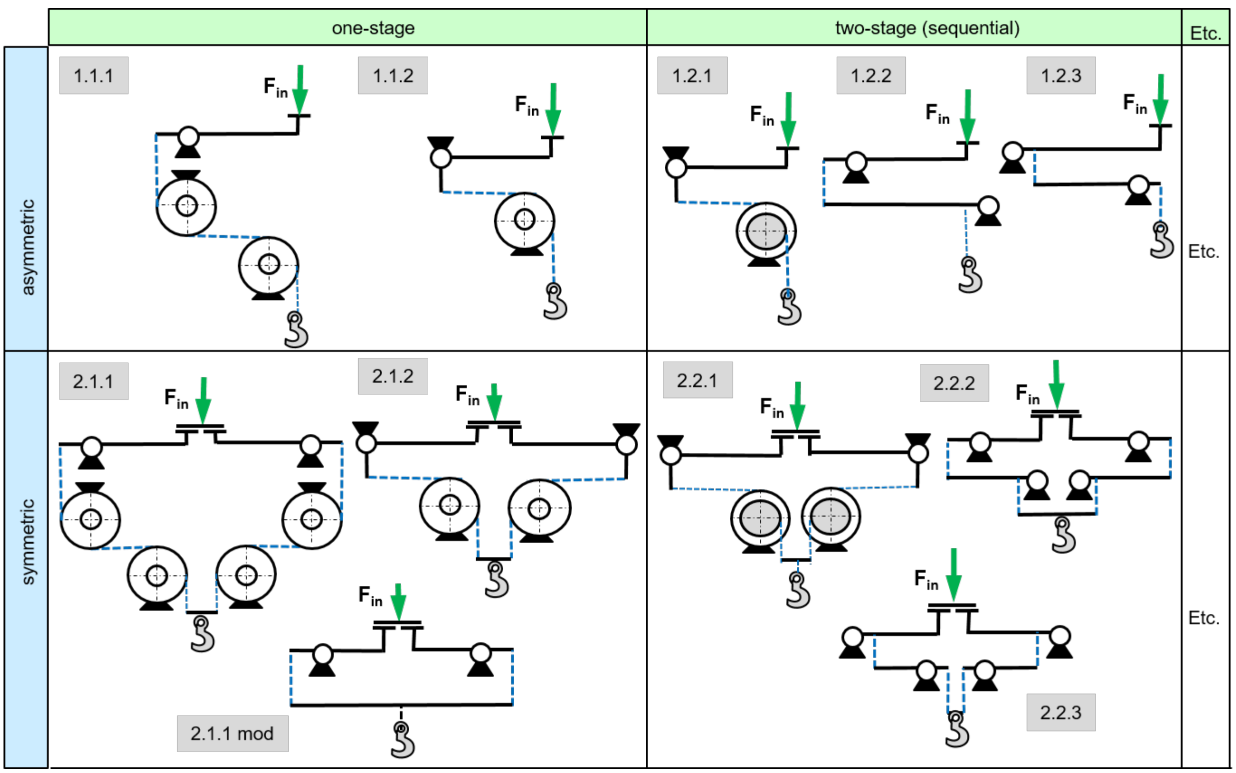

Figure 10. Classification scheme No. 2 for lifting facility

Please note that the presented schemes according Fig. 9 and Fig. 10 are abbreviated versions of a wide collection of generated classification schemes for the introduced lifting mechanism. After having completed several schemes which contain most of the available force increasing working principles the first evaluation of the created lifting mechanisms took place. In general, the versions with a horizontal knee-lever (Fig. 9) are obviously very effective with respect to force increasing capacity, reduced complexity, number of parts, easy to use etc. The next step of this lifting facility design is to perform calculations for the most promising variants in order to gain an overall multiplying factor of about 20 between the input and output force as demanded in the requirements list.

4. Development of an Innovative Nutcracker

A nutcracker is another typical exercise used in the design methodology lecture. Actually the basic or elementary function is to separate material, i.e. remove the nut shell from the kernel, which requires solutions for a material separation. Even if this can be done in many ways, e.g. mechanically, chemically, thermally, using laser-cutting etc., the prevailing nutcrackers on the market are based on a mechanism, which allows to produce manually an increased force/pressure to crack the nut shell. Therefore, by analyzing existing and known solutions the same procedures may be followed as described in the previous chapters, with the only difference, that initial solutions already exist und a brainstorming beforehand is not necessary. The analysis of nutcrackers with respect to their design characteristics reveals, that mostly force increase mechanisms are employed, i.e. different kind of levers, knee-levers, spindle/screw/rotating wedge etc. (cp. Fig. 8). Further characteristics and design arrangements like symmetric/asymmetric, horizontal/vertical, single/double, one-stage/two-stage etc. can also be identified. Fig. 11 (left) shows for example a nutcracker which is based on a one-armed lever in a symmetric layout. Fig. 11 (right) depicts a nutcracker which uses a two-stage force increase mechanism (one-armed lever and knee-lever, horizontal) and has an asymmetric overall layout.

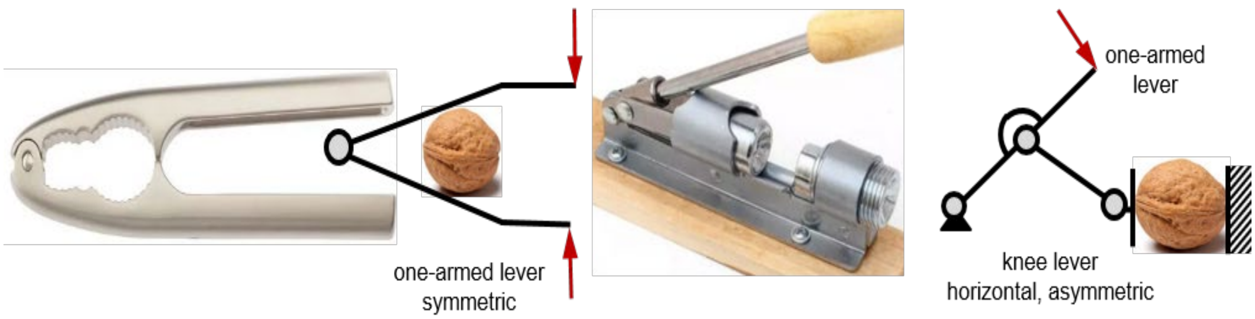

Figure 11. Nutcrackers: one-stage / symmetric (left) and two-stage / asymmetric (right)

Collecting the most important design characteristics allows the subsequent preparation of classification schemes in order to derive new and possibly innovative designs, which are not yet available on the market and which have possibly distinguished features. Figure 12 (left) shows a nutcracker, which incorporates a two-stage force increase mechanism (one-armed lever and eccentric wheel) in an asymmetric layout. This nutcracker seemed to be promising and has been worked out in order to achieve an appropriate force transformation ratio, adjustability to various nut sizes, ergonomic handling, stylish appearance etc. The final version (Fig. 12, middle and right) has been registered as a patent (Götze 2009).

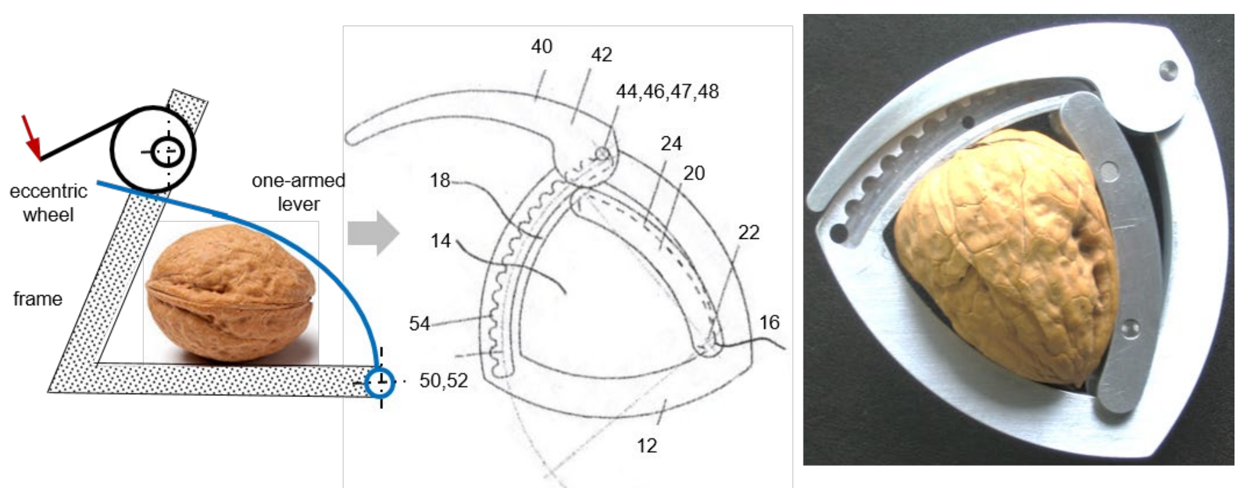

Figure 12. Nutcracker concept (left), patent (middle), and realization (right)

5. Outcome and Conclusion

Innovative and distinguished products are the key to the long-term growth and success of an enterprise. This requires talented employees and designers which have the competence and capability to generate ideas and smart solutions for given tasks. From the perspective of an engineering design education the challenge is to prepare students in a way that they will achieve these capabilities. Students and design beginners usually have poor problem solving experience. Therefore, the instructors face the challenge to convey appropriate means and techniques to foster creativity and the generation of ideas and solutions. It has long been recognized, that a structured systematic design process and the use of appropriately embedded techniques is inspiring with respect to the number and variety of generated ideas. In this context, the development of classification schemes, which has been demonstrated and described in detail, is a good means to extend the number of solutions in different directions. Classification schemes facilitate the identification of important product characteristics and initiate the combination of essential solution characteristics. It makes the design process and the methodology more understandable. Students experience the production of ideas and design variants, which encourages and strengthens their confidence, and a systematic variation is definitely a source of creativity and innovation. They benefit also from written documentation, visualization of solutions in formal schemes, and of comprehensive worked out exercises. Note: Experienced design engineers have a lot of solution options of given tasks in their minds and are able to retrieve appropriate solution patterns when specific design problems come up, but these patterns are not available for beginners, they have to work for them.

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