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COMPLEMENTARY USE OF DESIGN METHODOLOGIES IN EDUCATIONAL ENGINEERING DESIGN PROJECTS: A CASE STUDY

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Abstract - The challenge of a nowadays well-grounded engineering education is preparing industry ready graduates, that is, to provide students with the skills to master the complexity of products in terms of innovation, invention and problem solving combined with soft skills abilities. This addresses particularly the engineering design education, which in general should be mainly based on practical studies represented by engineering design projects. In order to supply industry with work-ready practitioners, the effectiveness and efficacy of design education respectively design projects is a crucial aspect. This article presents some findings of an efficient use of design methodologies and techniques when carrying through design projects in the faculty of Mechanical Engineering and Mechatronics at the University of Applied Sciences, Deggendorf, Germany. Engineering design projects are compulsory for students within their curriculum. The projects aim at fostering and stimulating students creativity by means of a complementary use of design methodologies and techniques. By taking advantage of this approach the systematic generation of ideas in the course of a design project is presented, which eventually led to the development of an innovative product.

Keywords - Engineering design methodologies / educational student projects / creativity and innovation / systematic design.

I. ENGINEERING PROJECTS IN EDUCATIONAL CONTEXT

Nowadays industrial working challenges require new teaching methodologies which consider the curriculum as a whole and form professionals with problem solving experiences. Therefore, it is commonly agreed that design education should be also based on practical studies represented by engineering design projects. Taking the common definition of design creativity as “the ability or process of developing novel and useful ideas, solutions or products” [1] instructors face the question of how to provide a creativity stimulating and motivating environment, how to structure the process at all, how to deliver and request information in an appropriate manner by taking into consideration the theories of methodical design which have been sufficiently worked out and outlined in literature and publications. Pahl and Beitz [7] proposed a sequential decomposition of the design process that is clarifying the task, conceptual design, embodiment design and detail design. Suh [8] developed the so-called axiomatic design and created a domain concept that is customer, functional, physical, and process domain. The inventive problem solving method TRIZ (Teorija Rešenija Isobretatelskih Zadač) [5, 6] was developed by analyzing thousands of patents thus developing knowledge of different kinds of contradictions and means of overcoming them. More abstract heuristics were also identified and confirmed through repetition in multiple cases. The key concepts in TRIZ theory are ideality, contradictions, substance field analysis, laws of system evolution, a knowledge base of

physical effects, 40 inventive principles, and an algorithm for solving problems.

In order to support problem solving capabilities all methodologies recommend certain aids and methods for use and incorporate them into the design process [4, 7]. Nevertheless, design methodologies are difficult to understand for some reasons. The most crucial challenge in finding design solutions is actually to define the interrelationship between several design models and to combine them in an appropriate way (Fig. 1). The possibilities of connecting instances of these entities in order to create solution grids are almost endless. Every design task respectively requirement of a product relates to one or more functions respectively function structures. 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/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 function/sub-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.

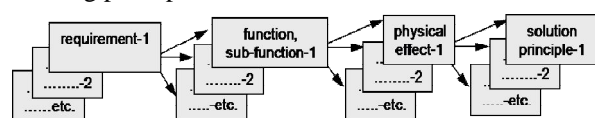


Fig. 1 : Interrelationships between design models

To support problem solving activities and to overcome certain shortages recognized when

conducting student design projects a process model was presented in [2] how to manage such projects. It determines information about involved personnel, project meetings, homework stages, produced documents, design checklists for fundamental design techniques such as the preparation of function structures, morphological matrices, classification schemes and the complementary use of TRIZ techniques (Fig. 2). The proposed structure is supposed to serve as a guideline for undergraduate students conducting one or two semester long senior design projects in mechanical engineering and mechatronics. The project described in chapter 2 was conducted competitively and quite independently by student teams. Some aspects of the results are described in [3], this paper gives a more detailed insight and the complementary use of TRIZ is also added.

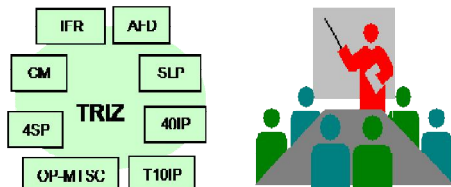
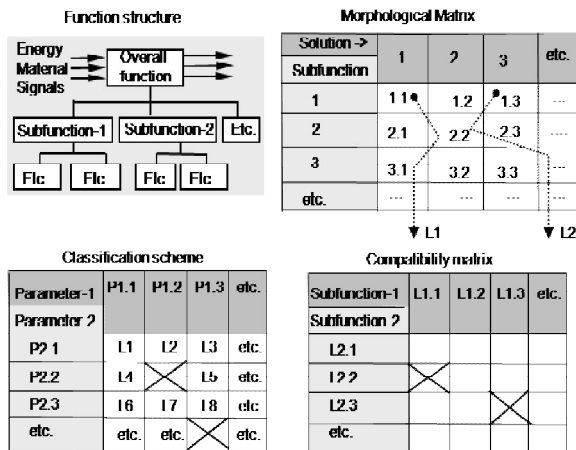


Fig. 2 : Complementary design techniques

II. CASE STUDY: DEVELOPMENT OF A TOOL RACK

A. Task definition and the application of TRIZ techniques

In the following the development of an innovative tool rack for tightening screws of flanges is described. This educational engineering design project was conducted in close cooperation with a local company. When mounting flange connections (Fig. 3, left) first a sealing is put between the opposing areas of the two halves which then are aligned and pressed against each other by means of screws, nuts and also stud bolts. In order to realize leak-proof connections screw specific torque stages (e.g. 15%, 40%, 100%) have to be applied successively. Additionally specific sequences of the process have to be obeyed, i.e. alternately tightening

in a crossed manner for initial rounds respectively in a strict rotation for final rounds (Fig. 3, center). Dependent on flange types, number of screws, sealing types, pressure ranges the number of tightening operations varies significantly, e.g. amounts to 80 for a mid-range flange. High pressure flanges require high screw torques and therefore electric, pneumatic or hydraulic power wrenches are employed in practice. These tools, however, are quite heavy, their handling is often laborious and time consuming. Therefore, the project aims at the optimization of the tightening process especially with respect to tool handling, time consumption and quality of the process [3, 9].

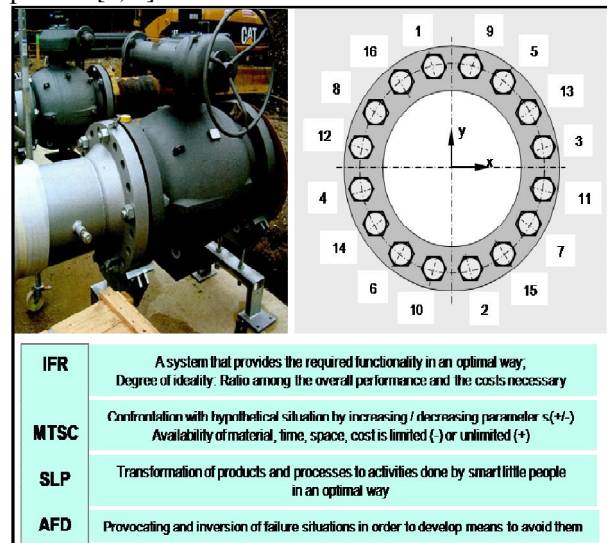


Fig. 3 : Flanges in plant construction and tightening order of screws (upper), TRIZ-methods (lower)

Based on the initially elaborated specifications list an abstraction and overall problem formulation was aspired by omitting requirements that have no direct bearing on the function. In this phase especially the TRIZ methods Ideal Final Result (IFR), Operator Material/Time/Size/Cost (MTSC), Smart Little People (SLP), Anticipatory Failure Determination (AFD) were applied (Fig. 3, right). These methods represent quite an abstract and inventive approach to problem solving with the prerequisite that not all constraints have to be taken strictly into account, e.g. energy supply, geometric limitations, budget demands etc. By regarding this aspect, a broad vision of the problem is permitted and the predetermined ways of conventional thinking are avoided. The additional usage of the method Use Resources (UR) guarantees to reason about available and useful facilities and capabilities. Also the Substance-Field-Analysis (SFA) is considered at this stage. An aspired output within the start-up meeting was the definition of an ideal solution from which an abstract function and furthermore sub-functions can be derived afterwards. Some excerpts are listed in the following:

Operator MTSC (+/-): (-) Avoid the necessity of the facility so that it is not required anymore, e.g.

avoid the use of screws completely; look for other flange connection techniques: welded connections, plug-in connectors, clamps; avoid flanges at all. (+) Having a facility which tightens all screws concurrently in a correct order, with correct torque stages, which measures the torque repeatedly, which allows programmable necessary operation sequences in advance and indicates failures.

AFD (Anticipatory Failure Determination): Forget to tighten screws at all; tighten screws incorrectly; make screws inaccessible for the tool; do not measure torque stages; tighten screws disordered and not crosslike.

SLP (Smart little people): For smart little people (dwarfs) this task would be a real challenge. They would have to use some sort of ladders, lifts, rails or ropes to reach the working positions. In order to handle the tool properly it should provide force enhancing effects and probably counterweights.

Use Resources (UR): All objects that could potentially be useful to achieve the ideal final result, e.g. components and connections between components; shape of objects (protrusions, hollow spaces); flange; tube; existing tools, in this case hydraulic tools; tube fittings; tube connectors; types of available energy, existing facilities, stands etc.

Substance Field Analysis (SFA): No relevant output was created using this technique.

IFR (Ideal Final Result), Version 01: Having a facility which allows the tightening of two or more screws of a flange concurrently and without major effort. Taking the IFR-V-01 as a guideline for the subsequent brainstorming session several ideas were produced and systematically modified by applying inventive principles of TRIZ (Fig. 4).

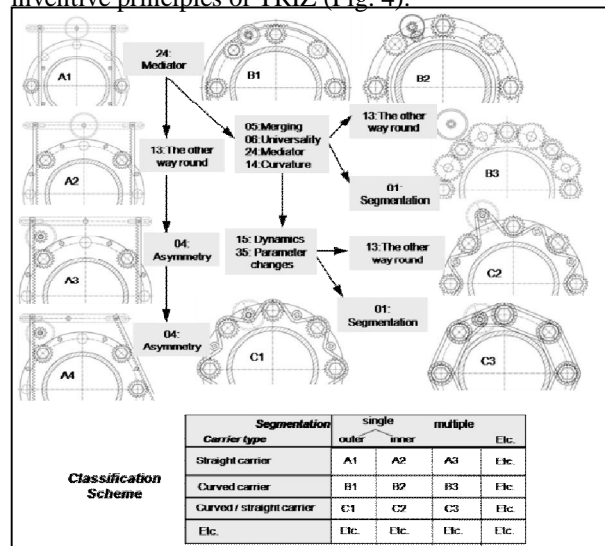


Fig. 4 : Application of TRIZ – Inventive Principles

The solution A1 consists of two straight geared racks which serve as force transferring elements (Mediator) to apply torque at two screws concurrently via geared hub adapters. The two racks are connected by means of a lever which is simply supported and

driven by a motor. The application of IP “The other way round” leads to the solution A2 which has the two geared racks turned around and allows for applying torque at four screws concurrently. The concept A3 makes use of IP “Asymmetry” by placing the drive asymmetrically having effect directly on one of the geared racks. The solution concept A4 increases the degree of “Asymmetry” by changing the position of one of the geared racks and the pivot of the leverage. The solution B1 makes use of a curved geared rack which transfers torque onto two or more screws from outside and is driven by a motor from inside. This concept represents actually “Merging”, “Universality” and “Mediator” and especially “Curvature” compared to A1. B2 represents “The other way round” by applying torque from inside and having the motor drive at the outside. The principle “Segmentation” leads to concept B3, where the curved rack is split into several gear wheels arranged between the geared hub adapters of the screws. The application of principles “Dynamics” and “Parameter changes” leads to solution C1 by replacing stiff with flexible parts like chains and belts to provide force transfer. C2 represents principle “The other way round” compared to C1, and C3 makes use of several chains or belts instead of one, therefore principle “Segmentation” is realized. In order to record conceived basic ideas and to allow the generation of further ones a classification scheme was drawn up (Fig. 4, lower). The criterion of the rows is represented by the carrier type (curved / straight) transferring the torque motion and the criterion for the columns by segmentation and arrangement features of the carrier. Reasoning about additional criteria and blank spots in the scheme is very inspiring and often leads to unconventional and surprising solutions.

B. Resolving conflicts and working out sub-functions

Managing conflicts by application of TRIZ separation principles: After a first evaluation procedure some difficulties were identified. A concurrent torque distribution via gear wheels is inflexible because not applicable for other flange diameters. Though a stiff connection between distributed torque activators provides an equal number of revolutions, it is, however, inappropriate with respect to providing equal local torque stages. This is actually a typical design conflict: Torque should be applied and be present but should not be present at certain screws when the torque stage has already reached its limit. The notion of contradiction respectively conflicting design parameters is a key aspect in TRIZ theory. Through a careful analysis of a problem its inherent contradictions can be identified. These are conflicting situations inside a system which cause problems and restrict its performance. The TRIZ way of resolving contradictions is first of all to identify their type,

which may be “physical” or “technical”. Technical contradictions relate to two parameters which conflict each other and are resolved by Inventive Principles (IPs). Physical ones create a conflict with the same parameter (e.g. torque). TRIZ normally manages physical contradictions by four separation principles which were applied in the present case and generated some new ideas:

- Separation in Time: Separate a process into single steps when it is difficult to do it concurrently, thus useful or harmful effects and functions are realized respectively avoided at different time periods: Applying torque not concurrently but screws or bushings are tightened one after another.
- Separation in Space: Separate a process spatially and divide a system into parts or sub-systems in order to assign specific functions to them: Applying torque concurrently by using several independent torque tools which are spatially separated.
- Separation between the parts and the whole: Assign conflicting requirements to specific parts of the whole system: Modify e.g. the geared rack so that when the torque limit is reached at certain screws a tripping gear or spring mechanism guarantees that no more torque is applied.
- Separation on Condition: Change the conditions for a harmful process which takes place concurrently together with the useful process: Modify e.g. the hub adapters so that when the torque limit is reached at specific screws a tripping gear or spring mechanism makes sure that no more torque is applied.

In consideration of these ideas the decision was made not to follow up the idea of a central drive and distributed applied torques but generate torque directly at the screws by using standard hydraulic power wrenches. The Ideal Final Result was redefined like this: Having a facility which allows the tightening of at least two screws concurrently with standard tools and without major effort. Taken this IFR as the overall functionality relevant sub-functions were sought after. Four sub-functions were identified and listed within a morphological matrix (Fig. 5). This sort of scheme enumerates all possible solutions for sub-functions. The combinations of solutions for given sub-functions result in overall solutions satisfying the overall task [10]. At first all sub-functions were analyzed with respect to their anticipated importance. For the sub-functions 1.2, 1.3 and 1.4 standard solutions could be found, which were directly inserted.

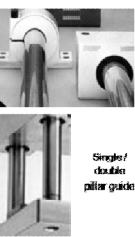
Subfunction	Variants				
1.1 Allowing x/y-positioning	See Figure 7				
1.2 Allowing z-positioning					
1.3 Compensator support reaction forces					
2 Applying torque					

Fig. 5 : Morphological matrix for tool rack

Managing conflicts by application of TRIZ contradiction matrix: A TRIZ way of solving technical contradictions is through applying one or more of the 40 IPs as found appropriate. The general TRIZ design problem derives from analysis and classification of a large number of problems in various engineering fields and suggests a set of general design solutions respectively IPs from which the designer can derive particular solutions for his specific problem. Generally 1 to 5 IPs are found appropriate for solving any specific contradiction. To use the contradiction matrix, the main function respectively sub-functions (39 technical parameters: improving feature) of the system must be identified, then the matrix contains IPs suggested to overcome contradictions (39 technical parameters: worsening feature). In the present case three contradictions were expressed like this: First, an increasing weight of a moving object (torque tool) which is desirable (power) leads to the undesirable worsening features length of moving object (rack dimensions), reduced speed (tool) and adaptability. Second, an increasing adaptability (tool rack) leads unfortunately to an increasing weight, amount of material and device complexity. Third, an improved ease of operation leads also to an increasing amount of material and device complexity. When looking up the TRIZ contradiction matrix several IPs are frequently recommended to resolve the contradictions, for instance dynamics, anti-weight, pneumatics and hydraulics, equipotentiality etc. (Fig. 6). These suggested IPs were perpetually kept in mind in the course of the project as guidelines for potential ideas.

Worsening Feature ->	03: Length of moving object	09: Speed	35: Adaptability or versatility
Improving Feature	01: Weight of moving object	15, 08, 29, 34	02, 08, 15, 38
01: Weight of moving object	15, 08, 29, 34	02, 08, 15, 38	29, 05, 15, 08

Worsening Feature ->	01: Weight of moving object	26: Amount of material	36: Device complexity
Improving Feature	01, 06, 15, 08	03, 35, 15	15, 29, 37, 28
35: Adaptability or versatility	01, 06, 15, 08	03, 35, 15	15, 29, 37, 28
33: Ease of operation	—————	12, 35	32, 26, 12, 17

No.	Inventive Principle	Frequency
15	Dynamics	6
08	Anti weight	4
29	Pneumatics and hydraulics	3
12	Equipotentiality	2
35	Parameter change	2
Etc.	Etc.	<1

Fig. 6 : Contradiction matrix and proposed inventive principles

- Dynamics : Make objects/system adjustable to changing conditions; divide an object into parts capable of moving and changing relative position.
- Anti-weight : Compensate for the weight; merge objects with other objects that provide lift or a re-stabilizing effect.
- Equipotentiality : Change operating conditions so that an object need not be raised or lowered; limit position changes; create conditions to compensate, reduce, eliminate, balance out forces.

Application of TRIZ inventive principles for specific sub-function: The sub-function “1.1 Allowing x/y-positioning” turned out to be one of the more essential ones therefore required an intense examination. Again several inventive design principles were taken subsequently and systematically into consideration. Fig. 7 presents some excerpts of ideas and solutions which were generated at this stage.

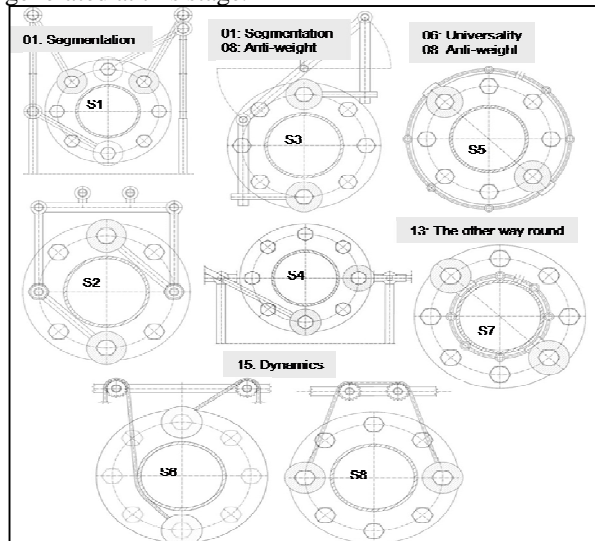


Fig. 7 : Application of TRIZ – Inventive Principles for sub-function “Allowing x/y-positioning”

The solutions S1, S2 and S4 are characterized by eccentrically located pivot points and turnable levers which can be operated independently. The opposite

lever ends allow for the integration of counterweights. The lever movements of S3 are interdependent having the possibility of a counterbalance. All these solutions take advantage of the principle “Segmentation” in order to keep the outer dimensions within certain limits. Reaction forces may be supported by a stand or crane. With S6 and S8 counterbalanced tools are connected via chains or belts which are deflected by one or two pulleys or gear pinions. Actually these solutions were initiated by the application of the inventive principle “Dynamics”. The variant S5 features rolls and connectors which build up a flexible and concentric ring around the cylindrical part of the flange. This allows the enhancement of the facility diameter according flange sizes and measures. The two torque producing tools are integrated within the ring structure, arranged oppositely to each other (Anti-weight / Equipotentiality) and can be rotated around to reach all screws. This design eliminates the need for other parts and therefore incorporates the principle “Universality”. S7 is similar to S5, but instead of reaching the screws from the outside the whole device may rotate around the tube and reaching for the screws from inside (The other way round). In order to collect and depict basic ideas and solutions resulting from brainstorming sessions a classification scheme was additionally set up. The classifying criteria for the columns and rows were determined to be “Translation” and “Rotation” which in combination represent planar motions with the necessary degrees of freedom.

C. Evaluation and embodiment design

After several compatibility studies among elaborated sub-functions some solution concepts were developed and evaluated. The final concept consists of solution S5 for sub-function “1.1”, a double pillar guide for sub-function “1.2”, taking the flange itself for the compensation of reaction forces as solution for sub-function “1.3” and applying torque by means of two standard torque tools as solution for sub-function “1.4”. This overall working principle was considered being worth for embodiment design and further detailing. In the following some characteristics of the developed tool rack are described (Fig. 8).

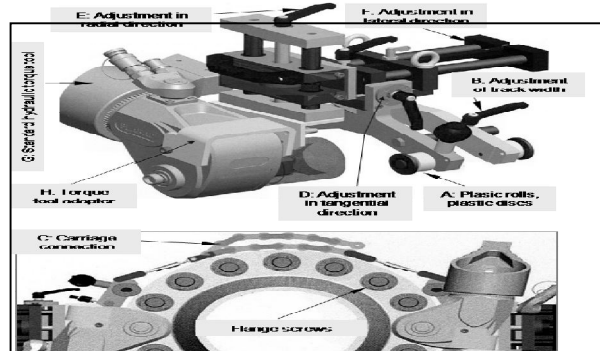


Fig. 8 : Final design of tool rack

Compensate reaction forces: The whole rack consists of two carriages realizing the contact to the

flange. Four bolts which serve as axles for plastic rolls are attached on each carriage. Additional plastic discs are fitted which guide the carriage laterally (A). The track width can be adjusted by means of round bars and for even wider flanges the rods, which are fixed with clamping levers, can be replaced with longer ones (B). On both sides knobs are mounted in order to pull the carriage around the flange. In the upper area guiding elements realized by T-slots for the tangential motion are placed. The connection between the two carriages is established by a total of four pieces of chain (C), which have extended studs on both end sides in which turnbuckles are hooked into for adaptation to different flange sizes and tensioning of the facility. A specific unit enables a movement of a certain length in the tangential direction (D) and ensures the compensation of tolerances and clearances between the two carriages which are coupled to each other. The main component is a threaded spindle with a handle for operation. An adjustment in a radial direction (E) is realized by a double column guide and a trapezoidal thread spindle so that the radial position of the hydraulic wrench is adjustable according to the radial dimensions and screw positions. The movement in z-direction is led by two columns and carried out manually (F). The square bar in the middle is set under pressure by a lever to lock in work and start position by means of a locking pin. The adapters for the various standard types of hydraulic wrenches are each structured similarly (G). An u-shaped bar connects the two lateral threads on the wrenches which are already in place. On this bar another angle bracket with an arc-shaped slot is mounted, so that a rotational movement about the tool axis is possible and which can be locked in an end position by a locking pin. An overall final solution was worked out, so far the developed prototype has turned out quite satisfactory.

III. CONCLUSION

By the means of an origin product design an example was presented which demonstrates that applying systematic design methodologies is able to promote and foster the creativity of designers and eventually led to a novel product which is not yet available on the market. One of the main goals in educational design projects is to demonstrate

- the necessity of developing a variety of solution concepts, which increases the probability of having proper variants from which the best can be selected afterwards,
- that it is useful to be familiar with a set of tools for the generation of ideas and their modification in various directions along the course of a project.

It has been experienced that

- without the application of specific techniques at first only a few and quite simple solutions are created and that these get more sophisticated with the subsequent application of additional techniques which proves that creativity is ceaselessly in flux when inspired continuously,
- the number, quality and variety of ideas are higher compared to those generated by trial and error,
- the confidence and competence of students are strengthened by the complementary use of techniques and switching between them.

Nevertheless, every design project is different and often imponderabilities occur. Even the order of activities depends on the experience and decisions of personnel involved, the given task and state of information. In the case of origin design it is in general good practice to start with techniques on a quite abstract plane like functional structures, TRIZ-IFR/MTSC/SLP/AFD and getting more concrete by the usage of classification schemes, morphological matrices, compatibility matrices and the ongoing use of TRIZ methods. Therefore, in order to identify certain patterns or principles, the conduction of further comprehensive engineering design examples is necessary to improve the evaluation of the complementary use of design techniques.

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