CONCEPTUAL DESIGN OF MULTI-DOMAIN SYSTEMS:

PRODUCTS AND MATERIALS

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LIST OF SYMBOLS AND ABBREVIATIONS

IFR	Ideal Final Result
RMCS	Reactive Material Containment System
Su-Field	Substance Field
TRIZ	Theory of Inventive Problem Solving

GLOSSARY

ARIZ: Algorithm for the Solution of Inventive Problems.

Analogy (or Conflict) Based: A design method where a designer uses the construct of generalities (in the form of conflicts) to transfer design knowledge between the product and materials domain, making use of the system conflict as the common interface, and the various TRIZ tools to complete the analogy.

Conceptual Design: Concerning the Conceptual Design phase as defined by Pahl and Beitz. During the *conceptual design phase*, the basic solution path created through a determination of concepts. In terms of Pahl and Beitz, a concept or principal solution may be as vague as a specification of working interrelationships needed for the fulfillment of functional interrelationships [81]. The conceptual design phase is followed by the *embodiment design phase* in which designers start from a principal solution or multiple concepts and determine the structure of the system based on given performance requirements. Details of the final design are then finally specified in the *detail design phase*.

Designer: A person characterized by the active role played in the design process, where possible roles include being a (1) decision maker, (2) participant within a design process, (3) creative entity, (4) information manager.[40]

Design Freedom: The amount of options remaining available to a designer for consideration at a particular point in time, related to the resources at disposal. This is also a measure of a designer's independence in making a particular decision.

Design Knowledge: Knowledge about the product being designed as pertaining to the problem comprised of specifications of form, function and performance.

Design Space: The continuous or discrete set of options under consideration by a designer at a particular point in time and the region over which the designer has influence.

Function Based: The use of functions (ideal input-output relationships) to collectively model the required behavior of the desired system.

Function Structure: A graphical device used to model a system at an abstract level by illustrating the transformation of energy material and signal.

Ideal Final Result (IFR): A statement of the best possible design outcome where the design problem's requirements are fully fulfilled without having used any material or energy resources. Used as the target at which to aim problem solving efforts.

Innovative: The development of problem solutions that are beyond incremental or obvious changes to technical problems, often involving the novel use of a technology or scientific phenomenon. Innovative (or inventive) problems are problems for which only an innovation or invention is sufficient for a solution, i.e., not a mere problem of dimensions or specifications.

Level of Abstraction: The level of detail regarding a problem under consideration, best suited to making a decision from a given perspective. Through abstraction, complexity is reduced and essential problem characteristics are emphasized so that coincidental solution paths may be avoided and more generic (non-intuitive) solutions may be found [81].

Multi-Domain Systems: Types of problems where a designer seeks to fulfill performance requirements placed on the product generally through the design of both the product and the design of the material.

Physical Contradiction: A statement that captures the crux of the design problem on the physical level by stating that a certain design trait must be present to satisfy one aspect of a design and must not be present to satisfy a different aspect of a design.

Principal Solution (Concept): The foremost conceptual design variant used for further development in the embodiment phase. This should not be confused with Solution Principle; an underlying problem solving principle.

Products and Materials: The product is the overall outcome of the design activity and the materials are the sub-constituents of the product. In this context, it is referring to the domains of the product or the domain of the materials.

Requirements list: List of specifications that a design must satisfy in order to meet the design goals and be deemed successful. Specifications are categorized as either demands or wishes and used as checkpoints and guidance along the design process.

Su-field: Literally Substance-Field, is a graphical representation of the technical problem(s) in the form of objects, or substances, and the fields (including forces) acting on them.

Scientific Effects: Tabulated physical phenomenon associated with a desired effect or property.

Solution Principle: An underlying problem solving principle that leads to the solution. In this general sense, the term has been applied in work based on the Systematic Approach of Pahl and Beitz. The TRIZ usage of this term refers to a specific set of 40 principles used to solve Technical Contradictions (See Appendix Table A.7-Table A.9). A solution principle is used as an analogy to generalize a solution. This should not be confused with Principal Solution; the foremost conceptual design variant used for further development in the embodiment phase.

Standard Solutions: Algorithmic general solution triggers to typical technical problems.

Solution Trigger: A device that is used to prompt a designer to discover a solution to a problem. This includes solution principles, scientific effects, standard solutions, design analogies, etc.

Technical Conflict: A statement that captures the crux of the design problem on the technical level by stating that the improvement of a desirable design trait worsens an undesirable design trait, or vice versa. Discovering the technical contradiction generalizes a problem.

TRIZ: Suite of problem solving tools initially developed by Genrich Altshuller and titled in the original Russian *Teoriya Resheniya Izobreatatelskikh Zadatch* (hence, TRIZ) and translated into English: Theory of Inventive Problem Solving. Sometimes this is abbreviated to TIPS in English works, however TRIZ will be used throughout this thesis.

SUMMARY

A key challenge facing designers creating innovative products is concept generation. Conceptual design is more effective when the design space is broadened by using an integrated design of product and material concepts approach. Conceptual design can also be accelerated by including problem solving and solution triggering tools in its structure. In this approach, structured analogy is used to transfer underlying principles from a solution suitable in one domain (i.e., product or mechanical domain) to an analogous solution in another domain (i.e., material domain). The nature of design analogy does not require as full of an exploration of the target domain as would otherwise be necessary; affording the possibility of a more rapid development. The addition of problem solving and solution triggering tools to a design method also decreases the design time and/or improves the quality of the final solution.

This approach is formulated through a combination of the Theory of Inventive Problem Solving (TRIZ) proposed by Altshuller, and the systematic approach of Pahl and Beitz, for products that are jointly considered at the product and material level. These types of problems are ones where customer performance requirements are fulfilled through both the designed product and the designed material. The systematic approach of Pahl and Beitz is used as the base method through which TRIZ is used as a means of transferring abstract information about the design problem between the domains with the aim of accelerating conceptual design. This also allows for multi-domain design tools such as Su-Field-Model integration with design repositories for the transfer of information at different levels of abstraction; expanding the design space and effectively directing the designer. The explanation of this approach is presented through a simple example of a spring design improvement and validated through concept generation of a reactive material containment system.

CHAPTER 1

INTRODUCTION TO MULTI-DOMAIN DESIGN: INTEGRATED PRODUCT AND MATERIALS DESIGN

1.1 BACKGROUND AND MOTIVATION FOR MULTI-DOMAIN DESIGN: INTEGRATED PRODUCT AND MATERIALS DESIGN

1.1.1 Background on Concept Flexibility

Generating concepts, that is, determining key specification such as functionality, physical structure, and performance expectations has been shown to be crucial to the success of new products [10, 30, 88]. A *concept* being defined as “an idea that is sufficiently developed to evaluate the physical principles that govern its behavior” [112]. Since conceptual design is so important yet wide open, the value of flexibility is obvious at the conceptual level. Krishnan and Bhattacharya [57] state that increasing emphasis on market leadership and investor value creation have turned many companies’ attention to conceptual design as a source of growth, renewal and competitive advantage. During the conceptual design phase, where the direction for the product is set and most of the resources are allocated, designers need the flexibility to discover, frame and choose solutions that meet system level requirements. Concept flexibility is therefore a perquisite to use new product development as that source of “of growth, renewal and competitive advantage”[57]. Indeed working with a single concept is a recipe for disaster [111] and it has been shown that being able to explore more areas of the design space through concept flexibility correlates to higher quality design [35].

It is claimed that a majority of the costs of a product from manufacturing, maintenance and disposal are determined in the conceptual design phase [15, 117]. Therefore decisions made during this phase have a major impact on later development activities and mistakes made in conceptual design are difficult and expensive to correct. This makes conceptual design one of the most demanding steps in design work.

With this in mind, various approaches to increase a designer's ability to generate concepts have been proposed such as function-based systematic design [79], general solution finding methods, as well as analogy based approaches. For this work, a function-based systematic design is shown to be enhanced with analogy based tools to improve concept generation.

1.1.2 Systematic Product Design

A well known systematic approach to conceptual product design is the method created by Pahl and Beitz [82]. The essential information flow and steps of this process are represented in Figure 1.1. There are two types of thinking involved in the design process, intuitive and discursive thinking. Systematic design is based on discursive thinking: "a conscious process that can be communicated and influenced, in which scientific knowledge and relationships are consciously analyzed, varied, combined in new ways, checked, rejected, and considered further" [82]. This type of thinking is essentially the foundation of information transformation, as each piece of the design is processed through the designers mind to successively work from initial problem information to final details. Intuitive thinking plays a role in this process, although structuring thought in logical sequences reduces the reliance of success on a designer's opportune flash of inspiration.

1.1.2.1 Overview

With the desire to develop an approach that promotes discursive thinking, the systematic approach of Pahl and Beitz is a process of "step-by-step analysis and synthesis." The goal is to work from qualitative to quantitative through a number of iterative loops, with each iteration occurring continuously within and between steps. Every task involves an initial confrontation of the problem, a definition phase and a creation phase (within which there are evaluation and decision steps). Systematic design does not rely on chance, integrates a designer's intuition, gives standardization to design, is adaptable and reduces iteration while keeping its benefits by guiding it in small loops. This process is indispensable in original design because it ensures nothing essential has been overlooked. The overall goal of systematic design is to create products that, "satisfy the customer needs, reach the market at the right time and are sold at the right price."[82]

The design process is divided into the following main phases:

1. Planning and task clarification: specification of information
2. Conceptual design: specification of principle solution (concept)
3. Embodiment design: specification of layout (construction)
4. Detail design: specification of production

The diagram of this successive process from abstract to concrete as proposed by Pahl and Beitz is shown in Figure 1.1.

Each phase of the design process can be viewed as a core transformation and a summarized walk through of the phase is presented.

1.1.2.2 Core Transformations

"Designing is the process of converting information that characterizes the needs and requirements for a product into knowledge about a product"[82]. The structure of a transformation is:

[Information]x[TRANSFORMATION]= [Knowledge]

Where some sort of transformation is applied to the information to create new knowledge that is fed into the next transformation.

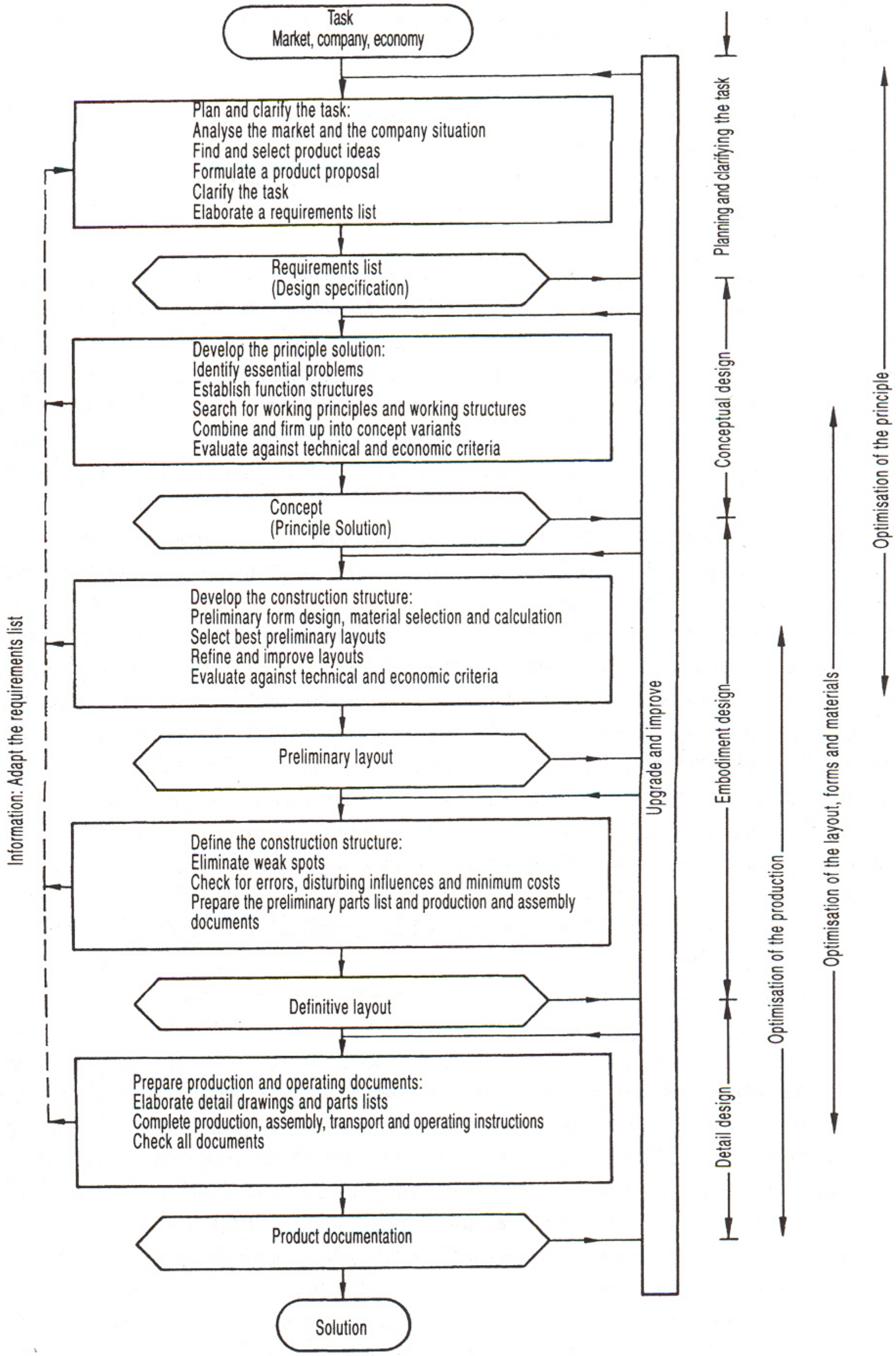


Figure 1.1: Pahl and Beitz design process [82]

1.1.2.3 Planning and Clarifying the Task

It is necessary to clarify the given task in more detail before starting product development.[82] Task clarification is important because an error at the stage of understanding the problem will cause the product to be completely off task. Shown in Figure 1.2 is a flow chart of the clarification of task transformation.

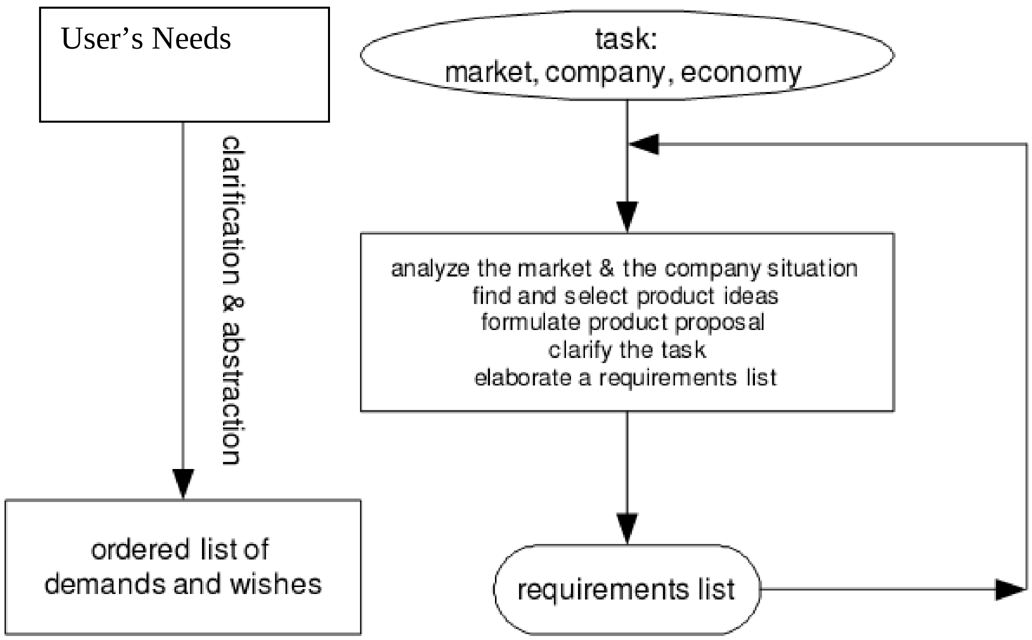


Figure 1.2: Clarification of Task Phase

During this phase the following questions are answered:

- What are the objectives that the solution will satisfy?
- What properties must it have?
- What properties must it not have?

The first transformation encountered is:

[user's needs]x[technical interpretation]=[Product proposal]

This transformation is used to uncover what the customer really wants. Through market research, technological forecasting, customer feedback, and other methods the design team converts that information into a product proposal. This is necessary to build a functional requirements list. Once the product proposal is completed, the second transformation takes place:

[product proposal]x[assessment]=[Requirements List]

The requirements list is the **key document** in the design process. The development of the requirements list serves as a starting point for design. It is also a metric used in evaluating a progressing design, yet it is a living document and is modified throughout the process. The assessment used in developing a requirements list involves "collecting information about the requirements that must be fulfilled and identifying existing constraints and their importance."[82] This assumes that what goes into the list as demands and wishes can be classified as such, and therefore, anything that cannot fall into one of those two categories should be rejected. It also assumes that the product proposal is concrete enough to create functional requirements, yet abstract enough to allow for design freedom. Therefore the product proposal should be formulated in solution neutral terms.

1.1.2.4 Conceptual Design

"Conceptual design is identifying the essential problems through abstraction, establishing function structures, searching for appropriate working principles and combining these into a working structure. Conceptual design specifies the principal solution." [82] Displayed in Figure 1.3 is a flow chart for the transformation in conceptual design. In Conceptual Design there is one core transformation plus essential sub-transformations:

[requirements list]x[abstraction]=[principal solution]

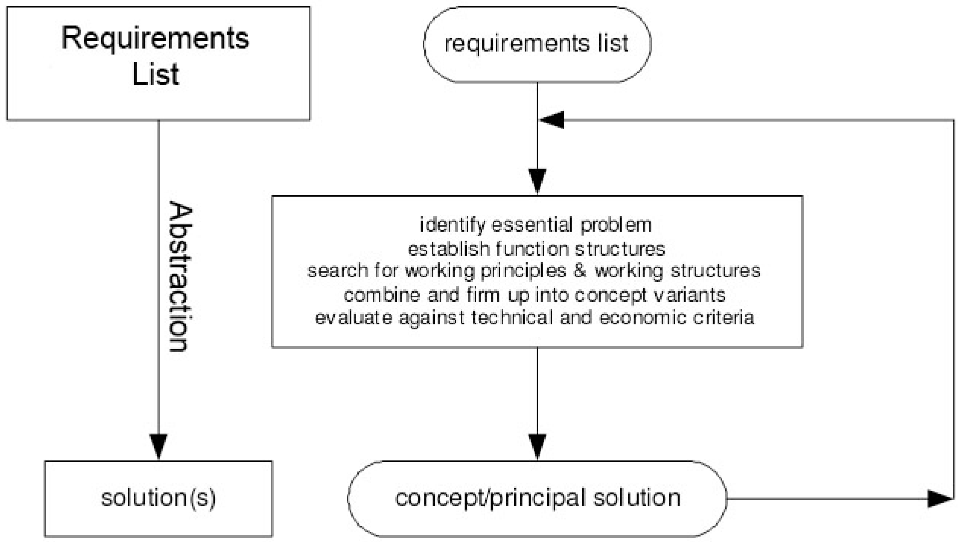


Figure 1.3: Conceptual Design Phase

This is a large transformation and is important in design because performing it keeps the solution pool large in the beginning, or promotes design flexibility, and helps you narrow down on an acceptable design. It also allows the designer to keep the design process abstract while still moving forward. Assumed with this transformation is that the requirements list is formulated in somewhat solution neutral terms.

Abstraction can be broken down further into smaller transformations:

[information that is particular or incidental]x[extraction]=[essential information]

This transformation is important because through it a designer extracts the crux of the problem. Again, this assumes that information is solution neutral.

[all constrains]x[elimination]=[genuine restrictions]

Through this step, a designer gets rid of the information and constraints that are unimportant to the solution. This assumes that you have some sort of evaluation method, tool or metric available. This can be considered a refining of the requirements list.

[essential information & genuine restrictions (abstracted information)+requirements list]x[modeling in EMS transformation]=[function structure]

The function structure is important because it lets a designer model the design in an abstract way that maps directly to multiple concrete components of the solution. The fact that the essential information & genuine restrictions are combined with the requirements is reasoning for breaking the transformations into a nested, as opposed to sequential, format. As a note, function structures are a simplistic model of physical transformations:

[Energy + Materials + Signals]x[functions]=[altered Energy + Materials + Signals]

[function structure]x[search for working principles]=[working structures]

Performing this step widens and then narrows the solution set into ones that can be combined in a reasonable manner. Assumed is that there are available working principles. If an infeasible function is created, a working principle cannot be found. Also assumed is that the overall function structure has been sufficiently subdivided into parts small enough to have one working principle mapped to it.

[working structures]x[selection]=[principal solution]

The designer's goal within this step is to narrow down on a solution. Assumed is that the designer has an effective selection method that can be trusted. "In the embodiment and detail design phases it is extremely difficult or impossible to correct fundamental shortcomings of the solution principle."[82] It is for this reason that conceptual design becomes so important.

1.1.2.5 Embodiment Design

"Embodiment design results in the specification of a layout."[82] This phase in shown in Figure 1.4.

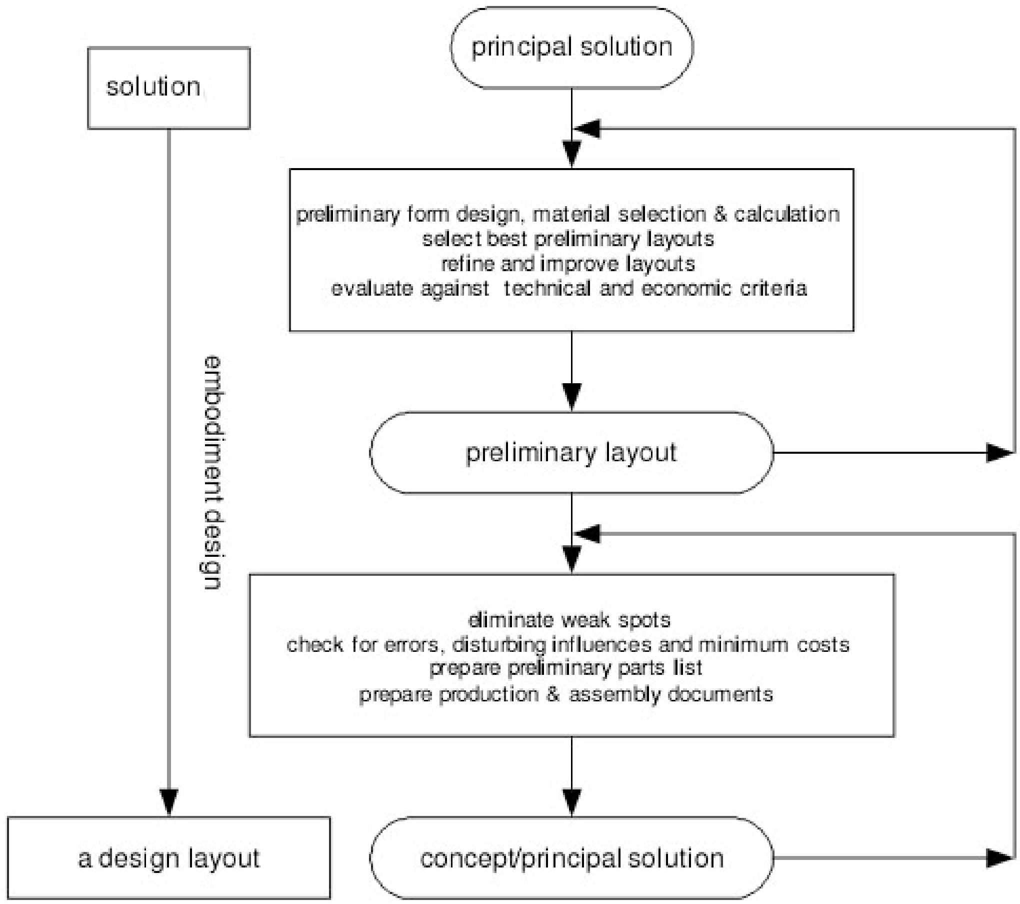


Figure 1.4: Embodiment Design Phase

The transformation that corresponds to this phase taking the principal solution, and transforming it into the preliminary layout through a series of sketches, calculations, evaluations, etc.:

[Principal Solution]x[rough sketching, calculations, evaluation, requirements etc.]=[preliminary layout or form design]

Through this important transformation step, a designer brings the design idea to fuller realization. Within this step are most of the calculations and the creation of the physical form of the design. Assumed during this phase is that the goals in mind during embodiment design are in line with goals in the proceeding sections. For example, if it is desired to embody the design in such a way that allows for disassembly, this should be reflected in the function structure before proceeding to embodiment design. Major changes must happen in previous steps.

1.1.2.6 Detail Design

"Designers should not relax their vigilance at the detail design stage."[82] This phase is shown in Figure 1.5.

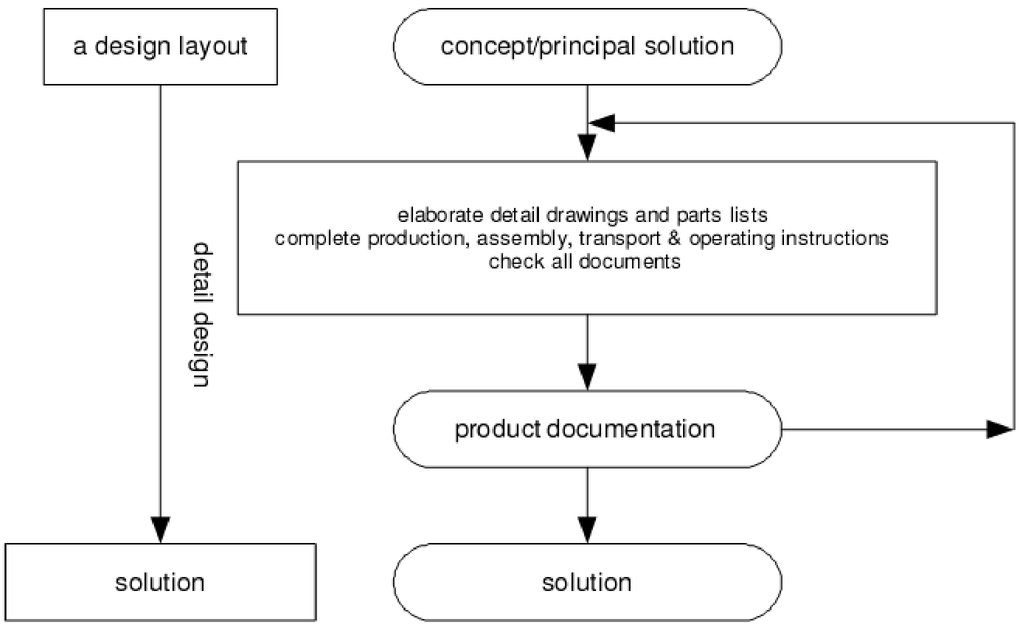


Figure 1.5: Detail Design

Within this final phase the real, working, fully functional and complete solution is brought through to detailed documentation. Iterations at this level (in the sense of going back to previous phases) are very time consuming and costly, so care must be taken in previous design phases to avoid this. The preliminary layout is something that is built upon, and not just used as a reference in this phase. Assumed of course is that the design is in working fashion except for the details, hence the name.

[Preliminary layout or form design]x[detailed document preparation]=[full specifications and production documents]

1.1.3 Function Based Systematic Conceptual Materials Design

This section has been leveraged and modified from Matthias Messer's Ph.D. dissertation [69].

Materials are fundamental to design, and throughout the history have dictated its opportunities and its limits. The evolution of materials began with humankind's use of naturally occurring materials. Materials have had a profound impact on the evolution of word civilizations. Historians have classified periods in this evolution by the materials that were the state-of-the-art during these periods. Thus, the vocabulary now contains phrases like the Stone Age, the Bronze Age, and the Iron Age. Each of these eras is characterized by the material that was most advanced of its time. By the twentieth century an embryonic technology involving synthetic materials emerged known commonly as plastics. This was a profound departure from the traditional approach of exploiting natural materials with their known defects and limitations.

Synthetic plastic materials replaced traditional materials in a diverse range of industries. The reason was their extensive range of physical properties that could comply precisely with the performance requirements. However, in the following, a variety of functional materials, such as gallium arsenide or magnetostrictive materials, have been developed to exploit functional properties instead of solely structural properties. The availability of functional materials has then made the development of advanced composite materials possible. The characteristic of advanced composite materials is that a combination of two or more constituent materials creates a material with engineering properties superior to those of the constituents – albeit at the expense of more challenging fabrication technologies.

It is not the age of just one material; it is the age of an immense range of materials and the combinations these allow. There has never been an era in which the evolution of materials was faster and the sweep of their properties more varied. The availability of materials expands so rapidly that designers may not keep track. Yet, innovative designs are often enabled through innovative materials. Also, there is no reason to expect that the pace of material development will slow. Innovations in the materials domain will continue to drive disruptive technologies, mostly in response to engineering problems, i.e., in a problem-directed (need driven) fashion rather than through "technology push" (technology driven).

Designing materials to solve engineering problems may lead to achieve system performance goals for the first time or realize "smart" materials and "artificially intelligent systems". In the encyclopedia of chemical technology [58], *smart materials* are defined as objects that sense environmental events, process that sensory information and then act on the environment. Smart materials may inherently act as sensors or actuators. In their role as sensors, a smart material responds to changes in its environment by generating a perceivable response. For example, a thermochromic material could be used directly as a device for sensing a change in the temperature of an environment via its color response capabilities. Smart materials such as piezoelectric crystals could also be used as actuators by passing an electric current through the material to create a force. The goal of materials design thus becomes to tailor materials depending on what primary system functions they are intended to serve. Materials design from a systems perspective may thus lead to "*artificially intelligent systems*", i.e.,

- environments featuring automation and information technology, such as central sensor controlled and programmable talking washing machines, or
- embedded, information-rich, multimodal environments that are anticipatory and context-aware of occupants, such as recognition systems

(body tracking, voice, gesture, aural, touch, smell, taste), and computationally-assisted task augmentation via embedded interfaces.

Future approaches might even feature increasing cognition and context-aware response levels suggestive of biological systems, but may also see an evolution of the personal environment (i.e., a trend towards personalization) and a devolution of traditional physical boundaries, as described by [63]. However, enhancing existing function-based systematic design approaches by incorporating the potential embedded in materials design to increase a designer's concept flexibility, in other words developing a function-based systematic approach to the integrated design of product and materials concepts, is crucial when facing dynamic demands.

Current materials design approaches do not address the conceptual design phase – the most crucial design stage in which decisions allocate the vast majority of a product's resources – in a systematic fashion. Besides the development of advanced methodologies for material selection [7, 8], a paradigm shift towards materials design with the objective of tailoring the chemical composition, constituent phases, microstructure and processing paths to obtain materials with desired properties for particular applications has begun [26, 59, 66, 75, 83, 96]. So far, however, materials design has mostly been exercised in the embodiment phase focusing on simulation-based multi-scale modeling techniques developed recently [14, 26, 83].

As argued by Eberhart and Clougherty [36], no matter how fast the computer, if it must search for an optimum property using accurate analysis models of an infinite number of materials, it will still require infinite time to perform the search. Hence, the viewpoint of materials design as an automated search exercise is very limited. Also, scientific, mostly complex multi-scale models might not be necessary in many cases because the goal of materials design is not to accurately predict material properties but to satisfy performance requirements. Furthermore, bottom-up analysis is not design. The key to materials design is interplay of multi-scale modeling with human decision-making.

With respect to systematic conceptual materials design, the idea is to establish function-based systematic conceptual materials design focusing on phenomena and associated solution principles – structure-property relations – but not an infinite number of cases or material artifacts. In this context, the essence of the systematic approach to conceptual materials design presented in this thesis is to enable designers identifying underlying phenomena, associated solution principles and related analogies rather than a prescriptive set of directions simply to instruct in the implementation of new materials and technologies. Also, materials design is an emerging multidisciplinary field with two main trusts in mechanical engineering (specifically materials science and chemistry) and electrical engineering (specifically electronics). By focusing on phenomena and associated solution principles embodying identified functional relationships and associated analogies, but not the material artifact, a designer is able to overcome disciplinary boundaries and transfer solutions from multiple domains to the design task. But, as a result, this approach requires a much more active engagement by the designer than do the typical selection approaches.

If knowledge of a material/system is tied only into an account of its properties/specifications and a description of its current application, then that knowledge may become obsolete along with the material/system quickly. By operating at the level of phenomena and associated solution principles, a particular material/system at any given time is only illustrative of the possibilities, not their determinant. As materials/systems cycle through evolution and obsolescence, the questions that are raised by their uses should remain. Hence, it is crucial to leverage phenomena and associated solution principles to design and develop products that have a dynamic behavior and provide that knowledge in classified form for easy retrieval.

1.1.4 Review of Systematic Problem Solving Techniques (TRIZ) and Axiomatic Design

Design principles can be used at any point to aid solution finding processes based on principles or solution triggers that will help a designer find inventive solutions to a clarified problem.

Altshuller for example extracted from the analysis of many thousands of patents, 40 inventive principles which became the essence of the TRIZ tool for technical conflict resolution [5, 6, 77]. TRIZ is Russian acronym for "The Theory of Inventive Problem Solving". Studies of patent collections by Altshuller, the founder of TRIZ, has indicated that only one per cent of solutions was truly pioneering inventions, the rest is represented by the use of a previously known idea or concept but in a novel way. Thus, the conclusion is that an idea of a design solution to a new problem might be already known, however just applied in a different domain.

Hence, TRIZ, based on a systematic view of the technological world, provides a wide-ranging series of techniques and tools, such as the "patterns of evolution of technological system", "substance field analysis", "contradiction analysis", "required function analysis", "algorithm for inventive problem solving", "40 inventive principles", as well as "76 standard solutions and effect database". However, the main axiom of TRIZ is that the evolution of technological systems is governed by objective patterns. These patterns can be employed for conscious development of technological system and inventive problem solving, replacing inefficiencies of blindly searching.

Similarly, Suh and coauthors [108, 109] proposed design principles governing the analysis and decision making process in developing high quality product or system designs. In general, their axiomatic design is considered to be a design method that addresses fundamental issues in Taguchi methods. It helps designers to structure and understand design problems, thereby facilitating the synthesis and analysis of suitable design requirements, solutions, and processes. This approach also provides a consistent framework from which metrics of design alternatives have been quantified. However, at its core, two design axioms provide a rational basis for evaluation of proposed solution alternatives and the subsequent selection of the best alternative. The axiomatic character of these two design axioms however is flawed, as discussed in the literature [22].

The basic premise of the axiomatic approach to design is that there are basic principles that govern decision making in design, just as the laws of nature govern the physics and chemistry of nature. These two basic principles, called the "Independence Axiom" (maintain independence of functional requirements) and the "Information Axiom" (minimize the information necessary to meet the functional requirements), are derived from the generation of design practices. The corollaries and theorems, which are direct consequences or derived from these two axioms, tend to have the flavor of design rules or principles.

Axiomatic design pays much attention to the functional, physical and process hierarchies in the design of a system. At each layer of the hierarchy, design principles are used to assess design solutions. However, TRIZ on the other hand abstracts the design problem as either a contradiction, or a Su-field model, or a required function realization. Then corresponding knowledge base tools are applied once the problem is analyzed and modeled. Though approaches to the solutions are of some differences, many design rules in axiomatic design and problem-solving tools in TRIZ are related.

Other design principles have been proposed in the design literature, such as in the context of design flexibility by Qureshi and coauthors [90] and Keese and coauthors [54] or in the context of transformers, i.e., systems that exhibit a change in state to facilitate new or enhanced product functionality, by Singh and coauthors [102, 103] or Skiles and coauthors [104]. Also, Parkinson and Chase propose some principles of adaptive robust design which suggest ways to make a system which can adapt to the variation introduced by the environment of use, manufacturing processes or by the requirement of the user [85]. In essence, the basic design rules “simplicity, clarity, and safety” identified by Pahl and Beitz [81] could also be understood as design axioms. However, these principles are more concerned with achieving product flexibility than drivers within TRIZ which guide designers to achieve concept flexibility.

1.1.5 Reactive Material Containment System Example Problems

A reactive material containment system example problem based on work by Messer [70] is used to test the systematic approach for integrated product and materials concept generation developed in this work. Currently, reactive materials are transported to their destinations in enclosures consisting of monolithic panels. Also, the more or less advanced materials of the reactive material containment system are mostly selected from a finite set of available materials. However, in order to minimize adverse economic and environmental effects while ensuring safe handling at satisfactory reactivity, customers pose conflicting requirements such as:

- minimization of reaction probability during transport,
- maximization of reaction probability during usage,
- maximization of collision resistance, and
- minimization of system weight.

Therefore, the overall system has to be designed in order to ensure satisfactory performance, i.e., reactivity, of the reactive material to be transported as well as its safe handling, i.e., protection against collisions which may cause impacts, high temperatures and blasts as shown in Figure 1.6, while minimizing overall system weight. Thus, to solve this design problem, functionalities (and related properties) from the chemical and mechanical domains are required and they are coupled. Also, the reactive material containment system involves decisions on both the system and material level.

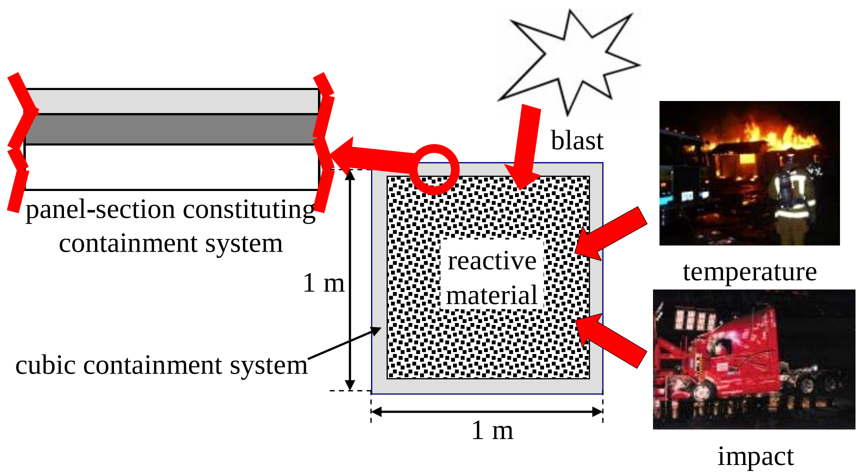


Figure 1.6: Reactive material containment system example [70].

On the system level for example, a decision has to be made on configuring the containment system – potentially featuring various panel concepts, ranging from monolithic to composite panels, or unreinforced to stiffened to multilayer sandwich panels. Also, a designer is confronted with material level decisions to better achieve performance requirements. For example, by selecting a sandwich structures to configure the overall containment system, various microscale cellular material or truss structure core configurations can be designed that feature increased energy dissipation per unit mass to better sustain blasts. Also, in contrast to selecting a reactive material, reactive metal powder mixtures might be designed with multiple functions in mind. Reactive metal powder mixtures feature reactivity and strength that can be combined with the containment system strength or in its extreme makes a containment system obsolete. However, by for example designing reactive metal powder mixtures concurrently with the containment system, reactivity and level of blast protection can be customized and hence increase a designer's concept flexibility.

In the context of this example problem, the goal is to show how to increase system performance as well as a designer's concept generation flexibility through the integrated design of materials and product concepts. For example, currently designers are limited in the sense that they can only select a certain quantity of reactive material while designing a containment system concept. Having conceptually designed the containment system, most likely the strongest and toughest as well as lightest materials available are selected to embody the containment system concept and fulfill the given performance requirements best.

By designing products and advanced multifunctional materials in an integrated fashion from the conceptual stage on, designers may gain greater flexibility, as in its extreme envisioned in Gershenfeld's personal nano-fabricator assembling any object atom by atom [37]. For example, designers do not need to limit themselves to select an available reactive material but may consider the design of Multifunctional Energetic Structural Materials (MESM), i.e., reactive metal powder mixtures, serving the dual purpose of providing both energy storage and strength to a reactive system. Furthermore, designers can consider the design of multifunctional panels that compromise the containment system, providing the functions of both strength and increased energy absorption per unit mass.

The reactive material containment system example is a reasonably complex multi-domain design problem. The design problem allows significant increase in system performance by exercising systematic conceptual design not only on various system levels down to the component level, but, also on the materials level. Moreover, the problem is suitable because many aspects of integrated product and materials design can be demonstrated.

1.2 FRAME REFERENCE FOR PRODUCT AND MATERIALS DESIGN

It has been estimated that while the "time frame for the introduction of a new commercial product is between 18 to 24 months from the time the product concept is frozen to the point of product validation"; (in reference to the aerospace industry) the time frame for new material development is between 2 and 20 years [29]. As a consequence, there is a need to promote and accelerate materials development and design. Displayed in Figure 1.7 is the interrelation of product and materials design.

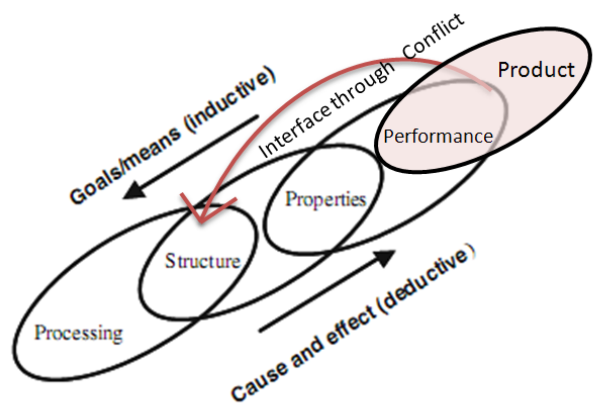


Figure 1.7: Olson's linear concept of 'Materials Design' [75]—modified.

McDowell and Olson advocate that design should follow a top-down, concurrent design of materials and products model [67]. Subsequently, a process that brings forth the knowledge of how product requirements can be placed on materials by transferring the problem to that domain helps the development of technology, if for no other reason than to direct how or in what aspect the material should be explored, or the possibilities that functions and requirements might be fulfilled by a material so that it can be designed in those directions. Therefore, in the concurrent conceptual design of a product and material, the transfer of relevant information between the material domain and the product domain is critical. Referring to Figure 1.7, this transfer of information happens along the curved arrow from Product/Performance (grayed oval) to material Structure. With a basic understanding of concept flexibility, product design, materials design, and the need for concurrent design of products and materials, the gaps needing to be bridged in order for this to happen can be found.

1.2.1 Research Gaps and Overview

Within systematic conceptual design methodologies such as the one proposed by Pahl and Beitz [81], it is seen that focus so far has been on the mechanical or electrical system level domain only, such as connections, guides and bearings, power generation and transmission, kinematics, gearboxes, safety technology, ergonomics as well as production processes. In the conceptual stages, current systematic design methodologies do not include the materials level.

Some works [26, 95] include integrated product and materials design, but this is found in the embodiment and detail design stages rather than in the conceptual stage. Traditionally, systematic design methodologies have been based only on material selection after a principal solution has been developed from the conceptual design phase. The classic example of this is the Pahl and Beitz design-process [81], which involves material selection during the embodiment design phase, as shown in Figure 1.1, after the principal solution is developed.

Table 1.1: Research gaps in conceptual design approaches.

Research Gaps	
Gap 1	Systematic approaches to make use of the potential in materials design for concept generation.
Gap 2	Methods and tools to increase a designer's concept flexibility in the context of integrating multi-domain design, specifically product and materials design.
Gap 3	Methods and tools to extend existing systematic conceptual product and systems design approaches to the materials level.

Current systematic conceptual design approaches do not make use of the potential in materials to increase a designer's concept flexibility. Also, strictly function-based design approaches are built on functional modeling (and not analogical problem modeling) and do not allow for systematic mappings facilitating concept generation.

It is acknowledged that most applications require materials to satisfy multiple functions that cannot be defined in isolation from system level conditions and performance requirements. Therefore, the focus in this work is on enhancing existing systematic design approaches by extending the potential in materials design through analogy and other tools to the higher levels of design, specifically product and system levels. The overall intent of this is to increase a designer's flexibility to generate concepts.

The proposed approach consists of a function based design method that integrates the design of product and material concepts using structure-property relations at multiple length scales to drive the materials design with the aid of experiential knowledge based problem solving and solution triggering tools. Three questions are investigated while developing this systematic approach.

1.2.2 Intellectual Questions for Investigation

The first research question is, "**How can a designer generate concepts in materials design that supplement concepts in product design to fulfill the design goals of innovative products?**" This relates to:

i) the integration of product and material concept generation, and

ii) the rendering of a systematic and domain-independent method to support a wide range of products. The hypothesis to address these two points of the first question has two components:

Hypothesis 1a) The first component is supplementing materials selection with materials design to integrate product and material concept generation. This provides capabilities for synthesizing customized materials with specific performance characteristics by involving phenomena and associated solution principles on the multi-scale materials level (i.e., the multiple ovals found in Figure 1.7) to drive concept generation[70].

Hypothesis 1b) The second component is experiential knowledge based problem solving and solution triggering tools to create a systematic and domain-independent method (TRIZ). This allows a designer to better define problems and find solution principles (or things that trigger a solution in a designer's mind) that have worked in the past regardless of domain.

The second research question is, "**How should solution principles and problem formulations used in the past mostly for the mechanics domain be integrated into the function based design method to be applicable to multi-scale materials design?**" This relates to problem solving and solution triggering tools (TRIZ) integration.

Hypothesis 2) The hypothesis is that problem formulations and solution triggers developed for use in the TRIZ methodology can also be integrated into function based design for multi-scale materials by allowing TRIZ problem modeling (Su-Field models with systems conflicts) to be developed alongside function structures (with the potentially improved performance by using a CAD type software), and used to inform later design process steps. As mentioned, and illustrated earlier in Figure 1.7 with the curved arrow, the mechanism for transfer between the product and materials domain is an analogy tool, making use of the system conflict the chief common interface, and the various TRIZ tools to complete the analogy. To apply TRIZ in a systematic process, the Algorithm of Inventive Problem Solving (ARIZ) is used [6] [94]. ARIZ has been developed over a number of years, and is a detailed, sequential process that systematizes the individual TRIZ heuristics.

The third research question is, "**How should function structures and problem formulations be connected to solution triggers at the appropriate length scales for materials design?**"

Hypothesis 3) This hypothesis involves mapping pre-existing abstracted problem formulations and solution trigger mappings (TRIZ Matrix) to functions and length scales, creating an additional length scale dimension for the pre-existing mappings. The TRIZ matrix relates two design characteristics that are in conflict to possible solution triggers to create innovative solutions, and with an additional length scale dimension, the tool is better suited to materials design. Also, analogical techniques found in TRIZ can be used for the structure of augmentations to a design catalog, using the conflict as the common interface. The premise is that a problem is first defined in terms of function, which dictates the behavior required, and therefore can be linked to a repository of solutions that exhibit this behavior. In the figure of the design repository (Figure 1.8), a snippet of the two components of the repository are shown. In the first section, the underlying phenomenon is found by relating the input and output of the key function in a table of phenomena. Once the phenomenon is found, a design catalog can be opened for that phenomenon based on the desired length scale. Solution variants are then displayed, categorized by "solution principle" (note: this is not a TRIZ solution principle, and can be thought of more as an embodiment principle). Shown in the bottom section of Figure 1.8 is a portion of the catalog for (in)elastic deformation at the macroscale for the "fundamental structural element" "solution principle". The hypothesis is that this existing process is improved by modifying the first portion of the design repository to include the analogical tool of an analogy and the second portion of the tool (specifically the length scale partitions) is applied to TRIZ tools, specifically the TRIZ Technical Contradiction matrix Table A.6.

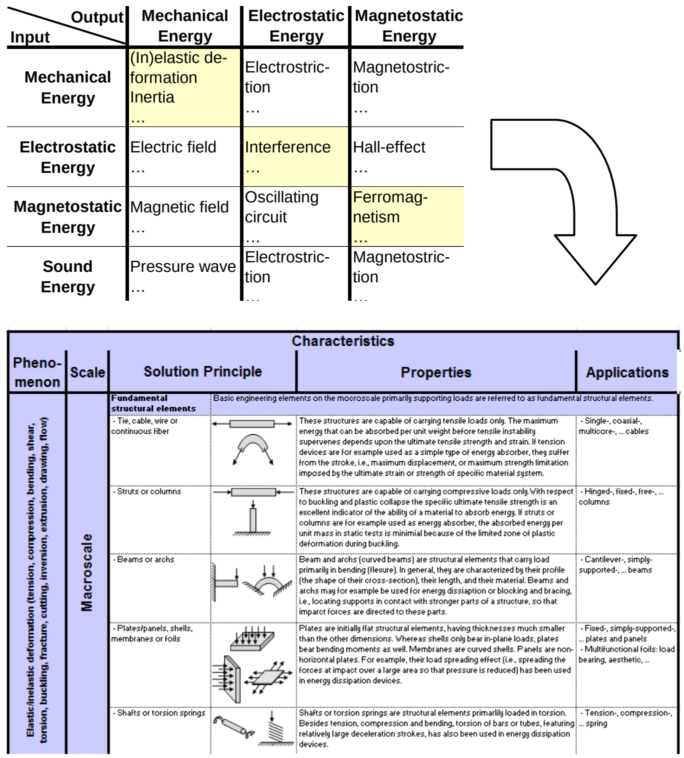


Figure 1.8: Design Repository [69]

1.2.3 Validation Strategy

A primary concern in any research effort is the validation and verification of the proposed approach and the achieved results. The validation and verification strategy for this research is based on the validation square introduced by Pedersen and coauthors [87, 99] and illustrated in Figure 1.9.

Pedersen and coauthors propose a framework for validating design methods in which the usefulness of a design method is associated with whether the method provides design solutions correctly (structural validity) and whether it provides correct design solutions (performance validity). This validation framework is called "validation square". In this framework, it is distinguished between four elements: theoretical and empirical structural validity as well as theoretical and empirical performance validity.

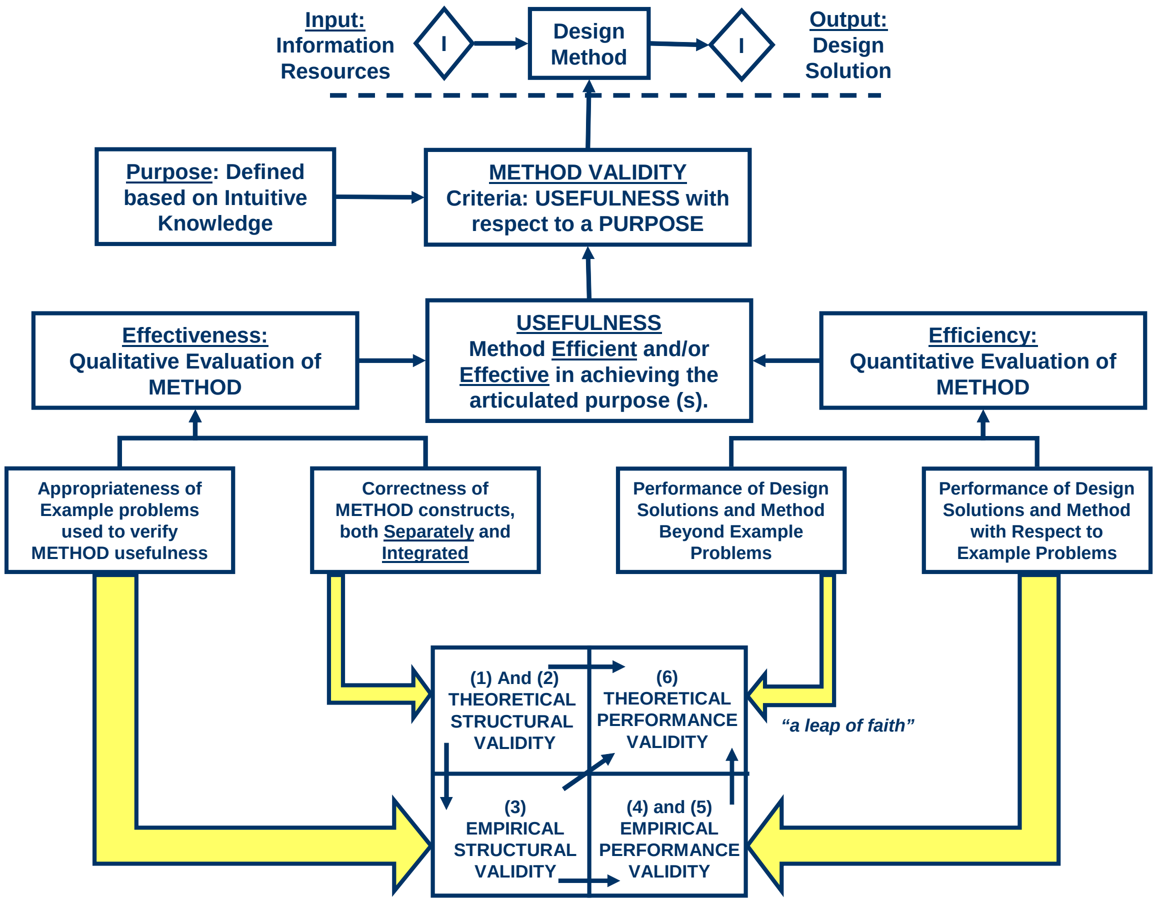


Figure 1.9: Validation square used to validate design method adapted from Seepersad et al. [99].

Theoretical structural validity involves accepting the individual constructs constituting a method as well as the internal consistency of the assembly of constructs to form an overall method. *Empirical structural validity* includes building confidence in the appropriateness of the example problems chosen for illustrating and verifying the performance of the design method. *Empirical performance validity* includes building confidence in the usefulness of a method using example problems and case studies. *Theoretical performance validity* involves building confidence in the generality of the method and accepting that the method is useful beyond the example problems. While theoretical validity can be established with an extensive literature review as well as careful mathematical and analytical reasoning, empirical validity requires appropriate example problems for illustrating and verifying the proposed design methods.

Specific tasks to verify and validate the hypotheses proposed in this research are summarized in Figure 1.10 and described in the following. Specific tasks for each research hypothesis are then mapped to specific actions and chapters in which they are addressed in.

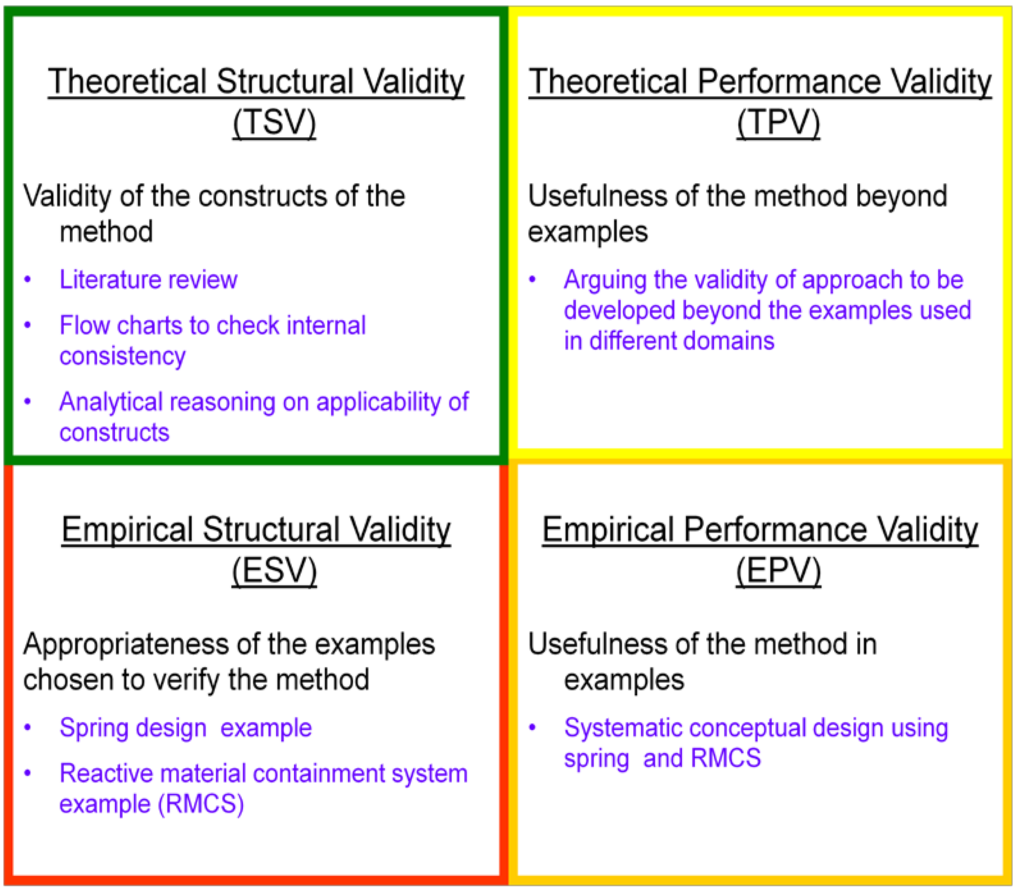


Figure 1.10: Overview of Validation Tasks

Task 1: Establish ***theoretical structural validity*** by *i)* searching and referencing the literature related to each of the constructs employed in the proposed systematic design approach, *ii)* conducting a gap analysis and exploring the advantages, disadvantages, and accepted domain of application, as well as *iii)* using flow charts as well as *iv)* reasoning for checking the internal consistency.

Task 2: Establish ***empirical structural validity*** by *i)* documenting that the reactive material containment system and optoelectronic communication system example problems are similar to the problems for which the constructs are generally accepted, *ii)* documenting that these example problems represent actual problems for which the design methodology is intended, and *iii)* documenting that the data associated with these example problems can be used to support a conclusion.

Task 3: Establish ***empirical performance validity*** by using the representative example problem to evaluate the outcome of the proposed design methodology in terms of its usefulness. Empirical validity will be established through design of the reactive material containment system.

Results obtained by applying the method to the reactive material containment system will be evaluated with respect to concept flexibility indicators. To accept that usefulness is linked to applying the method, usefulness will be evaluated by looking at the collective group of indicators. Having demonstrated utility of the systematic approach, the observed usefulness is linked to the constructs developed in this thesis and verified using results obtained from the examples scenarios.

Task 4: Establish ***theoretical performance validity*** by showing that the design methodology is useful beyond the reactive material containment system spring design example problem. This involves *i)* showing that the example problem is representative of a general class of problems and *ii)* strengthening confidence in the design methodology by generalizing findings. From success in tasks 1 to 3 and logic, the general usefulness of the method can be inferred. Although a case for generality may be made, every validation strategy ultimately relies on a "leap of faith" [87].

1.2.4 Road Map of Thesis

Figure 1.11 is a road map to the thesis in the context of validation, and how each of the chapters is related to the different aspects of validation. The logical and sequential order of the chapters is around the perimeter, following the bold arrows. The relation between each section and the validation square is shown with the arrows emanating from the validation square.

The context for the thesis is set in the first chapter by providing the motivation, frame of reference, research questions, and hypothesis. These are necessary to logically introduce the next three chapters where the constructs (Chapter 2), structure (Chapter 3), and additional components (Chapter 4) are described.

Theoretical Structural Validation is carried out with a thorough description of the TRIZ method and the Pahl & Beitz method (which together form the foundation for this work), as well as the constructs to be included to deal with multi-scale materials design (Chapter 2-literature review). Following the literature review section is Chapter 3, containing a presentation of the step-by-step method with augmentations and an implementation flow-chart for this approach, further explained with the use of a spring design example. In this illustrative example, a spring designed using each of the individual constructs of the method.. This is part of Theoretical Structural Validity because it serves to help communicate the method more effectively. Chapter 4 is a presentation of the details to the design tools utilized in the method. In Chapter 3, these tools are treated more as 'black boxes' and through this chapter all of the inner workings and developments are explained.

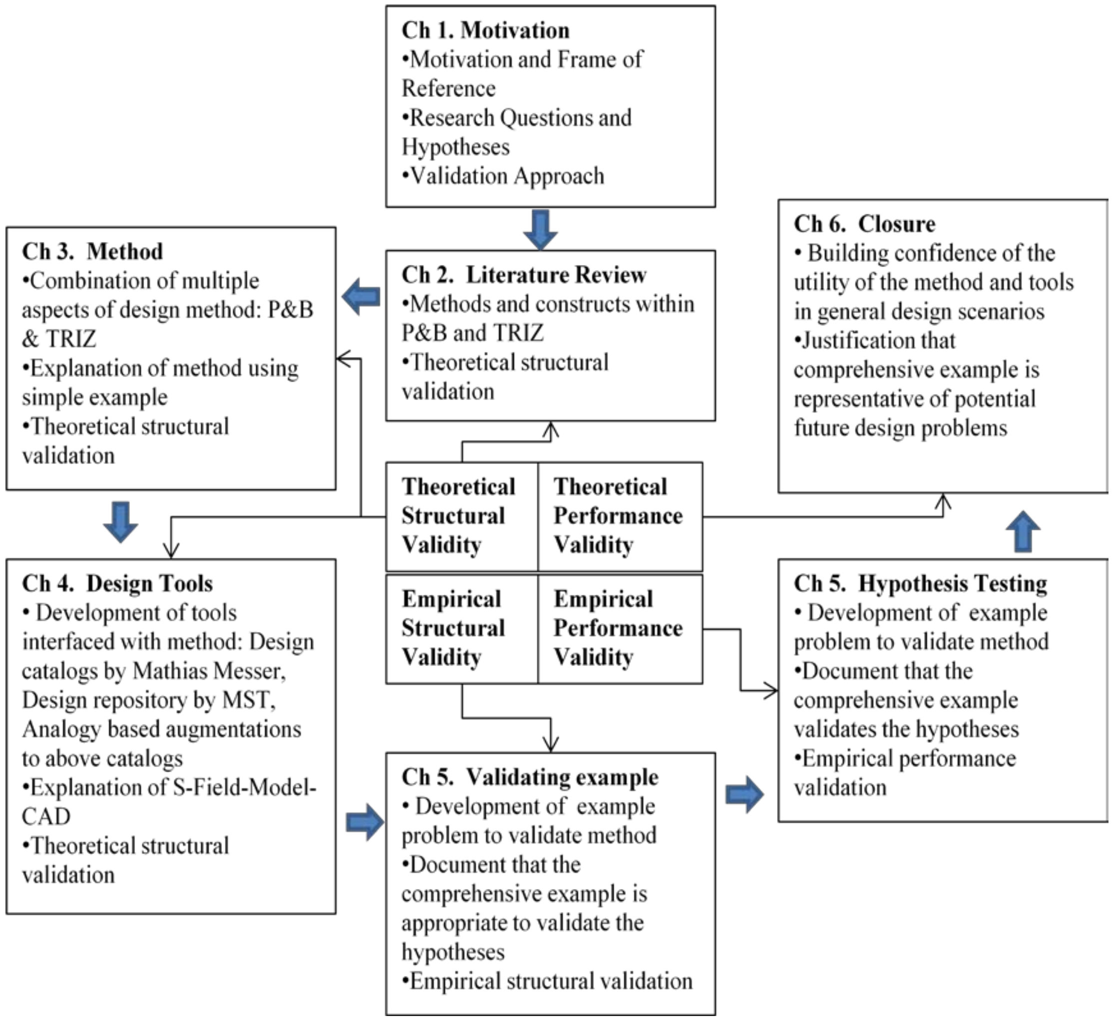


Figure 1.11: Roadmap of Thesis

Presented in Chapter 5 is the development of the example used for validation, or the Empirical Structural Validity. For Empirical Structural Validation, Section 0- 5.2 and Section 5.4.1, the appropriateness of the spring design example as well as a blast resistant panel example used in Empirical Performance Validation, Section 5.3 and Section 5.4.2, is substantiated by showing that the method is relevant to the examples, the examples are representative of actual problems and the examples can support the hypotheses. In this example, a blast resistant panel is designed with more design parameters and considerations than the simple spring example. An example with a complex nature is needed to show that the problem can be used to exercise the details of the method that only become applicable when complexity in the problem is introduced and to show the depth of possible solutions.

Within the constructs of Empirical Validation, the end purpose through the usage of a blast resistant panel is to test the hypotheses. There are three hypotheses that correspond to the different aspects of the method that are tested. Testing within Empirical Performance Validation, a complex example (blast resistant panel) is designed with more design parameters and considerations than the spring example to build confidence in the usefulness of the method and thereby validate the hypotheses.

Table 1.2 below is used to explain which sections of the example are appropriate to validating which hypothesis (ESV) by explaining how they will be validated (EPV).

Table 1.2: Hypothesis Validation.

Chapter 5- Design of a blast resistant panel	H1a- supplementing materials selection with materials design to integrate product and material concept generation	Demonstrate material concept generation along side of product concept generation, by showing the outcomes of the method having both.
	H1b - experiential knowledge based problem solving and solution triggering tools to create a systematic and domain-independent method	Demonstrate that the use of the problem solving tools is independent from the domain by applying them to the multiple domains within the blast panel example.
	H2 - problem formulations and solution triggers developed for use in the TRIZ methodology can also be integrated into function based design for multi-scale materials by allowing TRIZ problem modeling (Su-Field models with systems conflicts) to be developed alongside function structures (with the potentially improved performance by using a CAD type software)	Show the use of problem formulations borrowed from TRIZ on the blast panel in conjunction with standard P&B problem formulations, improving the outcome possible in either individually, by having improved outcomes.
	H3 - Mapping pre-existing abstracted problem formulations and solution trigger mappings (TRIZ Matrix) to functions and length scales. Also, analogical techniques found in TRIZ used for the structure of augmentations to a design catalog, utilizing the conflict as the common interface.	Show the solutions from the design repositories (both the length scale considerations for the TRIZ matrix, and the analogical use of conflicts in determining the solution route) for the blast panel.

The previous three steps in the Validation Square are intended to provide sufficient evidence to build confidence in the extension of the proposed method to other similar example problems. Based on the internal consistency of the proposed method, the degree to which the selected example problems adequately address the hypotheses tested, and the effective implementation of the proposed method in solving the example problems to show the validity in the claims of the hypotheses tested, one can judge it reasonable that applying the proposed method to similar example problems will produce practical and desirable results.

1.2.5 Contribution

The main contribution is the development of a systematic approach with an integrated conceptual design of products and materials by facilitating the transfer of problem formulations and solution principles in these multi-domain systems. This multi-domain approach is based on the understanding of the phenomena and associated solution principles at multiple levels and scales. This understanding built into a systematic approach includes the following key contributions:

1) A new relation between problem formulation and corresponding solution triggers and materials structure property relations and their classification in length scale specific design repositories, to facilitate conceptual design of materials in a systematic function based way. TRIZ focuses on the design conflict and builds analogies from that, and the intent here is to position TRIZ in the broader (i.e., Pahl and Beitz) function based design process.

2) Structure for a repository that contains expert design knowledge as well as problem formulation and tools.

Relevant Sections:	**Chapter 2**				**Chapter 3**			**Chapter 4**			
Exploratory Questions	2.1	2.2	2.3	2.4	3.1	3.2	3.3	4.1	4.2	4.3	4.4
RQ1 How can a designer generate concepts in materials design that supplement concepts in product design to fulfill the design goals of innovative products?								x	x		
Validation Prompt: In what capacity are the rewards and outcomes of the method beneficial and justifiable? Is a sufficient outcome achieved? (Empirical Performance Validity)								x	x		
Validation Prompt: How is the implementation of this approach justifiable? How do the steps and tools fit together? (Theoretical Structural Validity)	x	x					x				
RQ2 How should solution principles and problem formulations used in the past mostly for the mechanics domain be integrated into the function based design method to be applicable to multi-scale materials design?							x		x		
RQ3 How should function structures and problem formulations be connected to solution triggers at the appropriate length scales for materials design?						x	x		x		

CHAPTER 2

FOUNDATIONS AND CONSTRUCTS FOR FUNCTION BASED DESIGN OF INNOVATIVE MATERIALS WITH STRUCTURES-LITERATURE REVIEW

Discussed in this chapter are the constructs from which the design method is built: Design of Systems, Design of Materials, Flexibility in Design, Technical Conflict Resolution, and Physical Conflict Resolution. The purpose of this section is to allow the reader to become acquainted with the state of the art in terms of P&B and TRIZ. The emphasis is on presenting the constructs used in the following chapters, but also to show the gaps in each, and their need for each other. In relation to the Validation Prompt, "How is the implementation of this approach justifiable? How do the steps and tools fit together?", the emphasis is placed on showing the gaps that will be filled by connecting certain aspects together from each of the constructs. Also, in light of the question, gaps will be shown where there is a disconnect between what is required, and what the structure needs, pointing to the elements that will be used to fill those gaps. The relevant section titles and the status of each section are as follows.

2.1 THEORETICAL FOUNDATIONS USED IN THESIS

This and the next section (2.1-2.2) have been leveraged and modified from Matthias Messer's Ph.D. dissertation [69].

2.1.1 Design of Systems

Systems design refers to the design of functionally related, interdependent subsystems within a system boundary forming a complex system interacting with its environment by means of inputs and outputs *(here, "complex" refers to interconnected and interwoven system parts and disciplines).* In other words, a system can be divided into sub-systems and possesses the properties of all the subsystems and components plus other properties that the subsystems do not possess individually, as observed by Mistree [71].

Systems theory as an interdisciplinary science uses special methods, procedures and aids for the analysis, planning, selection and optimization of complex systems as described in the literature [12, 13, 16, 20, 21, 25, 32, 86, 116]. For complex engineering systems, however, the requirements for the entire system, including subsystem requirements, cannot be transformed in a single stage to detailed system and subsystem specifications.

The traditional industrial approach for designing complex engineering systems by simply transforming in multiple successive stages, termed requirements flowdown, or even a more advanced requirements flowdown and feedback approach [55] break down due to *i)* the number of variables and responses, *ii)* discipline expertise with computational expense, and *iii)* multiple objectives with uncertainty. But, more sophisticated optimization techniques have been developed to identify “optimal” combinations more effectively and efficiently at each transformation level.

In each case iteration between levels of transformation detail is still necessary. However, with the increase in computational capabilities and the development of methodologies for composing component simulation models together to develop overall system simulations, it is now progressively possible to evaluate the emergent behavior of complete systems. These capabilities have elevated the role of simulation in design from mere component failure analysis and parametric optimization to systems design and given rise to the field of simulation-based design.

Designing complex engineering systems, design optimization is now a mainstream discipline and a natural extension of the ever-increasing analytical capabilities of computer-aided engineering. Supply-chain management and other business factors are placing increased emphasis on a “systems” approach to product life cycle design. Addressing the “system” problem, trends and challenges in system design optimization have been reviewed by Paplambros and Michelena [84]. Also, Multidisciplinary Design Optimization (MDO) is an expanding field that has many wide ranging applications in system design optimization. Design problems having a number of disciplines that may exhibit non-linear dependencies on each other can be difficult to deal with using traditional optimization methods. Strategies such as sequential optimization are not able to produce the true system optimum as they do not properly take into account the discipline interactions. Only by considering these interactions during the optimization process can the true optimum of a coupled system be determined.

The problem of size and discipline expertise usually precludes the integration of system and multiple subsystem models into a single design problem. Hence, systems must be partitioned or decomposed readily for distributed design. Since complex engineering systems are not only composed of multiple subsystems, but are also multidisciplinary in nature, the partitioning or decomposition of a system can thus follow either the physical structure of the system (subsystem/component definitions) or the disciplines involved in designing the system. These approaches (physical partitioning versus discipline based decomposition) define informal (intuitive or heuristic) and formal techniques respectively. Many studies have been devoted to the decomposition of large systems and optimization problems, and many approaches for performing decomposition exist; an excellent review of hierarchical decomposition is presented by Koch [55].

Informal, physical structure based, natural system partitioning approaches are accepted over more formal approaches for mathematical decomposition in this thesis, simply because for most well-defined complex systems, the system partitioning and links between system and subsystem levels are already defined. For more complicated (less well-defined) complex systems, partitioning can be very difficult. But, then, more formal decomposition techniques can be selected from the literature to aid in partitioning the problem. However, dealing with complex engineering systems and specialized materials design, the following characteristics cause simple optimization approaches (such as requirements flowdown) to break down: *i)* the number of variables and responses, *ii)* discipline expertise with computational expense, and *iii)* multiple objectives with uncertainty. But, more sophisticated optimization techniques have been developed to identify “optimal” combinations more effectively and efficiently at each transformation level as described below in the context of design process flexibility.

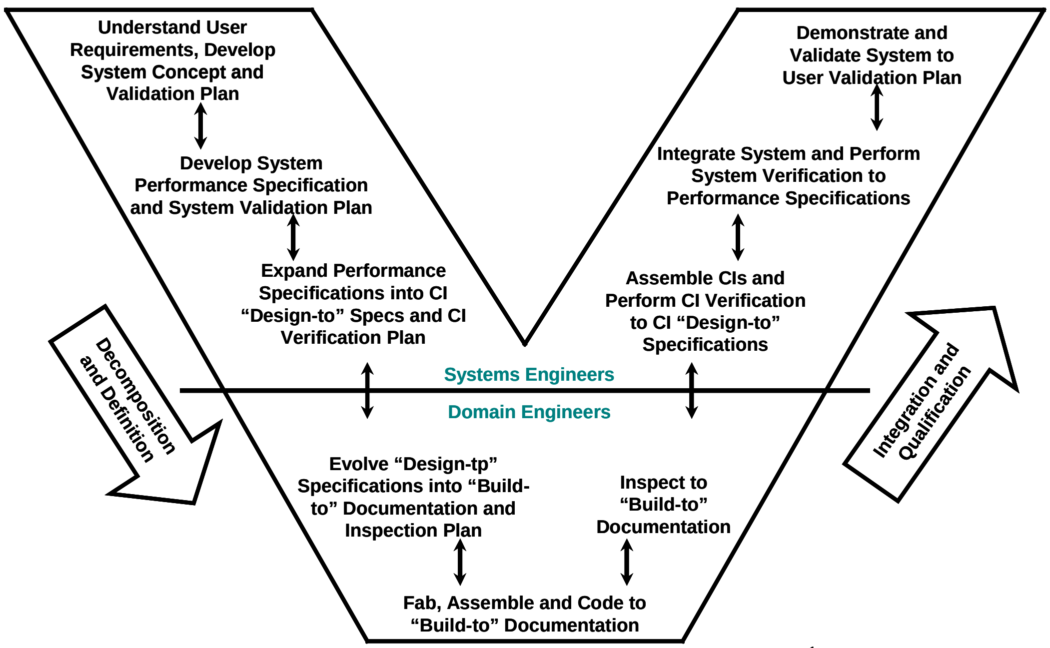


Figure 2.1: Systems Engineering “Vee” Model [41][1]

With respect to concept flexibility, the systematic approach to integrated conceptual materials and product design used in this thesis builds on existing systems engineering methodologies, such as the systems engineering “Vee” model after Forsberg and Mooz [41] shown in Figure 2.1. Especially the left or decomposition side of the “Vee” coincides with the early conceptual design phases, i.e., the definition of the system

[1] CI stands for configuration item.

requirements and specifications at the beginning of the system's life cycle. In the context of the materials and product system, principal solution alternatives including system specification and material properties developed in the conceptual phase are handed off to the domain engineers, such as material designers and scientists, as shown at the base of the "Vee". After individual physical components and multi-scale models are developed, responsibility then passes back to designers and system engineers, focusing on integration and qualification of the product and material system.

Systems designers must solve the most promising design process chain finding the solution that meets system-level objectives best. Thus, the focus of systems design is on:

- generating concepts, during which the majority of costs is committed, as illustrated in Figure 2.2,

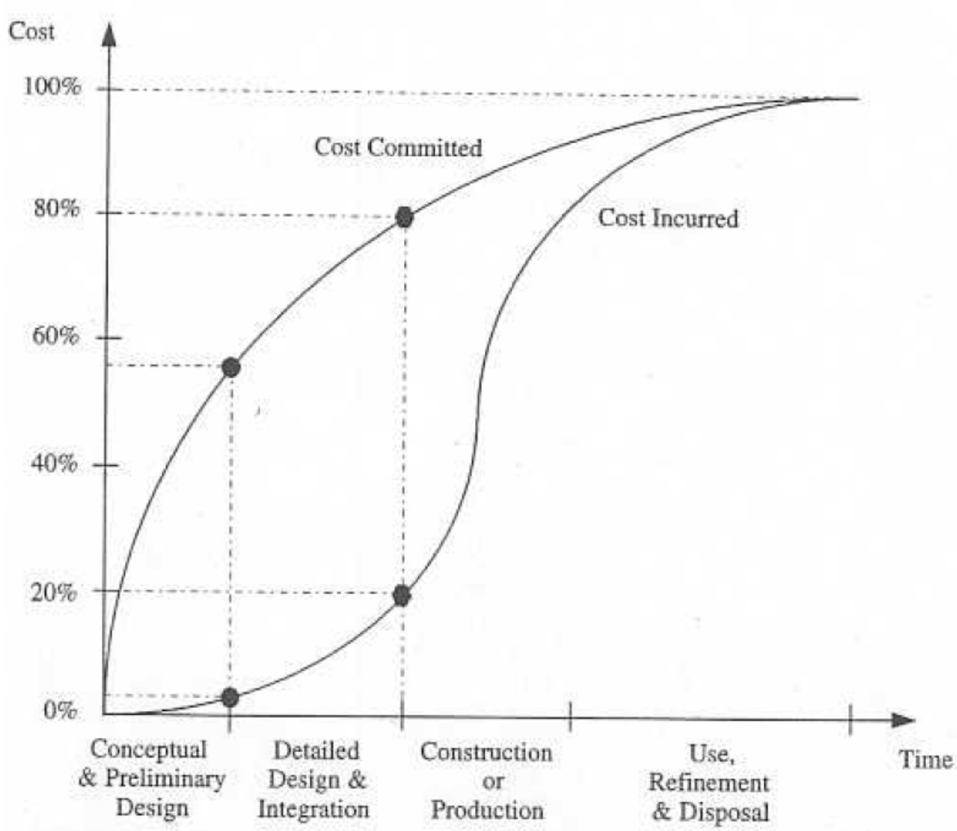


Figure 2.2: Cost commitment and incursion in a system life cycle [116].

- evaluating and selecting a satisficing principal solution and associated embodiment design-process alternative and framing subproblems, and
- combining solutions to various subproblems into compatible system-level solutions that meet performance requirements as closely as possible in the later embodiment and detail design phases as well during a system's operation.

Increasing a designer's concept flexibility through designing and exploring material concepts along with product concepts in a systematic integrated fashion from a systems perspective in order to facility concept generation has not yet been addressed in systems design, and is therefore an important topic of investigation.

2.1.2 Design of Materials

Besides the development of advanced methodologies for material selection [7, 8], a paradigm shift towards the design of materials has begun. The objective in materials design is to tailor the chemical composition, constituent phases, microstructure and processing paths to i) obtain materials with desired properties for particular applications and thereby ii) satisfy multiple performance requirements on the system level, subject to dynamic changes and constraints on certain materials properties such as density, strength, conductivity, etc. [26, 66, 75, 83, 96, 97]. Most existing approaches for materials design are focused on recently developed multi-scale modeling techniques that allow rapidly and accurately analyzing materials process-structure-property relationships [14, 26, 83]. So far, however, materials design is mostly leveraged in the embodiment and detail design phase where resources to develop computational models of materials are available.

Traditionally design engineers and materials scientists have adopted very different approaches. Primarily, new materials have been developed with empirical, trial-and-error techniques prominent in the natural sciences that cause length time frame and expense of new materials development. With these techniques, a material is treated as a black box subjected to repeated experiments. Experimental results then populate materials databases. Since so far integration of design engineering and materials science in current practice is still mostly limited to the selection of appropriate materials from the finite set of available material databases, lead times for the development of new materials have remained unacceptably expensive and long relative to product development cycles for new products [66, 76]. Furthermore, even though the performance of many engineered products and systems is limited fundamentally by the properties of available, constituent materials, most product design methods are still based on the selection of an appropriate material from a finite set of available materials with experimentally determined properties, even though the performance of many engineered parts and systems is limited fundamentally by the properties of available, constituent materials.

Methods to select materials from a database of available options have been proposed by Ashby [8]. These methods can be classified as selection by analysis, synthesis, similarity or inspiration [7]. Materials selection methods are key mapping materials properties to materials performance or behavior. However, the inherent difficulty with materials selection is the inability to tailor a material for application-specific requirements or novel system concepts. Necessary combinations of properties might simply not be available from materials in current databases. Also, methods for conceptual design are not applied to the "material" level. However, since successful design is so closely linked with materials science, there are exciting possibilities generated by supplementing materials selection with materials design capabilities for synthesizing customized materials with specific performance characteristics.

Koller clustered materials that exhibit various mechanical, thermal, electrical, magnetical, aesthetic, optical, etc. properties in tables for selection [56]. Ashby on the other hand focused clustering in graphical form – "bubble charts" which virtually represent material groups and their properties [7, 8]. Also, Koller as well as Ashby reviewed and summarized properties of a variety of metals, alloys, composites, dispersions, ceramics, glasses, polymers – hence, they established a classification scheme by broad designations of material types. Alternative classification schemes are by the general composition or form, others by use, and still others by geometry.

The key to materials design is interplay of multi-scale modeling with human decision-making. Hence, materials design must begin with a set of performance requirements that map to materials properties. Then, using knowledge of structure-property relationships, it is advantageous to identify a finite set of candidate material concepts that are likely to possess these properties. As pointed out by Eberhart and Clougherty [36], this is most efficient when constructing structure-property relations on the quantum scale and then study these materials experimentally, thereby turning computational empiricism into true design. The focus in this work is to identify and classify structure-property relations on multiple length scales to facility the design of material concepts to be further investigated through systems-based embodiment materials design, in line with Smith's observation that structure is best considered as a hierarchy, with each of its levels characterized by a different length scale [105]. Process-structure relations refer more to materials development and hence are not further considered.

In this context, systems based materials design is an emerging multidisciplinary field in which both science-based tools and engineering systems design methods are utilized to tailor material structures and processing paths to achieve targeted properties, performance, and functionality for specific applications [66]. Therefore, multi-scale modeling techniques [122], integrating information generated by different simulation models at different length scales in a consistent manner so that the overall system behavior can be predicted from the individual constituent models [14], are utilized to design materials at multiple scales achieving performance that was not possible before.

Conceptually, materials design offers the potential to build “bottom-up”, i.e., creating materials and structures with no defects and with novel properties. Furthermore, constructing “bottom-up” is imagined to allow for self-assembly, in which the random (non-continuum) motion of atoms will result in their combination, or for self-replication, in which growth occurs through exponential doubling.

Materials design depends on phenomena that operate at multiple levels and scales, spanning from materials to system levels, from angstroms to meters and from picoseconds to years. Hence, a hierarchy of models must be applied to specific levels as well as length and time scales, from quantum mechanics, to molecular dynamics to continuum to reduced order, to component, to subsystem, to system models, etc. Each model is used to inform the formulation of other models on higher levels or scales that capture the collective behavior of lower level or scale subsystems. But it is very difficult to formulate even a single model for macroscopic material properties that unifies all of the length scales [66]. While developing physics-based models that embody relevant process-structure-property relations on different scales for diverse functions has its own challenges, the complexity and restricted domain of application of these models limit their explicit integration across the length and time scales. Hence, it is advantageous to link models rather than developing a single, rigidly connected model.

The objective of materials designers is to tailor the chemical composition, constituent phases, microstructure, and processing to obtain materials with desired properties for particular applications [18]. For example, Olson [75, 76] employs a systems approach for designing advanced steels with multilevel microstructures on quantum, nano, and micro length scales as illustrated in Figure 2.3. Materials design efforts rely on continuous development and improvement of predictive models and simulations on a various length scales, quantitative representations of structure, and effective archiving, management, and visualization of materials-related information and data. Together, these components provide important deductive links within a hierarchy of processing, structure, properties, and performance. Such deductive, analytical tools are necessary but not sufficient for materials design. As proposed by Olson [75], materials design is fundamentally an inductive, goal-oriented, activity, aimed at identifying material structures and processing paths that deliver required properties and satisfy performance requirements, as illustrated in Figure 2.3. Hence, the materials design challenge is to develop methods that employ bottom-up modeling and simulation, calibrated and validated by characterization and measurement to the extent possible, yet permit top-down exploration of the hierarchy of material scales [66].

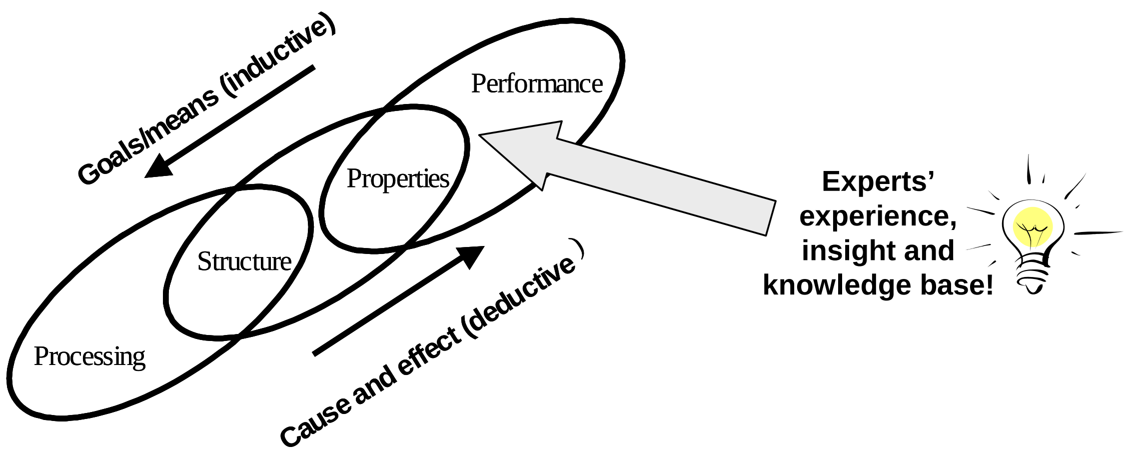


Figure 2.3: Olson's hierarchical framework of "Materials by Design" [75]

The inductive or deductive mappings that are necessary to support materials design according to Olson's hierarchy shown in Figure 2.3 specifically involve [66]:

- process-structure relations that are used to establish manufacturing constraints, cost factors, thermodynamic and kinetic feasibilities of process routes,
- structure-property relations between composition, phase and mesoscopic morphology and response functions or properties of relevance to desired performance attributes, and

- property-performance relations between properties and response functions and imposed performance requirements.

Olson's hierarchical design framework has been successfully applied to designing new classes of high performance ultrahigh-strength martensitic steels, semiconductor structures, gypsum, etc.

Aspects of how to get from performance requirements to a characteristic structure of a specific material concept however have so far been delegated to experts' experience, depth of insight and knowledge base as illustrated in Figure 2.3. Materials design approaches have focused so far on exploring one or two concepts based on expert intuition. Typically, these few principal solution alternatives are then scientifically analyzed and evaluated in the embodiment design phase to converge to a final design solution.

Examples of systematic design methodologies that make embodiment materials design less ad-hoc and intuitive while focusing on finding "satisficing" and robust solutions include the decision based design philosophy proposed by Mistree and co-authors [71] and the Robust Concept Exploration Method proposed by Chen [22, 23, 24], Seepersad [95, 98] and Choi [26, 27] and coauthors. Here, a material is viewed as a hierarchical system in its own right, with nanostructure and microstructure defining relation of structure to behavior at various length and time scales. This is required to address nonlinear, hierarchical nature of materials based on high performance computing and related simulation tools to provide a predictive foundation to support materials design. However, these *existing materials design approaches do not address the conceptual design phase* – the most crucial design stage in which decisions allocate the vast majority of a product's resources – in a systematic fashion.

Currently, the materials design community is focused on analysis – analysis meaning the prediction of achieved behavior [44]. Systematic and domain-independent design space exploration in the conceptual stage is however crucial. The early conceptual abstraction and synthesis part of design, i.e., generating concepts with characteristic properties of the structure based on given performance requirements or the expected behavior that the system should have in order to satisfy the functional requirements, is currently done in a more or less ad-hoc and intuitive fashion. However, exhaustive problem analysis must precede solution synthesis. But, synthesis in its general sense, i.e., the combining or mixing of ideas or things into new ideas or things, is currently not addressed methodically in materials design.

In design, synthesis, or in other words the association of elements to form a whole involving search and discovery as well as combination and composition [80], is crucial. In combination with abstraction, it is an integral part of every design process, especially in the early stages when designers focus on generating and selecting concept and thereby unrecoverably allocating most resources for the rest of the product life cycle. However, only relying on a designer's or design team's personal experiences during concept generation may result in the exclusion of a vast array of feasible concepts [62]. Also, as argued by Eberhart and Clougherty, synthesizing quantum scale structure-property relationships is key to materials design. Therefore, this thesis is built on a function-based and analogy linked approach for integrated design of material and product concepts in order to render conceptual design of materials, i.e., generation of feasible concepts, more systematic, i.e., less dependent on experts' experience, insight and intuition as illustrated in Figure 2.3.

2.2 METHODS AND TOOLS FOR CONCEPT GENERATION

A prominent area of research addressing a designer's flexibility in the conceptual and early embodiment design phases is focused on *concept flexibility* – in this thesis defined as the *ability to generate and select concepts, map their respective performance spaces as well as frame subproblems to allow response to dynamic demands at different points in a product's life cycle with ease*. The value of flexibility is obvious at the conceptual level. During the conceptual phase, the most crucial design stage in which decisions allocate the vast majority of a product's resources, system designers collaborating with expert designers need the flexibility to identify, frame and select the most promising solutions that balance system-level objectives depending on known or unknown dynamic demands. As has been shown in the car industry, applying set-based concurrent engineering and thereby emphasizing conceptual design efforts makes finding the best or better solutions more likely while keeping faster development cycles [106].

It is crucial to maintain concept flexibility, in other words being able to foster a number of concepts in response to known or unknown dynamic demands at the same time, as close to market introduction as possible when making conceptual design decisions. At the heart of concept flexibility is the ability to generate many concepts to realize functional relationships. It has often been said that working with a single concept is a recipe for disaster [89, 112]. Various approaches to achieve concept flexibility are reviewed in the following.

2.2.1 Systematic Function-Based Conceptual Design

It is difficult to determine the real origins of systematic design. Looking at the use of systematic variation of possible solutions, some authors trace it back to early master such as Pythagoras, Socrates, Archimedes or Leonardo da Vinci [77, 80], but, missing documentation prohibits a thorough analysis. In general though, up to the industrial era, designing was closely associated with arts and crafts. With the rise of mechanization then, principles of systematic design were increasingly developed and documented for widespread use. The historical background and current methods of systematic design methodologies are reviewed and summarized by Pahl and Beitz [80]. However, Redtenbacher and Reuleaux pioneered some of the earliest ideas on the principles of systematic design in the 1850s. The first step-by-step approach was developed Erkens in the 1920s. The concept of systematic design was stimulated in the 1950s and 1960s by Kesselring, Tschochner, Niemann, Matousek and Leyer – identifying the various phases and steps of the design process, and providing specific recommendations and guidelines for tackling them [114].

It is not possible to mention every researcher, but key contributions to systematic design were made by Hansen [46], Rodenacker [91], Roth [92], Koller [56], Erhenspiel [38] and Pahl and Beitz [114]. In an attempt to unify the diversity of existing function-based systematic design approaches and perspectives – such as the ones by Roth [92], Rodenacker [91], Koller [56] or Pahl and Beitz [81] – a generic approach to the function-based systematic design of technical systems and products, emphasizing the general applicability in the fields of mechanical, precision, control, software and process engineering, has been proposed by an "Association of German Engineers" committee (VDI guidelines 2221 and 2222).

However, systematic conceptual design has traditionally been linked to representing designs and engineering systems in terms of the functions they must fulfill. Functional relationships are usually combined in terms of energy, matter and information flows and enclosed by (sub-)system boundaries. One of the most well known function-based systematic design methodologies however is the one proposed by Pahl and Beitz for the mechanical engineering domain [80]. Pahl and Beitz propose a function-based systematic planning and design process for mechanical engineering (with reference to

VDI Guidelines 2221 and 2222), based on best practices from industry [80]. Pahl and Beitz divide the planning and design process into four main phases and propose main working steps for each of these phases, as described in detail in Chapter 3 for the conceptual design phase.

It has been shown that a systematic design methodology, involving strategically and tactically ordered successive steps of information transformations, supports designers to solve problems more efficiently and effectively than others [80], especially during conceptual design. Any systematic design method consists of one or several of the following general methods: analysis, abstraction, synthesis, method of persistent questions, method of negation, method of forward steps, methods of backward steps, method of factorization, method of systematic variation, division of labor and collaboration. From these general methods, functional decomposition, analysis, abstraction, synthesis and systematic variation are leveraged as core transformations for the function-based systematic approach presented to design product and material concepts in an integrated fashion in this thesis.

Function-based systematic design methodologies so far are based on conceptual product design followed by material selection in the embodiment design phase. Material selection in the embodiment design phase limits designers in that the potential embedded in materials design is not leveraged in the early stages of design. Conceptual design focus has so far been on design of various types of connections, guides and bearings, power generation and transmission, kinematics and mechanisms, gearboxes, safety technology, ergonomics, as well as production processes. However, considering phenomena and associated solution principles on multiple levels and scales from the materials domain when satisfying functional system requirements in the conceptual design phase, designers may overcome restrictions to product creation imposed by materials selection.

Also, systematic determination of system concepts that can be characterized by specific properties based on performance requirements, has not yet been exploited in materials design. Developing multilevel function structures, including the materials level, through functional analysis, abstraction and synthesis increases a designer's concept flexibility. Also, it supports clear definition of the interfaces in the integrated product and material system. This permits the definition of independent subproblems and their allocation to the individual disciplines and domain engineers involved. Within a function-based systematic approach, solutions can be systematically elaborated using several existing solution finding methods and tools, as reviewed in the following.

2.2.2 General Solution Finding Methods

Several solution finding methods have been proposed in the engineering, management, and education literature. Current state of the art methods are reviewed in the following. These methods are classified in:

- ***conventional methods*** (information gathering, analysis, synthesis, analogies, measurements, and model tests),
- ***intuitive methods*** (intuition, ideation cards, abstraction, brainstorming (method 635, gallery method), input/output technique, synectics (Gordon technique), lateral thinking, visual thinking, attribute listing, forced relationship technique, blockbusting, delphi method, and parameter analysis),
- ***discursive methods*** (method of persistent questions, checklisting, morphological thinking, method of negation (systematic doubting), method of forward steps (method of divergent thought), method of backward steps (method of convergent thought), method of factorization, method of systematic variation, systematic study of physical processes, systematic search with the help of classification schemes or design catalogs), and

- ***methods for combining solutions*** (systematic combination, combining with the help of mathematical methods).

<u>Conventional Methods</u>

Information Gathering

Information can be gathered from textbooks and technical publications, patent files, diverse websites and brochures published by competitors. A variety of tools are available for searching the many worldwide patent databases. Among these tools are the United States Patent and Trademark Office website (http://www.uspto.com), the European Patent Office website (http://ep.espacenet.com), and the Free Patents Online website (http://www.freepatentsonline.com). A number of software packages also exist for searching the various patent databases and providing an aid in understanding the complex relationships between patents. These include IPVisions, Aureka and PatentWeb, Public Web Examiner Search Tool. Literature search provides a most useful survey of known solution possibilities. Increasingly, this type of information is fed into computer databases and stored for future use. Real solutions can be found within the own or the competitor company, which may be altered through systematic variation. Furthermore, real solutions are found on the supplier market, in property rights, virtual marketplaces or virtual supply chains.

Analysis

Analysis is the resolution of anything complex into its elements and the study of these elements and of their interrelationships. It calls forth identification, definition, structuring and arrangement [81]. It calls for identification, definition, structuring and arrangement through which the acquired information is transformed into knowledge. Analysis is the prediction of achieved behavior, i.e., a set of physical properties achieved by the proposed design solution, from the structure which represents the artifact’s physical form [44].

Synthesis

Synthesis is the association of elements to form a whole involving search and discovery as well as combination and composition [81]. Synthesis involves coming up with the structure based on the expected behavior, i.e., in our context, the physical properties that the artifact should have, in order to satisfy the given requirements and performance goals based on the expected behavior described through idealized functional relationships.

Analogies

In the search for solutions and in the analysis of system properties, it is often useful to substitute an analogous problem or system for the one under consideration, and to treat it as a model [81]. For example, representing analogies to increase the probability of innovation has been investigated by Linsey and coauthors [62]. Analysis of natural systems for example can lead to very useful and novel technical solutions, stimulating creativity of designers. Currently, the connections between biology and technology are investigated in great detail by bionics and biomechanics.

Also, analysis of existing artificial (man-made) systems, products or processes is one of the most important means of generating new or improved solution variants in a step-by-step manner. It may involve the mental or even physical dissection of finished products and is aimed at the discovery of related logical, physical and embodiment design features.

Measurements and Model Tests

Measurements on existing systems, model tests supported by similarity analysis and other experimental studies are among the most important sources of information in design [81].

<u>Intuitive Methods</u>

Intuitive solutions suddenly appear as conscious thoughts and often their origins cannot be traced. Initial intuitive solutions are usually developed, modified and amended, until such time as it leads to the most promising solution of the problem.

Intuition

Intuition has led to a large number of good and even excellent solutions. But, the right idea rarely comes at the right moment, cannot be elicited nor elaborated and strongly depends on individual talent and experience. The prerequisite is a very conscious and intensive involvement with the given problem.

Ideation Cards

Ideas are documented on special cards and filed for future use.

Abstraction

Through *abstraction*, complexity is reduced and essential problem characteristics are emphasized so that coincidental solution paths may be avoided and more generic (non-intuitive) solutions may be found [81]. In other words, compared to an intuitive and ad-hoc solution finding process, designers may find better solutions containing the identified characteristics through abstraction.

Brainstorming

Brainstorming, initially proposed by Osborn [78], is a systematic, group-oriented technique for deliberately producing and developing a large number of ideas. In brainstorming, the quantity as opposed to the quality of ideas is emphasized. Important Brainstorming Spin-offs are the Method 635 (form group of about six; identify ideation task; participants write down three solution keywords; keywords are passed to neighbor, who records three further solutions or developments; ideas are passed again, a total of five times), the gallery method (form a group; identify ideation task; individuals sketch solutions for 15 minutes; group review sketches for 15 minutes; individuals further develop and refine ideas; group finalizes ideas and selects promising ones) and collaborative sketching (in which designers work on developing graphical representations of solutions to a design problem).

Input/Output Technique

The input/output technique [60] is the foundation for functional analysis, a staple of Value Engineering. After abstracting the essential elements (e.g. components, tasks, processes, …), the input and output flows that logically connect such elements are identified.

Synectics (Gordon Technique)

Synectics, as proposed by Gordon [45], is an operational theory of creativity. Two guiding principles, “making the familiar strange” and “making the strange familiar”, are respectively implemented through analogy and metaphorical analysis. In essence, Synectics is comparable to Brainstorming with the difference that its aim is to trigger off fruitful ideas with the help of analogies form nontechnical or semi-technical fields.

Lateral Thinking

Lateral Thinking, coined by DeBono [34], is founded on the principle that changing established information patterns generates creative ideas. It is implemented with a variety of tools, including “Plus-Minus-Interesting”, “Six Thinking Hats”, or random stimuli. These tools force individuals to change their limited, rigid perceptions and restructure information patterns anew.

Visual Thinking

The significant role of imagery in human thinking processes is emphasized by Visual Thinking as proposed by McKim [68]. It is carried out by interactions among perceiving visual stimuli, dreaming up visual images and sketching, doodling, painting, … . The interplay among such imagery provides a powerful technique for thinking.

Attribute Listing

Attribute-Listing, developed by Crawford [31], is a creative technique involving the attributes, i.e. descriptive qualities or characteristics, of concepts. Novel ideas are generated by altering attributes through modification, substitution and application elsewhere.

Forced Relationship Technique

Forcing relationships between normally unrelated things and ideas is the prescription for creativity in the so-called Forced Relationship Techniques [110]. By superimposing two or more different ideas that have no apparent connection, new and original associations can be generated.

Blockbusting

"Blockbusting" adopts a completely different approach to creativity, namely breaking habits and removing barriers that inhibit creative thinking. Conceptual blocks are "mental walls that block the problem-solver from correctly perceiving a problem or conceiving its solution" [4]. Such blocks are of the following types: perceptual, cultural, emotional, intellectual, cultural, expressive and environmental.

Delphi Method

In the Delphi method, as proposed by Dalkey and Helmer [33], experts in a particular field are asked for written opinions. The elaborate procedure consists of many rounds and must be planned very carefully. It is usually confined to general problems bearing on fundamental questions or on company policy. In the field of engineering design, the Delphi method should be reserved for fundamental studies of long-term developments.

Parameter Analysis

Parameter analysis [61] involves analyzing variables to determine their relative importance. The most important variables become the focus of the investigation, with other variables being set aside. After the primary issues have been identified, the relationships between the parameters that describe the underlying issues are examines. Through an evaluation of the parameters and relationships, one or more solutions are developed.

Combination of Methods

Any one of these methods taken by itself may not lead to the required goal. The different methods should be combined so as best to meet particular cases. A pragmatic approach ensures the best results.

Discursive Methods

Discursive methods are procedures that tackle problems step by step. Steps are chosen intentionally, can be influenced and communicated. A problem is rarely tackled as a whole, but is first divided into manageable parts and then analyzed. Individual ideas or solution attempts are consciously analyzed, varied and combined. Discursive methods do not exclude intuition, which can make its influence felt during individual steps and in the solution of individual problems, but not in the direct implementation of the overall tasks. The additional use of systematic procedures can only serve to increase the output and inventiveness of talented designers. Any logical and systematic approach, however exacting, involves a measure of intuition that is an inkling of the overall solution. No real success is likely without intuition.

The Method of Persistent Questions

The basic idea is to ask questions as a stimulus to fresh thought and intuition. A standard list of questions also fosters the discursive method [81].

Checklisting

Checklisting [43] is a method by which creative thought is stimulated by a pre-existing list of suggestions or alternatives. Catalogs of existing ideas and entities serve as a comprehensive form of checklist.

Morphological Thinking

Morphological thinking is "the study of the totality of all possibilities inherent in any set of circumstances" [124]. This systematic approach to creative discovery is achieved by enumerating all parameters characterizing a subject and combining the parameters in new and different ways. This is facilitated through the use of a morphological matrix.

The Method of Negation (Systematic Doubting)

The method of deliberate negation starts from a known solution, splits it into individual parts or describes it by individual statements and negates these statements one by one or in groups [81].

The Method of Forward Steps (Method of Divergent Thought)

Starting from a first solution attempt, one follows as many paths as possible yielding further solutions. This method is not necessarily systematic. It frequently starts with an unsystematic divergence of ideas [81].

The Method of Backward Steps (Method of Convergent Thought)

The starting point for this method is the goal rather than the initial problem. Beginning with the final objectives of the development, one retraces all the possible paths that may have led up to it. Only such ideas are developed as converge on the ultimate goal [81].

The Method of Factorization

Factorization involves breaking down a complex interrelationship or system into manageable, less complex and more easily definable individual elements (factors) [81]. The overall problem is divided into separate sub-problems that are to a certain degree independent. Each of these sub-problems can initially be solved on its own, though the links between them in the overall structure must be kept in mind.

The Method of Systematic Variation

Once the required characteristics of the solution are known, it is possible, by systematic variation, to develop a more or less complete solution field [81]. This involves the construction of a generalized classification, i.e., a schematic representation of the various characteristics and possible solutions.

Systematic Study of Physical Processes

If the solution of a problem involves a known physical effect, and especially when several physical variables are involved, various solutions can be derived from the analysis of their interrelationships – that is, of the relationship between a dependent and an independent variable, all other quantities being kept constant [81].

Systematic Search with the Help of Classification Schemes

Systematic presentation of data is beneficial because *i)* it stimulates the search for further solutions in various directions, and *ii)* it facilitates the identification and combination of essential solutions characteristics [81]. The usual two dimensional classification scheme consists of rows and columns of parameters used as classifying criteria. The choice of classifying criteria or of their parameters is of crucial importance. Solution proposals are entered in the rows in random order. These proposals are analyzed in the light of the headings (characteristics) and classified in accordance with these headings. This procedure not only helps with the identification of compatible combinations, but more importantly, encourages the opening up of the widest possible solution fields. Classifying criteria and characteristics can be useful when searching systematically for solutions and varying solution ideas for technical systems.

Use of Design Catalogs

Design catalogues are collections of classified known and proven solutions to design problems and contain data of various types and solutions of distinct levels of embodiment [81, 92]. They should provide quicker, more problem-oriented access to solutions.

<u>Methods for Combining Solutions</u>

It is often useful to divide problems and functions into sub-problems and sub-functions and to solve these individually (factorization method). Once the solutions for sub-problems or sub-functions are available, they have to be combined in order to arrive at an overall solution. Problematic though is the selection of technically and economically favorable combinations of principles from the large field of theoretically possible combinations.

Systematic Combination

For the purpose of systematic combination, classification schemes or "morphological matrixes" [124], where sub-functions and associated solution principles are entered in the rows of the scheme, are particularly useful. For solution finding, solution principles are combined systematically into an overall solution [81]. Problematic with this method of combination is to decide which solution principles are compatible, that is, to narrow down the theoretically possible search field to the practically possible search field.

Combining With the Help of Mathematical Methods

In principle, the combination of subsolutions into an overall solution with the help of mathematical methods depends on the knowledge of the characteristics or properties of the subsolutions that are expected to correspond with the relevant properties of the neighboring subsolutions [81]. These properties must be unambiguous and quantifiable. Hence, this method should only be used in the later stages of design if real advantages can be expected.

2.3 INTRODUCTION TO TRIZ

Before discussing the technical components of TRIZ, the individual tools, the interrelationships of them, or the benefits and drawbacks, it would be beneficial to explain what TRIZ is based on, why it was developed and what it is for. As the title of essential book on the subject, “Creativity as an Exact Science” suggests, efforts in TRIZ are directed at looking at design and creativity as a science, and as such pulls in elements from many fields of science. Knowledge is combined from cognitive science, psychology, natural science (effects and phenomena), philosophy (idealism), technology and business, among others. As a science, TRIZ can be seen as an answer to the study of determining and categorizing all regular features and aspects of technical systems and processes that need to be invented or improved, including the invention process itself. It is also desired that the development of TRIZ tools would derive appropriate information from applied knowledge of the natural sciences and practical experience. All sciences pass through stages of development, specifically starting with a description of the phenomena, categorization, isolation and experimentation of phenomena, and quantification. Though a field can be called a science that has activity going on in the first of these stages, only quantification can lead to the field being deemed an exact science if it occurs with a degree of precision, repeatability and reasoning. So in this regard, TRIZ or any conceptual design activity or creativity, will probably never reach the stage of an exact science, and Altshuller was somewhat over generous for using that term in the title his book. As a note, there is a trend for this sort of inflated or misplaced nomenclature in the literature dealing with TRIZ. For example, TRIZ stands for Theory of Inventive Problem Solving, and yet it isn’t a theory in the classical sense. Also, the system of organizing various TRIZ tool into a coherent process is ARIZ, or Algorithm for Inventive Problem solving, yet there is no *guarantee* that a designer will have a sufficient concept at the end of the activity, defying any notion one might have about the meaning of the word algorithm. So instead of calling it a science, it is a methodology, and consequently fits in with the other methods used in this work, chiefly the Systematic Approach of Pahl and Beitz.

2.3.1 Definition of TRIZ

"*TRIZ is a human-oriented knowledge-based systematic methodology of inventive problem solving.* "[94]

Breaking this definition into its key components:

Knowledge — TRIZ can be defined as a knowledge-based approach because the knowledge about the generic problem-solving heuristics (i.e., rules for making steps during problem solving) is extracted from a vast number of patents worldwide in different engineering fields and it makes use of knowledge of effect in science and engineering.

Human-oriented — Tools are designed for use by humans, not an automated process. The TRIZ practice is based on dividing a system into subsystems, distinguishing the useful and harmful functions of the system, and so on. Such operations are arbitrary, because they depend on the problem itself and on the context of the problem, so they cannot be performed by a computer. Computers are well equipped to perform repeated tasks, but not solve problems that are encountered only once, which is the case with conceptual design.

Systematic — Systematic refers to step-by-step process of analysis and synthesis. The goal is to work from qualitative to quantitative through a number of iterative loops, with each iteration occurring continuously within and between steps. A systematic approach does not rely on chance, integrates a designer's intuition, gives standardization to design, is adaptable, reduces iteration while keeping its benefits by guiding it in small loops and integrates with other systematic processes.

Inventive problems and solving – TRIZ makes use of abstractions for solving inventive problems. These types of problems usually contain contradictory requirements for the system, conflicting system states, or other non-ideal behavior. Solutions typically proceed by temporarily replacing the unknown desirable solution with an imaginary ideal solution and then searching for the ideal solution from resources in the environment or from inside the system itself. In this way, TRIZ makes use of contradiction, resources, ideal solution, and technical system evolution.

2.3.2 Principal TRIZ Tools

The most attractive aspect of TRIZ is the generalization built into the tools. This allows for there to be a relatively small number of tools that can be applied to a wide variety of domains. Presented below are these key tools used in TRIZ:

The Contradiction Matrix consists of technical contradictions between the characteristics to be improved and the characteristics that can be adversely affected. It relates these contradictions to a few inventive principles in each cell that may help resolve the contradictions. This can be found in the Appendix, Table A.6 .

Separations Principles help resolve the general physical contradictions between the opposite characteristics of a single subsystem.

Substance-Field (Su-Field)Analysis is a modeling approach based on a symbolic language that can record transformations of technical systems and technological processes.

The Standard Approaches to Inventive Problems (Standards, for short) is based on the observation that many inventive technical problems from various fields of engineering are solved by the same generic approaches. The Standards contain typical (from the TRIZ standpoint) classes of inventive problems and typical recommendations on their solutions, which usually can be presented in the context of Su-Field Analysis.

Algorithm for Inventive Problem Solving (ARIZ in its Russian acronym) is a systematic set of logical procedures for eliminating the contradictions at the crux of a problem that ties the TRIZ tools together. Due to the unification aspect of ARIZ, it is considered one of the most powerful and important instruments of TRIZ. It includes the process of problem reformulation and reinterpretation until the precise definition is achieved, and the logical and disciplined process of solving the problem with iterative use of most of the TRIZ heuristics. It is very solution neutral and similar to the systematic approach of Pahl and Beitz in its structure.

The starting point of TRIZ was the notion that most design tasks share some essential similarities, and consequently TRIZ has grown to describe an expansive set of abstract problems and solutions that can be *Analogs* of the problem with a deferent context. These phenomena and analogs become effective to the designer in generating concepts by helping him transfer inventions from one domain to another. Therefore the most basic of all TRIZ tools is the analogy. This brings forth a fundamental assumption in all TRIZ tools, and that is they are designed to help the designer in his thinking, not used instead of thinking, because an analogy depends on thought.

2.4 WHAT HAS BEEN PRESENTED AND WHAT IS NEXT

The discussion presented in this chapter is an explanation of the elements and constructs that go into the first half of the Validation Quadrant 1 (Theoretical Structural Validity); presented in the next chapter is an explanation of the second half of Quadrant 1.

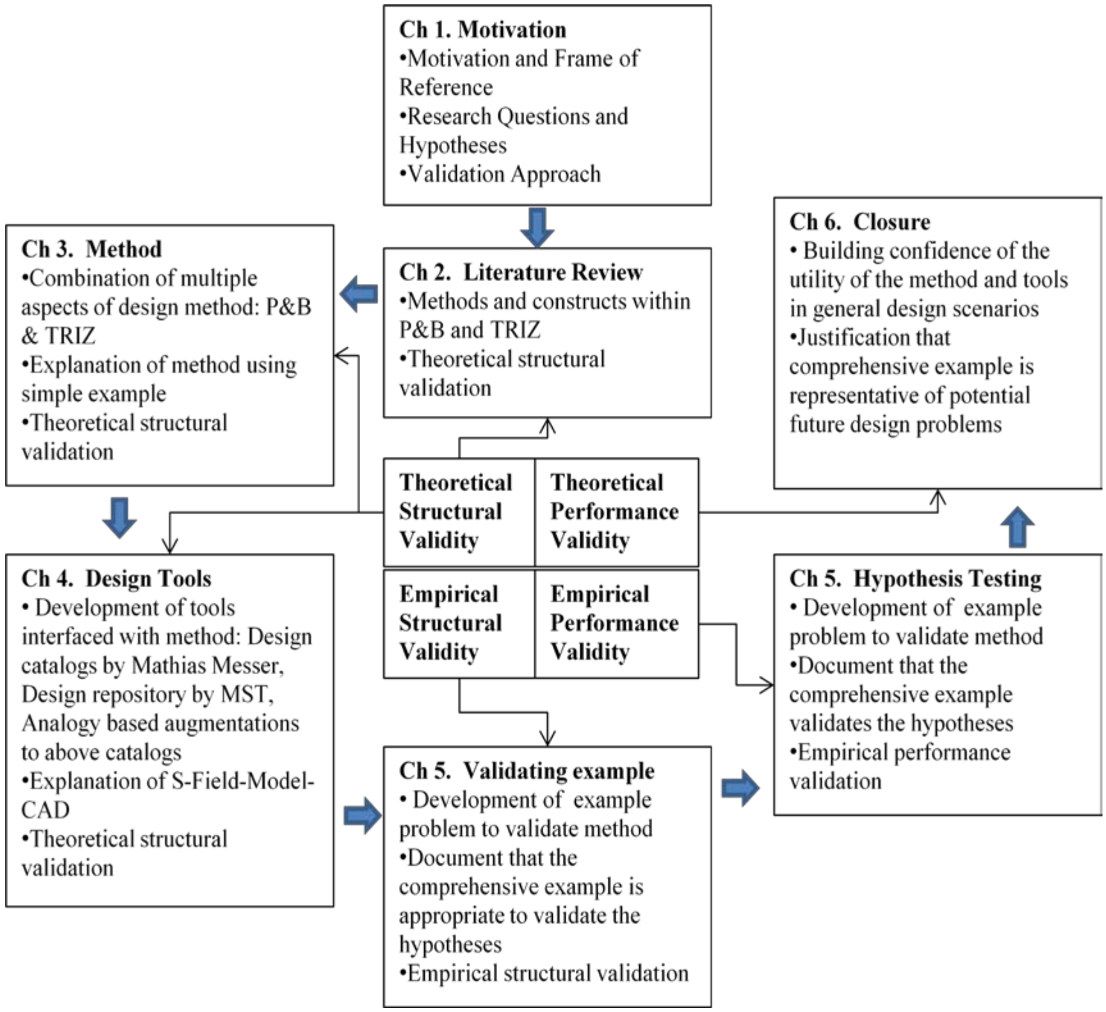


Figure 2.4: Thesis Road Map

CHAPTER 3

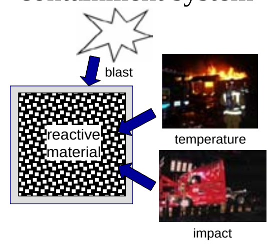
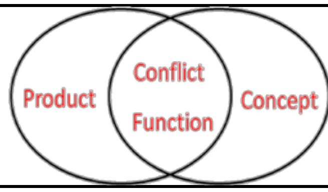
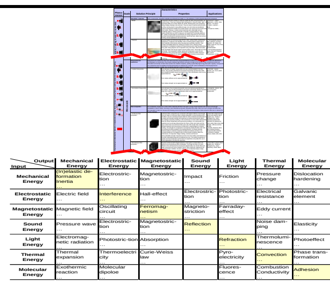
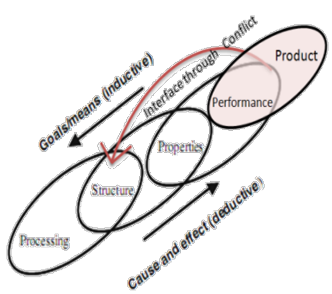
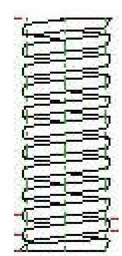
DEVELOPING THE MULTI-DOMAIN AUGMENTED PAHL AND BEITZ AND TRIZ METHOD

3.1 DESIGNING PRODUCTS AND MATERIALS CONCURRENTLY, SYSTEMATICALLY AND INNOVATIVELY

In this chapter, the Augmented Pahl & Beitz and TRIZ Conceptual Design (APTCD) method is developed and formulated by augmenting Pahl & Beitz with TRIZ, including the addition of other modifications. The requirements for the systematic approach addressed through the development of the method along with the broad level constructs used and developed to address these requirements are highlighted in Table 3.1. The corresponding hypothesis and validation examples are then shown on the right of Table 3.1 (next page).

This approach is formulated for products that are jointly considered at the material and product level. These types of problems are ones where a designer seeks to fulfill performance requirements placed on the product generally through both the product and the designed material. In this method, the systematic approach of Pahl and Beitz is used as the base method, and TRIZ is used as a means of transferring abstract information about the design problem between the domains with an aim of accelerating the conceptual design process. This approach also allows for cross design approach tools such as Su-Field-Model-CAD integration with design repositories to be used to transfer information at different levels of abstraction; expanding the design space and effectively directing the designer. The explanation of this approach is presented through a simple example of a spring design improvement. A reactive material containment system example is used in Chapter 5 to validate these components of the systematic approach. The APTCD method is used for answering Research Questions 1, 2 and 3, with an emphasis on Research Question 1.

Table 3.1: Constructs of the Systematic Approach to Address the Requirements and Validation Examples

Requirements	Constructs of the Systematic Approach	Hypothesis	Validation Examples
Broaden a designer's conceptual design space	Design catalogs, connecting materials design to product design, TRIZ	***R. H. 1:*** Systematic approach to the integrated design of product and material concepts from a systems perspective. Abstraction, synthesis, and systematic variation.	Reactive material containment system 
Integrating design of product and material concepts		***R. H. 2:*** TRIZ problem modeling (conflicts, Su-Fields) and ARIZ.	
Rendering conceptual design more systematic	Systematic multi-domain mappings	***R. H. 3:*** Systematic, function-based, conceptual materials design mappings	AND
Rendering conceptual materials design more domain-independent	 Design catalogs	***R. H. 1:*** Experiential knowledge based problem solving and solution triggering tools (TRIZ).	Spring Redesign
Accelerate conceptual design	Problem solving tools	***R. H. 2:*** TRIZ problem modeling (conflicts, Su-Fields) and ARIZ.	
Transfer design knowledge (underlying principles) from the product domain to the materials	 Analogy	***R. H. 2:*** The analogy tool helps transfer design knowledge by the use of the system conflict as the common interface.	

3.1.1 Frame of Reference

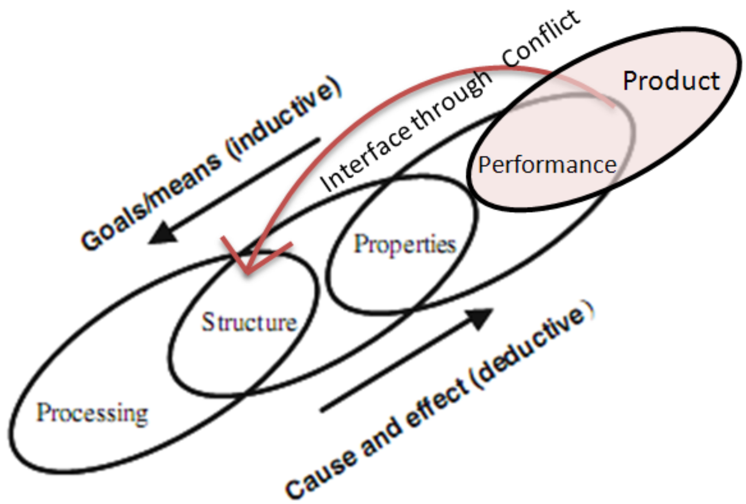


Figure 3.1: Olson's linear concept for 'Materials' Design'[75]—modified.

McDowell and Olson advocate that design should follow a top-down, concurrent design of materials and products model [67]. Subsequently, a process that brings forth the knowledge of how product requirements can be placed on materials by transferring the problem to that domain helps the development of technology. This is true if for no other reason than to direct how or in what aspect the material should be explored, but it also increases the possibility that functions and requirements might be fulfilled by the material. Therefore, in the concurrent conceptual design of a product and material, the transfer of relevant information between the material domain and the product domain is critical. Referring to Figure 3.1, this transfer of information happens along the curved arrow from Product/Performance (grayed oval) to material Structure. It is later shown that the driving mechanism for this transfer is the analogy tool of the conflict. The proposed approach consists of a function based design method that integrates the design of product and material concepts using structure-property relations at multiple length scales to drive the materials design with the aid of experiential knowledge-based problem solving and solution triggering tools. Two issues are investigated while developing this systematic approach.

The first issue is that of how a designer generates concepts for material design to create innovative products in supplement to the design goals of the product. This relates to:

i) the integration of product and material concept generation, and

ii) the rendering of a systematic and domain-independent method to support a wide range of products.

Addressing these two points for the first issue has two components:

a) The first component is supplementing materials selection with materials design in an effort to integrate product and material concept generation. This provides capabilities for synthesizing customized materials with specific performance characteristics by involving phenomena and associated solution principles on the multi-scale materials level (i.e., the multiple ovals found in Figure 3.1) to drive concept generation [70].

b) The second component is experiential knowledge based problem solving and solution triggering tools to create a systematic and domain-independent method (TRIZ). This allows a designer to better define problems and find solution principles (or things that trigger a solution in a designer's mind) that have worked in the past regardless of domain.

The second issue is that of how solution principles and problem formulations used in the past mostly for the mechanics domain should be integrated into the function based design method to be applicable to multi-scale materials design. This relates to problem solving and solution triggering tools (TRIZ) integration. Problem formulations and solution triggers developed for use in the TRIZ methodology can also be integrated into function based design for multi-scale materials by allowing TRIZ problem modeling (Su-

Field models with systems conflicts) to be developed simultaneously with function structures (with the potentially improved performance by using a CAD type software), and used to inform later design process steps. As mentioned, and illustrated earlier in Figure 3.1 with the curved arrow, the mechanism for transfer between the product and materials domain is an analogy tool, making use of the system conflict the chief common interface, and the various TRIZ tools to complete the analogy. To apply TRIZ in a systematic process, the Algorithm of Inventive Problem Solving (ARIZ) is used [6, 94]. ARIZ has been developed over a number of years, and is a detailed, sequential process that systematizes the individual TRIZ heuristics. In Figure 3.2 (next page), the systematic approach of Pahl and Beitz (2.a) [82], augmented with TRIZ in the form of ARIZ [65] (2.b), and function based design repositories (2.c) are represented.

These augmentations are structured in the form of core transformations to be compatible with the Pahl and Beitz process, where information processed results in specific new information and the augmentations work within the core transformations. Specifically, the core transformation of conceptual design in the Pahl and Beitz process, where the input is the Requirements List and the output is the Concept (or Principal Solution), is augmented with ARIZ by following the same core transformation, beginning with the problem (which can be in the form of a requirements list) and ending with the concept. In this augmentation, heuristics from both methods interact to produce a phase that is more comprehensive than the individual processes.

The proposed process is anchored in the four core phases of Pahl and Beitz: clarification of task, conceptual design, embodiment design, and detail design, where the primary area of concern for this work is the conceptual design phase. In Figure 3.3 a flow chart depicting the detailed clarification of task and conceptual design phase is shown.

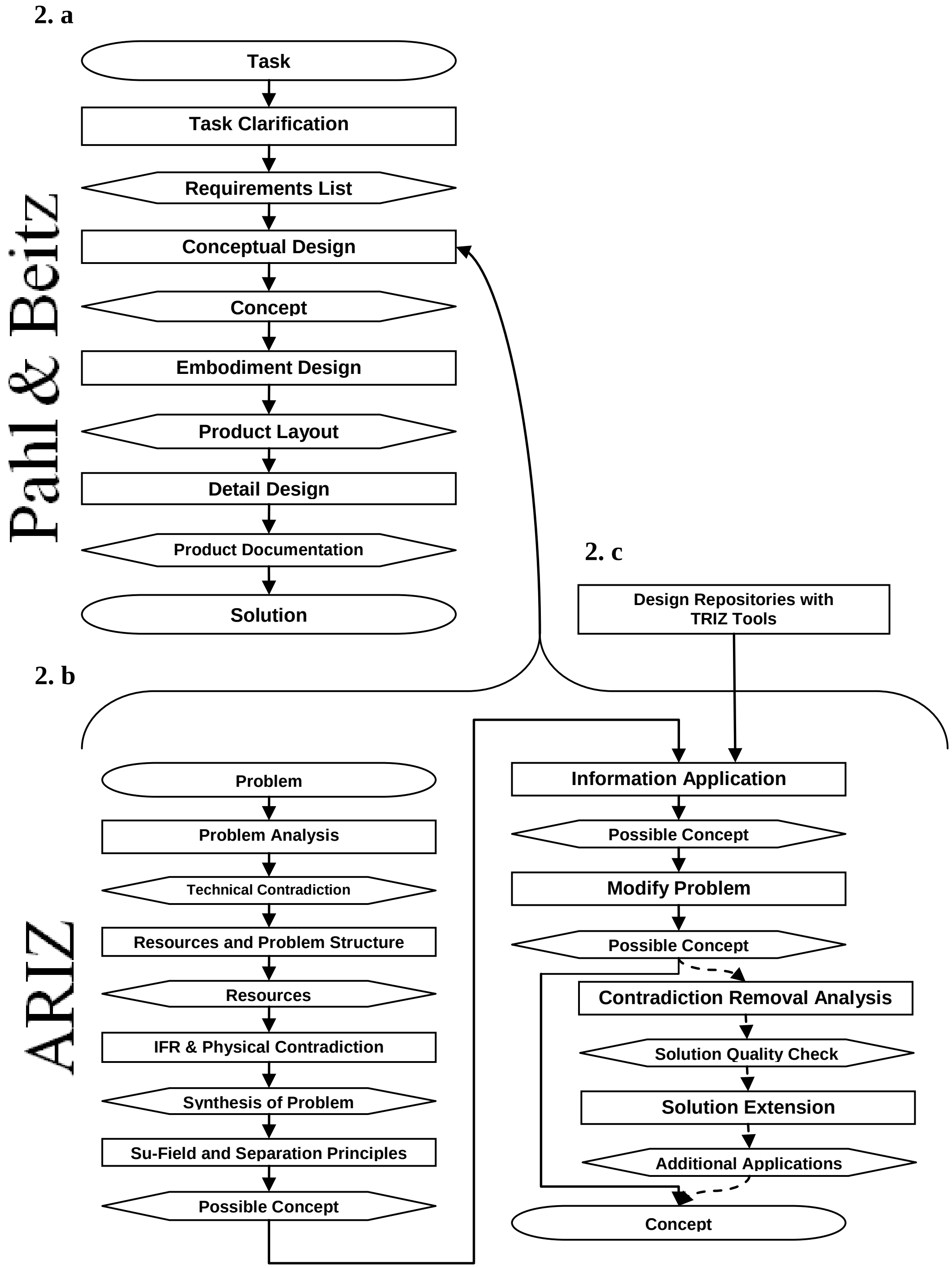


Figure 3.2: Augmentation of ARIZ (2.b) with modification (2.c), into the overall Pahl and Beitz process (2.a)

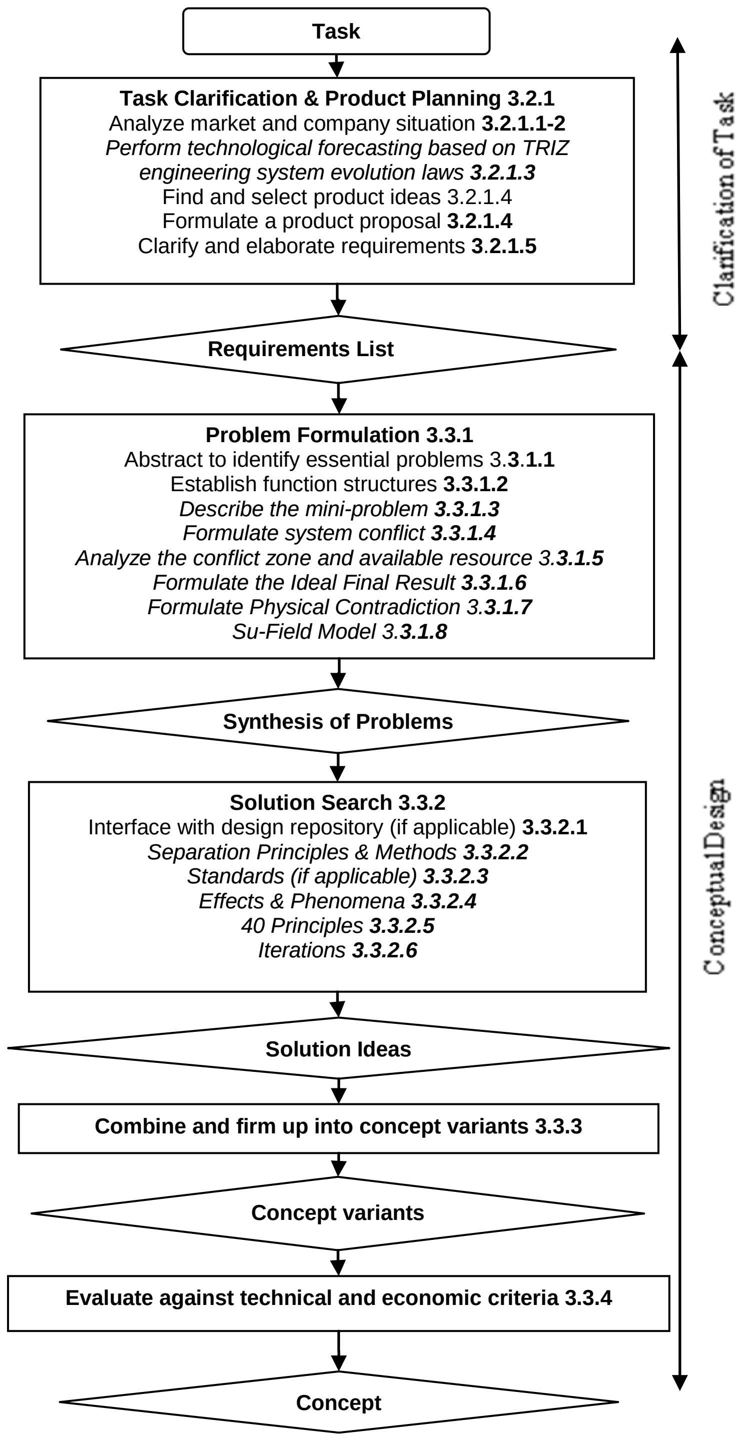


Figure 3.3: Augmented Pahl and Beitz systematic design approach and ARIZ conceptual design detail

3.1.2 Illustrative Design Problem to Explore Method

To demonstrate and explain the design process and tools used to satisfy the improvements needed, an example of the design of a spring is followed, as described below.

A spring is used to support a dynamic load with a certain input. The current helical compression spring made of 0.207 in diameter music wire (ASTM A228) with a spring index C=7 must be improved until a replacement spring can be acquired. The spring must be improved by providing an increased resistive force without overly changing the product line. It is assumed is that the spring currently gives a minimum force of 60 lb and a maximum force of 150 lb over a dynamic deflection of 1.00 in with a frequency of 1,000 rpm, and must be increased to a maximum of 160 lb while maintaining the minimum of 60 lbs. It is desired to improve the spring to obtain higher endurance strength and increase the resistance. Multiple options will be explored, but drastically changing the spring should be avoided if possible. The solution should also be low in cost and easy to implement, where the preference on the latter is to modify the existing design rather than to manufacture a new spring.

This example is appropriate for use in explaining this approach because it is a simplified representation of other problems that this method is intended for. The example is also appropriate because it originates with a mechanical system while allowing for the possibility of an innovative materials solution.

3.2 CLARIFICATION OF TASK

The design methodology founded on the systematic approach of Pahl and Beitz and augmented with TRIZ is detailed in the flow chart Figure 3.3, with the numbers next to each step in the process corresponding to the sections throughout this chapter. The contributions from the TRIZ body of knowledge are set in italics font in the figure.

3.2.1 Product Planning

The design process begins with clarifying the design task through the creation of a requirements list. Within the requirements list, all requirements are listed as either a demand (D) or a wish (W). Demands are requirements that must be met for a design to be considered successful; wishes should be considered whenever possible, unless their satisfaction compromises demands or more important requirements. The requirements list is used as a means of gauging design alternatives for selection. The steps, “Perform technological forecasting based on TRIZ engineering system evolution laws”, “Find and select product ideas”, and “Formulate a product proposal” though important, are not developed for the spring design because they are not applicable to a simplistic design problem, but are discussed generally.

3.2.1.1 Define Basic Market Demands

To define the basic market demands and ensure that no potential requirements are excluded, the categorical main headings from Pahl and Beitz are used to formulate design requirements. Those that are relevant are displayed in Table 3.2:

Table 3.2: Basic Market Demands

Geometry The overall geometry for the spring is set as the modifications must allow it to interface with the existing environment under the same operating conditions.
Kinematics The modifications must allow the design to continue to support the full range of motion, that is, a deflection of 1 inch and the same input frequency,
Forces The force ranged from 60 to 150 lbs. and now it must range from 60 to 160 lbs.
Material The spring is manufactured using music wire, ASTM A228.
Production The modifications must be able to be performed by a reasonably well equipped machine shop. Preference is given to modifications of lower cost or ease of implementation.
Quality Control The spring must still function as reliably as before, but with the necessary increased force when closed.

3.2.1.2 Document Customer-Specific Technical Performance Requirements

The assigned k value of 90 lbf/in must be increased to 100 lbf/in to provide more force. The initial deflection can be modified to allow the spring to maintain the initial minimum force.

3.2.1.3 Perform technological forecasting based on TRIZ engineering system evolution laws

Many papers and books are published concerning evolution of different systems and processes, and many are a collection of facts about historical occurrences coupled with speculation. Despite mathematically formulated methods, the fundamental applicability of any of the quantitative methods to technical systems and processes is questioned.[94]

On a qualitative level, TRIZ contains suggestions for system trends to help in forecasting where a product should be directed. They are as follows:

1. Trend of the Completeness of Parts of the System
2. Trend of Energy Conductivity of a System
3. Trend of Harmonizing the Rhythm of the Parts of the System
4. Trend of Increasing the degree of Idealness of the System
5. Trend of Uneven Development of Parts of the System
6. Transition to a super-system
7. Dynamization
8. Trend of the Transition from macro to micro level
9. Trend of Increasing the Su-Field development

3.2.1.4 Find and select product ideas to formulate a product proposal

With some direction set for how the technical system in question may develop, a decision must be made to select the product idea that will be developed. Though this is a large task, (and mentioned because of that) it is left more to product management than engineers, making the details of this step irrelevant to the emphasis of this work.

3.2.1.5 Clarify and Elaborate Requirements

The final step before the elaboration of the requirements list is determining if the compiled information is a demand or a wish, and is shown by a D or a W in Table 3.3, the requirements list.

Table 3.3: The Requirements List

D/W	*Requirement*
	Geometry
W	Maintain as little change in spring dimensions as possible
D	Spring must fit into existing structure
	Kinematics
D	Dynamic range of 1 inch
	Forces
D	Increase force by 10 lbs on the max range
	Material
D	Music wire ASTM A228
D	Increase stiffness
	Production
D	Does not create a completely new spring
W	Low cost and easy implementation
D	Modifications feasible with a well equipped machine shop
	Quality Control
D	Consistent force application
	Costs
W	Minimize cost of modification
W	Minimize cost of material

3.3 CONCEPTUAL DESIGN

3.3.1 Problem formulation

A process of abstraction, as presented by TRIZ, is used to ensure that a designer avoids fixation. This is also the first step in promoting the transfer to another domain. In the application of the TRIZ tools, beginning with problem formulation, the series of steps prescribed by the Algorithm for Inventive Problem Solving (ARIZ) are used to introduce them into the Pahl and Beitz process in an orderly way. ARIZ has been developed over a number of years, and is a detailed, sequential process on its own, though the intent here is to show how aspects of it can be used in a broader design process to allow for connection between domains, and as such, has been simplified somewhat to suit this purpose. The following is an expression of each step in terms of the spring design problem.

3.3.1.1 Abstract to identify the essential problems

The essential problem is that a force needs to be applied to a surface that is oscillating at 1,000 rpm through a distance of 1 in, such that the applied load ranges from 60 to 160 lbs. The current system is a helical compression spring as described with the aforementioned specifications; however, this only provides a load range under the same conditions of 60 to 150 lbs.

Once the essential problem is identified, an initial analysis of the problem can be performed by following these steps:

- *State the original problem as presented*
- State the "overall function" of the system

  "Provide force to a surface and store energy."[2]
- Define the subfunctions
- *Define the system boundaries along with its subsystems*

  "The system is composed of a spring and its coils and the boundary for design modifications are limited to the space that the spring currently occupies."
- *Identify any supersystem and environment*

  "The suspersystem is the ambient conditions of the spring, which can be considered at the minimum as a non-corrosive environment. It is not specified whether the spring operates in air or oil."

[2] The bold statements represent the spring design example for the applicable steps.

- *Identify the beneficial functions of the system*

  "The spring does provide force and stores energy."

- *Identify the detrimental or undesired functions of the system*

  "The spring does not provide enough force or store enough energy."

3.3.1.2 Establish function structure

With the above information, and usually in parallel to the previous step, a function structure is drawn to represent graphically the abstracted problem in solution neutral terms. The use of a function CAD based on terms from the Functional Basis [47] at this point can be beneficial in making the creation of the structure easier. Such a system is the FunctionCAD software currently being developed at the Missouri University of Science and Technology Design Engineering Lab. The computerization of the link between specific functions coupled with the inputs and outputs in a CAD system and a design repository as described by Matt Bohm and others [17] or Matthias Messer [69] could provide a means of directly connecting previous solutions to function structures. This is an interesting prospect for concrete solutions to standard problems given a sufficiently developed knowledge base, and this possibility is discussed in section 3.3.2.1. The need to connect problems to potential solutions at varying length scales at a more abstracted level is not solved by these repositories however. Thus, the function structure is created (regardless of the use in conjunction with a repository) as shown in Figure 3.4, and additional steps from TRIZ are added to the Pahl and Beitz process to further the problem formulation.

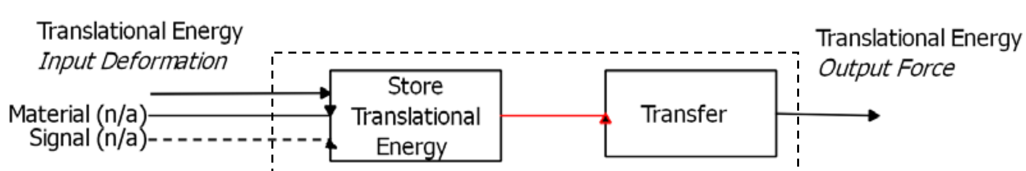


Figure 3.4: Function Structure for Spring

In Figure 4, the energy of the forcing surface is first stored in the spring through compression and later released through expansion. The system boundary is defined around the spring only (shown by the dotted line), and due to the nature of this problem, no material or signal is transmitted to or from the system so these flows are excluded.

3.3.1.3 Describe the mini-problem

A mini-problem is a description of the problem in such a way that there are minimal changes to the existing system: "The materials in the system remain mostly the same, yet more force is applied to the surface that the spring acts on by way of some minimal modification to these materials." In other words, a designer is looking at the problem this time in a way that allows the materials to not be replaced in the system, or no new parts added, but only modified in some sense to meet the new requirements. The description of the problem in this way allows for a way to search for a more direct solution that may be the easiest to implement.

3.3.1.4 System Conflict

The center of TRIZ, and transfer to another domain, is the construct of a conflict. It is the essence of a problem (and what turns a situation or task into a problem) and its proper formulation provides the key to finding a solution to it. This is similar to how Task Clarification is the crucial first step in the overall design of a system. TRIZ uses two types of conflicts that are encountered, defined, and used at different times. The first is known as the System Conflict (also known as the Technical Contradiction) and is the easiest to define. It has two names, arising from differences in the literature (compare [64] and [94]) that refer to a contradiction of technical demands that causes a conflict seen at the system level. The second type of conflict is known as the Physical Contradiction, and is developed later. Conflicts are also the key to allowing a problem to be generalized so that it can be related to other domains through analogy. It is the common interface, as depicted in Figure 3.1, and the embodiment of the transfer is seen at the application of an analogy to form a possible solution.

3.3.1.4.1 State the System Conflict (Technical Contradiction) Forward and Backwards

The System Conflict or Technical Contradiction is a conflict between two aspects of a design such that the improvement of the useful action yields the worsening of the harmful action, or vice versa. As such, the conflict should be stated in both the forward (improvement of the useful action yields the worsening of the harmful action) and reverse (lessening the harmful action yields a degradation of the useful action) sense. Furthermore, in order to standardize the form, the conflict should be described using 2 of the '39 Generic Engineering Parameters' of a design as put forward by TRIZ. A table of these specific parameters is given in Table A.5. Thus the Technical Contradictions stated in the forward and reverse sense are as follows:

1. Improving the *force* of a spring worsens the *ease of manufacture/device complexity*.
2. Decreasing the *device complexity* causes the *force* to be lessened.

3.3.1.4.2 Intensify the Conflict

Intensifying the conflict provides another way of understanding the problem, and has the form of: "the harmful action is completely eliminated, but the useful action is not performed at all" and vice versa.

1. The force is increased but the device cannot be manufactured because it is too complex or costly.

2. The device remains as it is but the force is not increased at all.

3.3.1.4.3 Select which intensified conflict version is helpful for examination

If there is a solution that leaves the existing spring essentially unchanged, yet the force is increased, then this solution is ideal, and so the second intensified conflict should be examined. The examination of this conflict involves searching for concepts where as much of the most beneficial aspect of the conflict is kept (the device remaining unchanged) while bringing the solution up to requirements

3.3.1.5 Analyze the Resources

An analysis of the existing resources can often be one of the most crucial steps in solving a problem in a given scenario where only the present resources can be used. It is also helpful in identifying where resources might be able to be used that would have gone to waste otherwise. Analyzing the resources involves the following 3 steps.

3.3.1.5.1 Describe the Operation Zone (space).

This operating zone corresponds to the system boundary in the function structure that is the spring itself and the surfaces that it interacts with.

3.3.1.5.2 Describe the Operating Time

The solution needs to be responsive to a dynamic deflection with a frequency of 1,000 rpms.

3.3.1.5.3 List the internal and external resource of the system and its environment.

In this example design, the designer has available any resources that would be available to a well equipped machine shop as well as the components of the system itself. The only object within the system is the spring and the moving surface. This is used to reacquaint the designer with the system resources that may not have been established in the initial problem formulation. There are 4 types of resources:

- Substance resources (internal and external)

- Field resources (internal and external)
- Time resources
- Space resources

3.3.1.6 Define the Ideal Final Result

The Ideal Final Result is the goal of the design. If this is achieved, and is feasible, then the design is successful. It is also useful, along with the requirements list, as a measure of assessment for concept selection and final design performance. It is developed in 2 steps:

3.3.1.6.1 State the initial Ideal Final Result (IFR-1).

The Ideal Final Result for the spring is: The spring is improved to specifications without using any material resources. Stated in other words: The 'resource' used to solve the problem will not complicate the device within the system boundary during its use while increasing the force. Note that the system boundary in the spring design example, as illustrated in Figure 3.4 of the Function Structure using the dotted line, consists of just the spring itself, and none of the external surfaces that it interacts with.

3.3.1.6.2 Reinforce the IFR by trying out different statements of the IFR.

Restate IFR by substituting words for *resource* such as: tool, object, environment, system, material state, configuration, and so on with as many as are applicable, while focusing on the internal resources. I.e., *The 'material state' used to solve the problem will not complicate the device within the system boundary during its use while increasing the force.*

3.3.1.7 Define the Physical Contradiction

The Physical Contradiction is the second type of contradiction used in TRIZ. Its formulation is important in understanding how a solution might solve the problem at a physical level (i.e., relying on a physical phenomena or scientific principle) and not merely a technical level. This contradiction is stated such that the conflict is shown to be the result of needing both the presence and absence of an aspect of a design to satisfy the design requirements. There are also two physical contradictions as there are two technical contradictions.

3.3.1.7.1 Define the Physical Contradiction on a Macro Level

The two physical contradictions correspond to the technical contradictions: one for Conflict 1 and one for Conflict 2, the "forward and reverse conflicts" as found in Section 3.3.1.4.1.

1. The spring must thicker/longer/exhibit a different geometry, to make the spring stiffer, or more resistive, yet not be thicker/longer/changed in the geometry, so that it is not more complex or harder to implement the change.

2. The spring must not be changed in complexity or ease of manufacture so that it is easy to implement the solution, yet the spring must be changed in order to increase the force.

To state the format of the Physical Contradiction in general terms, "The system must have or should be *property A* to fulfill *requirement B*, but must not have or should not be *property A* to fulfill *requirement C*. Stating the physical contradiction in this format allows for a formulation that contains a relation of the key function of the system to two requirements, where the key function is usually the *requirement B*. In the case of the spring design, the key function, as found in Figure 3.4, of storing and transferring energy (as understood to include the requirement for the increased spring force) is the *requirement B*. The second requirement, or *requirement C*, is the requirement placed on the system by some part of the problem statement; in the spring design case this is that the system shouldn't be significantly changed. The key to the physical contradiction is that there is a property of function that is essentially in conflict with *itself* in one form or another. The benefit in searching for these sorts of conflicts is that they allow a designer to see the crux of the problem on a physical level (and often *material* level) and not merely a technical level. Therefore, the solution to these problems is on the physical or material level, and frequently more innovative.[6]

3.3.1.7.2 Define the Physical Contradiction on a Micro Level

Transforming the previously mentioned Physical Contradiction defined on the macro level to the micro level can help reveal solutions, particularly of the material design sort. Doing so for the spring design example yields:

There must be more force between any given two atoms in the new spring, or there must be more pairs of atoms with more force between them (the sum of the forces between atoms must be increased) while not drastically changing the positions of such atoms (due to shape or material changes for example).

3.3.1.7.3 Refine the Ideal Final Result (IFR-2).

Now that the physical contradiction has been formulated (on both the macro and micro level), it is helpful to revisit the Ideal Final Result and refine it. This step can be seen as following directly from the IFR development (and in actuality the iteration of step 3.3.1.6.2) but with a side step of the development of the Physical Contradiction. has been developed.

3.3.1.8 Develop Su-Field Model

Problem modeling provides a means of representing the problem in a graphical and abstract way, yet in a more concrete and formulated fashion than words alone. Much like how the Function Structure as developed in Pahl and Beitz [82] is an abstracted graphical representation of a problem, the Su-Field model is a graphical representation of a problem as developed by Altshuller [5, 6]. The Su-Field model, however, is markedly different from a Function Structure, as a Function Structure is developed to encompass the entire solution, whereas an Su-Field model is created around just the crux of the problem. There are 2 components to an Su-Field model, a substance (hence, S-) and a field. The substance can be at any level of complexity, from single elements or materials, to complex systems. The term field is used also in a broad sense, including the traditional fields in physics (i.e., gravity, electromagnetism, etc.) as well as other fields such as chemical, thermal, pneumatic, etc. The basic structure of an Su-Field model is composed of a 3 component system where a field origination from a substance is acting on a second substance, or two fields acting on a substance. However, this is not always the case, and achieving a proper Su-Field is a process of creating an initial Su-Field and refining it until a complete model is created. For this there is a systematic process to transform an Su-Field. The Su-Field representation also allows a designer to analyze the problem's key elements and, following a procedure, assess what and how something must be changed in order to find a solution through the use of Standards.[94]

Shown in Figure 3.5 is the initial development of the Su-Field for this spring design problem.

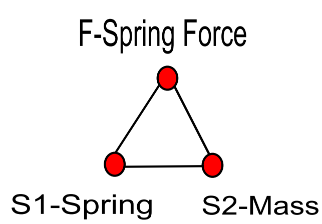


Figure 3.5: Su-Field Model of Problem

In the above Su-Field model, the spring system is represented as two substances, the spring and the mass it is pressing against, and the field that is the force of the spring. The decision on what to model in the Su-Field is based on the previous design steps and intuition. The designer is focused on the same thing that the function structure, contradictions, resources, operating zone and so forth are developed on, and this focal point if what should be modeled in the Su-Field. The Su-Field has different inputs and outputs from the function structure, but insight on how to select substances and fields can be obtained by evaluating the things that functions transform, namely: energy, material, and signal. In contrast, the Su-Field considers the source, nature, or entity associated with the action of the function, whereas a function structure considers only the result. So, for example, the spring has a function structure as previously shown in Figure 3.4 with a transformation of energy, with no material transformation, treated as a "black box", while the Su-Field shown in Figure 3.5 includes the entities involved in that function, treating them as a field or substance. The field interacting with that substance also falls under the energy, material, and signal categories, noting that the designer is looking within the function to represent graphically the action of this function using a combination of substances and fields.

To represent this graphically, Su-Field models are formed in triangles as the basic building blocks of the structure. Because of this, the Su-Field model is complete and does not need to undergo further transformation. (This is not surprising given the simplicity of the example.)

With the IFR defined on the micro level, the Su-Field analysis tool used to illustrate that a new force must be added to the system, and all of the varying forms of conflicts and contradictions, the problem formulation phase is complete. Now the design task is ready for a solution search. A designer should keep in mind that if a feasible and sufficient solution is encountered within the process, the solution search can be halted and the designer can continue to the embodiment design phase. For this example, however, all of the steps are covered regardless of finding a sufficient solution since the use of this example is an aid in displaying the method.

3.3.2 Solution Search

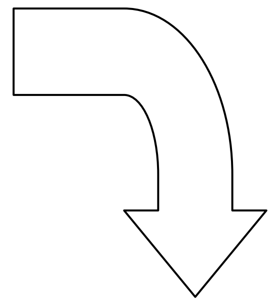
The first step in the solution search is to attempt to solve the problem at the physical level, which originates from the physical contradiction and the Su-Field modeling, as these solutions tend to be most innovative.

3.3.2.1 Interface with Design Repository

A design repository, as developed by Matthias Messer [69], is a tool intended to increase a designer's ability to explore design options with ease by providing a catalog of solution variants from underlying phenomena that cause a certain behavior. The premise is that a problem is first defined in terms of function, which dictates the behavior required, and therefore can be linked to a repository of solutions that exhibit this behavior. This catalog is explained in further detail in Chapter 4. In Figure 3.6, a snippet of the two components of the repository are shown. In the first section, the underlying phenomenon is found by relating the input and output of the key function in a table of phenomena. Once the phenomenon is found, a design catalog can be opened for that phenomenon based on the desired length scale. Solution variants are then displayed, categorized by "solution principle" (note: this is not a TRIZ solution principle, and can be thought of more as an embodiment principle). Shown in the bottom section of Figure 3.6 is a portion of the catalog for (in)elastic deformation at the macroscale for the "fundamental structural element" "solution principle".

This concept is consistent with the method presented because, at this point, a function structure has been created, and additionally, the conflict described helps a designer focus in on the key function to be fulfilled. It is, however, dependant on previous design knowledge and contains more concrete, standard solutions (i.e., it simply suggests the use of a spring). As such, it is not sufficient when innovation is required or in transferring information between domains at a higher level of abstraction. Also, it is dependent on the designer's selection on which length scale to explore and, to an extent, the "solution principle" or embodiment principle under which to view solutions. Because of these shortcomings, a variety of TRIZ tools are used later and the relevant solutions principles have been combined with Messer's design catalog.

Input \ Output	Mechanical Energy	Electrostatic Energy	Magnetostatic Energy
Mechanical Energy	(In)elastic deformation Inertia …	Electrostriction …	Magnetostriction …
Electrostatic Energy	Electric field …	Interference …	Hall-effect …
Magnetostatic Energy	Magnetic field …	Oscillating circuit …	Ferromagnetism …
Sound Energy	Pressure wave …	Electrostriction …	Magnetostriction …



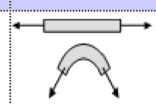
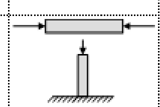
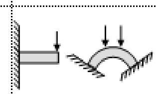
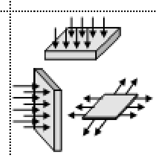
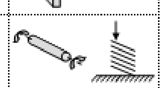
Phenomenon	Scale	Characteristics			
		Solution Principle		Properties	Applications
Elastic/inelastic deformation (tension, compression, bending, shear, torsion, buckling, fracture, cutting, inversion, extrusion, drawing, flow)	Macroscale	**Fundamental structural elements**	Basic engineering elements on the mocroscale primarily supporting loads are referred to as fundamental structural elements.		
		- Tie, cable, wire or continuous fiber		These structures are capable of carrying tensile loads only. The maximum energy that can be absorbed per unit weight before tensile instability supervenes depends upon the ultimate tensile strength and strain. If tension devices are for example used as a simple type of energy absorber, they suffer from the stroke, i.e., maximum displacement, or maximum strength limitation imposed by the ultimate strain or strength of specific material system.	- Single-, coaxial-, multicore-, ... cables
		- Struts or columns		These structures are capable of carrying compressive loads only.With respect to buckling and plastic collapse the specific ultimate tensile strength is an excellent indicator of the ability of a material to absorb energy. If struts or columns are for example used as energy absorber, the absorbed energy per unit mass in static tests is minimial because of the limited zone of plastic deformation during buckling.	- Hinged-, fixed-, free-, ... columns
		- Beams or archs		Beam and archs (curved beams) are structural elements that carry load primarily in bending (flexure). In general, they are characterized by their profile (the shape of their cross-section), their length, and their material. Beams and archs may for example be used for energy dissiaption or blocking and bracing, i.e., locating supports in contact with stronger parts of a structure, so that imparct forces are directed to these parts.	- Cantilever-, simply-supported-, ... beams
		- Plates/panels, shells, membranes or foils		Plates are initially flat structural elements, having thicknesses much smaller than the other dimensions. Whereas shells only bear in-plane loads, plates bear bending moments as well. Membranes are curved shells. Panels are non-horizontal plates. For example, their load spreading effect (i.e., spreading the forces at impact over a large area so that pressure is reduced) has been used in energy dissipation devices.	- Fixed-, simply-supported-, ... plates and panels - Multifunctional foils: load bearing, aesthetic, ...
		- Shafts or torsion springs		Shafts or torsion springs are structural elements primarlily loaded in torsion. Besides tension, compression and bending, torsion of bars or tubes, featuring relatively large deceleration strokes, has also been used in energy dissipation devices.	- Tension-, compression-, ... spring

Figure 3.6: Design Repository[69]

Using this catalog as it was developed by Messer is helpful, but the addition of the TRIZ principles used to solve Technical Contradictions gives the designer an additional attention directing tool without any additional effort. The modified table shown in Figure 3.7 is a selection of the repository including two additional columns on the right side of associated TRIZ Principles.

Macroscale	**Fundamental structural elements**	Basic engineering elements on the mocroscale primarily supporting loads are referred to as fundamental structural elements.				
	- Tie, cable, wire or continuous fiber		These structures are capable of carrying tensile loads only. The maximum energy that can be absorbed per unit weight before tensile instability supervenes depends upon the ultimate tensile strength and strain. If tension devices are for example used as a simple type of energy absorber, they suffer from the stroke, i.e., maximum displacement, or maximum strength limitation imposed by the ultimate strain or strength of specific material system.	- Single-, coaxial-, multicore, ... cables	1. Segmentation 3. Local quality	24. Intermediary
	- Struts or columns		These structures are capable of carrying compressive loads only.With respect to buckling and plastic collapse the specific ultimate tensile strength is an excellent indicator of the ability of a material to absorb energy. If struts or columns are for example used as energy absorber, the absorbed energy per unit mass in static tests is minimial because of the limited zone of plastic deformation during buckling.	- Hinged-, fixed-, free-, ... columns	1. Segmentation 3. Local quality	17. Another dimension
	- Beams or archs		Beam and archs (curved beams) are structural elements that carry load primarily in bending (flexure). In general, they are characterized by their profile (the shape of their cross-section), their length, and their material. Beams and archs may for example be used for energy dissiaption or blocking and bracing, i.e., locating supports in contact with stronger parts of a structure, so that imparct forces are directed to these parts.	- Cantilever-, simply-supported-, ... beams	1. Segmentation 3. Local quality	14. Spheroidality - Curvature
	- Plates/panels, shells, membranes or foils		Plates are initially flat structural elements, having thicknesses much smaller than the other dimensions. Whereas shells only bear in-plane loads, plates bear bending moments as well. Membranes are curved shells. Panels are non-horizontal plates. For example, their load spreading effect (i.e., spreading the forces at impact over a large area so that pressure is reduced) has been used in energy dissipation devices.	- Fixed-, simply-supported-, ... plates and panels - Multifunctional foils: load bearing, aesthetic, ...	30. Flexible shells and thin films.	14. Spheroidality - Curvature
	- Shafts or torsion springs		Shafts or torsion springs are structural elements primarlily loaded in torsion. Besides tension, compression and bending, torsion of bars or tubes, featuring relatively large deceleration strokes, has also been used in energy dissipation devices.	- Tension-, compression-, ... spring	15. Dynamics 35. Parameter Changes	11. Beforehand Cushioning 18. Mechanical Vibration

Figure 3.7: Design Repository[69]-- With Associated TRIZ Principles

Since the repository is in an electronic format, and the function structure is a required first step to know what function to explore, it is a logical next step to implement the function structure electronically (as previously discussed) and to connect it to the repository automatically. The solutions can then be explored, and if a sufficient solution is found, the design process can move on to the embodiment phase.

The computerization of the function structure also possesses similar possibilities for the Su-Field model. The Su-Field model is a model that has structured rules for how to analyze and develop or complete the model to find a solution, described in Section 3.3.2.3. The combination of a computerized function structure connected to a design repository and a computerized Su-Field model connected to the Standard Solutions would provide an effective means of transferring knowledge between domains in both a lower and higher level.

3.3.2.2 Apply the four Separation Principles

As with each of the steps in the solution search phase, if the previous procedure does not yield a sufficient solution, or if a further search is desired, the designer progresses to the next step. As an attention directing tool, TRIZ suggests applying four separation principles to overcome the physical conflict. These separation principles are shown below with their respective questions for the spring design example:

- Separate the opposite physical states in time.
  - Can the spring be thick at one instant and thin at another? Or can it be stiff at one time and weak at another?
- Separate the opposite physical states in space.
  - Can one location of the spring be stiff and the other weak? Can a particular location be strengthened?
- Separate the opposite physical states between the system and its components.
  - Can a component be strengthened apart from the whole system?
- Have both opposite physical states coexist in the same substance.

3.3.2.3 Apply Su-Field analysis and Standard Solutions

This step is done after the first development of the Su-Field model and the separation principles, as they can happen sequentially or parallel. However, it is listed here to allow for a solution to be found in the repository, that is, if one exists and is sufficient (as determined by the designer though the use of the requirements list). Furthermore, it also reminds the designer to keep the separation principles in mind while analyzing the Su-Field. The 76 Standards that Altshuller developed are difficult to apply and somewhat inhomogeneous in the content of the standards. For example, some of the "standards" are nothing more than an explanation of how to apply certain other standards.

To remedy this problem, Savransky [94] presents a systematic method to apply the standards developed by Altshuller [5, 6], shown in Table 3.4.

Table 3.4: Standard Solutions Algorithm

1.	Construct a model of the problem.
2.	Transform the model of the problem to the Su-Field form. **Note-0:** Complete model should have a product (S1), a tool (S2), and an interaction of a product and tool (F).
3.	Check if it is a measurement problem. If *yes*, go to step 4.1. If *no*, go to step 3.1. **3.1.** Check if a replacement of the initial problem in measurement or detection tasks is accessible. If *yes*, apply the Standards of group 4.1. If *no*, go to step 4. **Note-1:** If the direct transition is too complicated, first transfer the problem to a detection task, and then translate it to a measurement task.
4.	Check the completeness of the Su-Field. If the Su-Field is incomplete (or *no*), complete step 4.1, then go to step 5. If the Su-Field is complete, go directly to step 5. **4.1.** Check presence of harmful links. If present, go to step 4.1.1. If such a link is absent, go to step 4.2. **4.1.1.** Check if the introduction of substances and fields is allowable. If *yes*, apply Standards 1.1.1–1.1.6 or Standards of group 4.2. If *no*, apply the Standards of group 5.1, 5.2, 5.5. **4.2.** Check if introduction of substances and fields is allowable. If *yes*, apply Standards 1.1.7, 1.1.8, 1.2.3. If *no*, apply the Standards of groups 5.1, 5.2, 5.5.
5.	Check presence of harmful links. If *yes*, go to step 5.1. If *no*, go to step 6. **5.1.** Check if the introduction of substances and fields is allowable. If *yes*, apply Standards 1.2.1, 1.2.2, 1.2.4, 1.2.5. If *no*, apply the Standards of groups 5.1, 5.2, 5.5.
6.	Check presence of ferromagnetic substances in the Su-Field. If *yes*, go to step 7. If *no*, go to step 8. ***Note-2***: Check presence of any ferromagnetic substance in subsystems which could be included in the Su-Field under consideration.

7.	Check if introduction of a magnetic field is allowable. If *yes*, go to step 17. If *no*, go to step 8.
8.	Check if formation of the complex Su-Fields is allowable. If *yes*, apply the Standards of group 2.1. If *no*, go to step 9. **Note-3:** If the complication of the system is not restricted in conditions of the problem, it is often possible to solve the problem by formation of complex Su-Fields.
9.	Check if replacement of the Su-Field is allowable. If *yes*, apply Standard 2.2.1. If *no*, go to step 10. **Note-4:** Replace any field except magnetic and electrical. **Note-5:** Replacement of a field is inadmissible if the replacing field is a source of hindrances.
10.	Check if the system is dynamic. If *yes*, go to step 11. If *no*, apply Standards 2.2.2–2.2.4. **Note-6:** Remember the principle of increased dynamism of the technique.
11.	Check if the structure of components of the Su-Field is coordinated. If *yes*, go to step 12. If *no*, apply Standards 2.2.5, 2.2.6, or 4.3.1 and of groups 5.3 and 5.4. **Note-7:** Remember duality of this law! It may be necessary to misbalance consciously the components.
12.	Check if dynamics of components of the Su-Field are coordinated. If *yes*, go to step 13. If *no*, apply Standards 2.3.1–2.3.3 or 4.3.2 and 4.3.3.
13.	Check if introduction of ferromagnetic substances and magnetic fields is allowable in Su-Field instead of current components. If *yes*, apply Standards 2.4.1 or 4.4.1. If *no*, go to step 14.
14.	Check if introduction of the ferromagnetic additives is allowable in available substances. If *yes*, apply Standards 2.4.5 or 4.4.3. If *no*, go to step 15.
15.	Check if introduction of the ferromagnetic additives is allowable in the environment. If *yes*, apply Standard 2.4.6 or 4.4.4. If *no*, go to step 16.
16.	Check if use of electrical fields and/or currents is allowable. If *yes*, apply Standards 2.4.11 and 2.4.12. If *no*, go to step 20.

17.	Check if Su-M_Field is dynamic. If *yes*, go to step 18. If *no*, apply Standards 2.4.2, 2.4.3, 2.4.4, 2.4.7, 2.4.8, and 4.4.2. **Note-8:** At step 7 we introduce only a magnetic field, and at step 17 we come to Su-M_Field, making ferromagnetic substance dynamic (Standards 2.4.2–2.4.4) or making all components dynamic.
18.	Check if structure of components Su-M_Field is coordinated. If *yes*, go to step 19. If *no*, apply Standard 2.4.9.
19.	Check if dynamic of components Su-M_Field is coordinated. If *yes*, go to step 20. If *no*, apply Standards 2.4.10, 4.4.5, and of groups 5.3 and 5.4.
20.	Apply the Standards of the third class to the solution of the problem in the following sequence: Standard 3.2.1, and then 3.1.1, 3.1.2, 3.1.3, and 3.1.5. **Note-9:** Standard 3.1.4 can be applied at any stage of development of bi-systems and poly-systems.

This process is also presented in the large flow chart spanning Figure 3.8 and Figure 3.9:

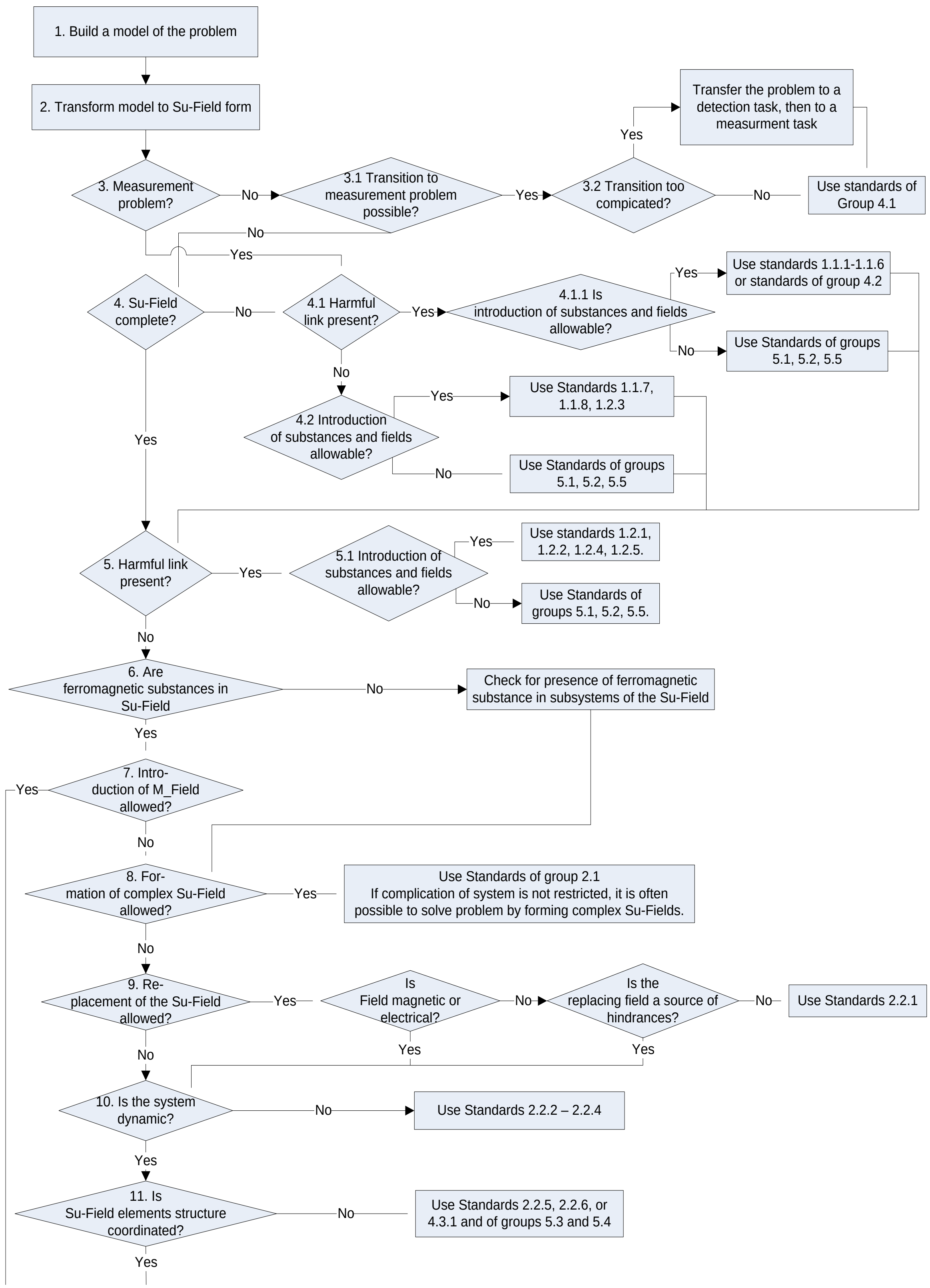


Figure 3.8: Flow Chart of Standard Solutions – Part A

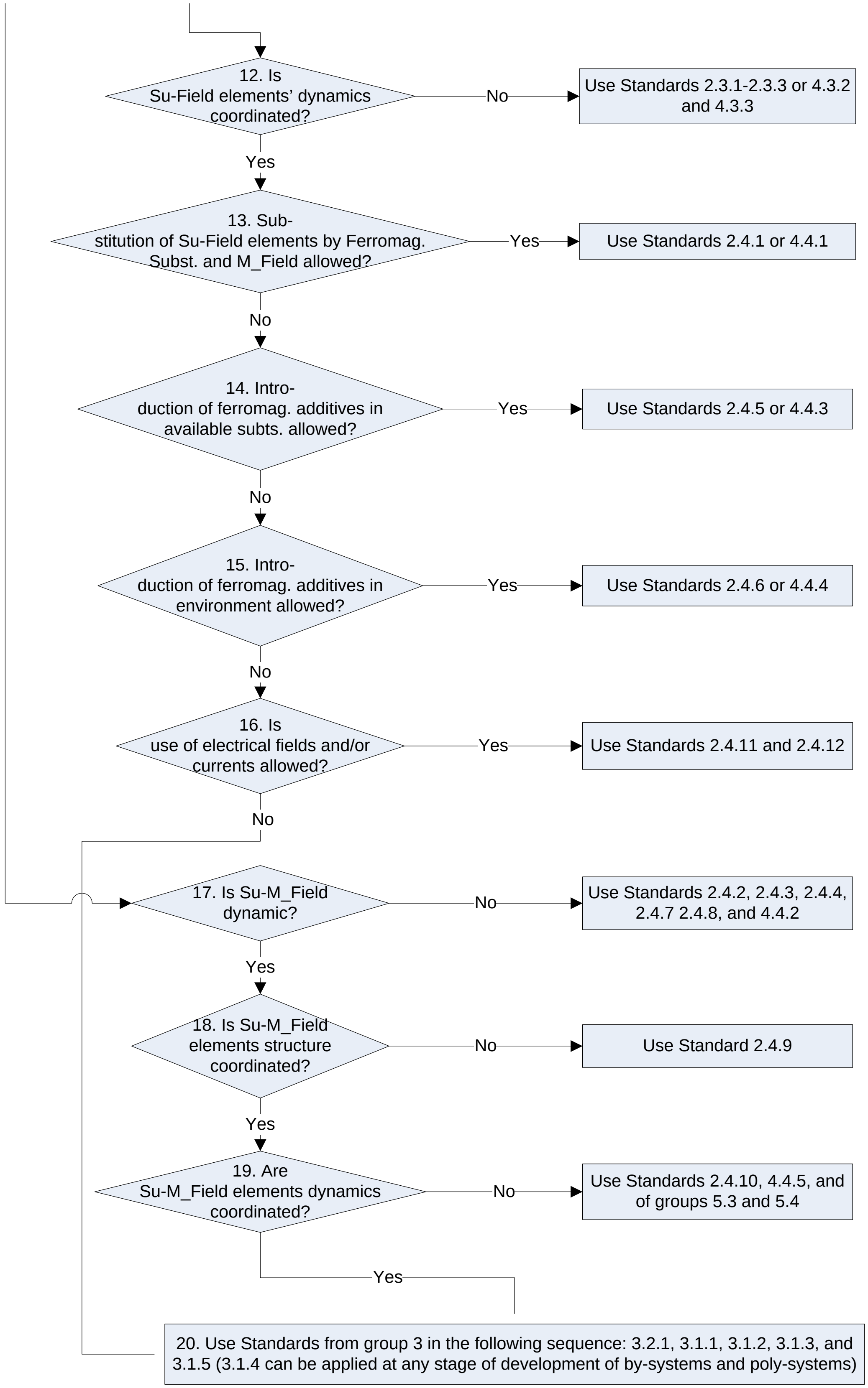


Figure 3.9: Flow Chart of Standard Solutions – Part B

The TRIZ Standards referenced in the above flow chart are found in Table 3.5:

Table 3.5: TRIZ Standard Solutions

Altshuller's Standard Solutions of Invention Problems
Class 1. Construction and Destruction of Su-Field Systems
1.1. Synthesis of Su-Fields
1.1.1. Making Su-Field
1.1.2. Inner complex Su-Field
1.1.3. External complex Su-Field
1.1.4. External environment Su-Field
1.1.5. External environment Su-Field with additives
1.1.6. Minimal regime
1.1.7. Maximal regime
1.1.8. Selectively maximal regime
1.2. Destruction of Su-Fields
1.2.1. Removing of harmful interaction by adding a new substance
1.2.2. Removal of harmful interaction by modification of the existing substances
1.2.3. Switching off harmful interaction
1.2.4. Removal of harmful interaction by adding a new field
1.2.5. Turn-off magnetic interaction
Class 2. Development of Su-Fields
2.1. Transition to complex Su-Fields
2.1.1. Chain Su-Field
2.1.2. Double Su-Field
2.2. Forcing of Su-Fields
2.2.1. Increasing of field's controllability
2.2.2. Tool fragmentation
2.2.3. Transition to capillary-porous substances
2.2.4. Dynamization (flexibility)
2.2.5. Field organization
2.2.6. Substances organization
2.3. Forcing of Su-Fields by fitting (matching) rhythms
2.3.1. Field-Substances frequencies adjustment
2.3.2. Field-Field frequencies adjustment
2.3.3. Matching independent rhythms
2.4. Transition to Su-M_Field systems
2.4.1. Making initial Su-M_Field (or "proto-Su-M_Field")
2.4.2. Making Su-M_Field
2.4.3. Magnetic liquids
2.4.4. Capillary-porous Su-M_Field
2.4.5. Complex Su-M_Field
2.4.6. Environment Su-M_Field
2.4.7. Usage of physical effects
2.4.8. Su-M_Field dynamization
2.4.9. Su-M_Field organization

2.4.10. Matching rhythms in Su-M_Field
2.4.11. Su-E_Fields
2.4.12. Electrorheological suspension
Class 3. Transition to Super-System and to Microlevel
3.1. Transition to bi-systems and poly-systems
3.1.1. Creation of bi-systems and poly-systems
3.1.2. Development of links
3.1.3. Increase of difference between system's elements
3.1.4. Convolution
3.1.5. Opposite properties
3.2. Transition to micro-level
3.2.1. Shift to micro-level
Class 4. Standards for System Detection and Measurement
4.1. Roundabout ways to solve problems of detection and measurement
4.1.1. Change instead to measure
4.1.2. Copying
4.1.3. Sequential detection
4.2. Synthesis of Su-Field measurement systems
4.2.1. Creation of measurable Su-Field
4.2.2. Complex measurable Su-Field
4.2.3. Measurable Su-Field at environment
4.2.4. Additives in environment
4.3. Forcing of measuring Su-Fields
4.3.1. Physical effects applications
4.3.2. Resonance
4.3.3. Resonance of additives
4.4. Transition to Su-M_Field systems
4.4.1. Measurable proto-Su-M_Field
4.4.2. Measurable Su-M_Field
4.4.3. Complex measurable Su-M_Field
4.4.4. Environment measurable Su-M_Field
4.4.5. Physical effects related to magnetic field
4.5. Direction of measuring system evolution
4.5.1. Measurable bi- or poly-systems
4.5.2. Evolution line
Class 5. Standards for Using Standards
5.1. Adding substances at construction, reconstruction, and destruction of Su-Fields.
5.1.1. Round-about ways:
5.1.1.1. "Emptiness" instead of substance
5.1.1.2. Field instead of substance
5.1.1.3. External addition instead of internal one
5.1.1.4. Particularly active addition in very small doses
5.1.1.5. Substance in very small doses
5.1.1.6. Addition is used for awhile
5.1.1.7. A copy instead of a subsystem
5.1.1.8. Chemical compound
5.1.1.9. Addition is obtained from the subsystem itself
5.1.2. Substance(s) separation

5.1.3. Substance(s) dissipation
5.1.4. Big additives
5.2. Adding fields at construction, reconstruction, and destruction of Su-Fields
5.2.1. Using existing fields
5.2.2. Fields from environment
5.2.3. Substances as fields sources
5.3. Phase transitions
5.3.1. Change of the phase state
5.3.2. Second type phase transition
5.3.3. Phenomena coexist with phase transition
5.3.4. Two-phase state
5.3.5. Interaction between phases
5.4. Application peculiarities of physical effects
5.4.1. Self-driven transition
5.4.2. Increase of output field
5.5. Creation of particles
5.5.1. Substance destroying
5.5.2. Integration of particles
5.5.3. How to use Standards 5.5.1 and 5.5.2

Following this method of applying the standard solutions for the spring design results in the following decisions:

1. Construct a model of the problem.
2. Transform the model of the problem to the Su-Field form. **Refer to Figure 3.5**
3. Check if it is a measurement problem. **No, go to step 3.1**
4. Check if it can be transitioned to a measurement problem. **No, go to step 4**
5. Check the completeness of the Su-Field. **The Su-Field is complete, go to step 5.**
6. Check for the presence of harmful links. **No, go to step 6.**
7. Check for the presence of ferromagnetic substances in the Su-Field. **Yes, go to step 7.**
8. Check if introduction of a magnetic field is allowable. **Yes, go to step 17.**
9. Check if S-M_Field is dynamic. **No, apply standards: 2.4.2, 2.4.3, 2.4.4, 2.4.7, 2.4.8, and 4.4.2**

   2.4.2: Making S-M_Field

   2.4.3: Magnetic liquids

   2.4.4: Capillary-porous S-M_Field

2.4.7: Usage of Physical Effects

2.4.8: S-M_Field dynamization

4.4.2: Measureable S-M_Field

The two relevant standards for this problem are the standards in bold, **2.4.2: Making S-M_Field, or 2.4.7: Usage of Physical Effects**.

A designer is therefore suggested to consider what types of phenomenon are available for the required effect, which is found by scanning through the Physical Effects table.

Another way of connecting to the Standard Solutions, depending on the approach that is most suited to the problem (i.e., if the development of the Su-Field through the algorithm isn't as apparent as defining the energy transfer functions), is to use the links within the catalog of solution principles. The catalog, as shown in Figure 3.7, has another column to direct the designer to standard solutions that are relevant. The same section of Figure 3.7 is shown in Figure 3.10, but with the additional column to direct a designer to the relevant Standard Solutions. In this particular section, the only relation made is for the spring solution principle, but the entire catalog can be seen in Table A.11-Table A.16.

In Figure 3.10, the Standard Solution related to the spring principle is **4.2-2.2.4.** The number for this has two components. The second number, **2.2.4,** is the TRIZ Standard Solution number, as it correlates in Table 3.5. Looking 2.2.4 up in that table will reveal that this Standard Solution is "Dynamization (flexibility)", or forcing the Su-Field to have some degree of a dynamic flexibility. The first number, 4.2, relates to the categorizations of Su-Fields for use with Standard Solutions per Table 3.6. The format of this table is such that most Standards can be presented in simple IF→THEN form:

IF a problem of a *goal* is given as Su-Field *conditions* and *constraints* according to the problem circumstances, **THEN** such problems are solved by *action*.[94]

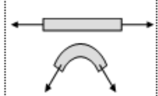
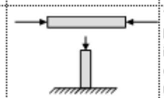
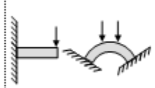
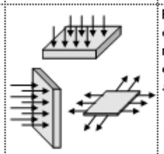
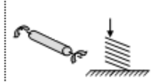
Solution Principle		Characteristics Properties	Applications	Associated TRIZ 40 Principle(s) Strong	Weak	Standard Solution of TP Relation (w/ related Altshuller's Numbers)
Fundamental structural elements	Basic engineering elements on the macroscale primarily supporting loads are referred to as fundamental structural elements.					
- Tie, cable, wire or continuous fiber		These structures are capable of carrying tensile loads only. The maximum energy that can be absorbed per unit weight before tensile instability supervenes depends upon the ultimate tensile strength and strain. If tension devices are for example used as a simple type of energy absorber, they suffer from the stroke, i.e., maximum displacement, or maximum strength limitation imposed by the ultimate strain or strength of specific material system.	- Single-, coaxial-, multicore-, ... cables	1. Segmentation 3. Local quality	24. Intermediary	
- Struts or columns		These structures are capable of carrying compressive loads only.With respect to buckling and plastic collapse the specific ultimate tensile strength is an excellent indicator of the ability of a material to absorb energy. If struts or columns are for example used as energy absorber, the absorbed energy per unit mass in static tests is minimial because of the limited zone of plastic deformation during buckling.	- Hinged-, fixed-, free-, ... columns	1. Segmentation 3. Local quality	17. Another dimension	
- Beams or archs		Beam and archs (curved beams) are structural elements that carry load primarily in bending (flexure). In general, they are characterized by their profile (the shape of their cross-section), their length, and their material. Beams and archs may for example be used for energy dissiaption or blocking and bracing, i.e., locating supports in contact with stronger parts of a structure, so that imparct forces are directed to these parts.	- Cantilever-, simply-supported-, ... beams	1. Segmentation 3. Local quality	14. Spheroidality - Curvature	
- Plates/panels, shells, membranes or foils		Plates are initially flat structural elements, having thicknesses much smaller than the other dimensions. Whereas shells only bear in-plane loads, plates bear bending moments as well. Membranes are curved shells. Panels are non-horizontal plates. For example, their load spreading effect (i.e., spreading the forces at impact over a large area so that pressure is reduced) has been used in energy dissipation devices.	- Fixed-, simply-supported-, ... plates and panels - Multifunctional foils: load bearing, aesthetic, ...	30. Flexible shells and thin films.	14. Spheroidality - Curvature	
- Shafts or torsion springs		Shafts or torsion springs are structural elements primarlily loaded in torsion. Besides tension, compression and bending, torsion of bars or tubes, featuring relatively large deceleration strokes, has also been used in energy dissipation devices.	- Tension-, compression-, ... spring	15. Dynamics 35. Parameter Changes	11. Beforehand Cushioning 18. Mechanical Vibration	4.2 - 2.2.4

Figure 3.10: Repository section with Standard Solution Relation Column—modified from [69]

Table 3.6: Standard Solutions: IF-THEN Structure [94]

	Aim/Conditions	Constraints	Action	Altshuller's Numbers and Notes
Aim: Optimization of Su-Fields				
1.1	Minimal (dosed, optimal) mode	Hard, or even impossible, to achieve	Use the maximal mode followed by removal of surplus part	1.1.6
1.2	UF maximal mode	Maximal mode is intolerable on one substance (e.g., S1)	Retain maximal mode maintenance but direct it to another substance (e.g., S2) related to the first one (e.g., S1).	1.1.7
1.3	Selective mode	No restrictions on F value	Add a protective substance where minimal mode is needed, and add a substance giving a local field where maximal mode is needed.	1.1.8 F is maximal in some sectors and minimal in other sectors.
Aim: Destruction of Su-Fields				
2.1	Both UF and HF take place between substances in Su-Field	The substances must not necessarily be in direct contact	Add a new, free, or sufficiently inexpensive substance S3 between the substances S1 and S2.	1.2.1 Take S3 from the outside in the finished form or made of substances available under the action of fields; e.g., S3 is bubbles, "emptiness," foam, etc.
2.2	The same conditions as above	1.2.1 + the usage of foreign S3 is barred.	Add a new, free, or sufficiently inexpensive substance S3 between S1 and S2, and this third substance is a modification of the first two.	1.2.2 S3 is already available in a technique; S3 is just modified for performing new functions.
2.3	The same conditions as above	S1 and S2 must be in direct contact	Pass to double Su-Field, where available field F1 retains its UF, and added field F2 neutralizes (compensates) HF (or transforms it into useful one).	1.2.4
2.4	HF of a field on substance exists	No restrictions	Introduce a substance that will eliminate HF itself.	1.2.3, 1.2.5M
Aim: Construction of Su-Fields				
3.1	The given substance is hardly changeable in the needed direction	No restrictions on adding new substances and fields	Completion (synthesis) of Su-Field due to introduction of new (missing) components.	1.1.1 When performing operations with thin, operations with thin, fragile, and easily deformable substance, a subsystem is joined during these operations with a substance making it hard substance making it hard (strong). Then

				this subsystem can be removed by dissolving, evaporation, etc.
3.2	The same conditions as	No restrictions on adding new substances into existing subsystem	Transition (constant or temporal) to internal complex Su-Field, introducing additions into available substances S1 or S2. Such additions must increase Su-Field controllability or add needed properties to it.	1.1.2 Sometimes one and the same solution, depending on the statement of a problem, can be obtained by constructing (complex) Su-Field. S3 is an addition to the tool S2.
3.3	The same conditions as above	Restrictions on adding new substances to available ones S1 or S2	Transition (constant or temporal) to external complex Su-Field, joining outer substance S3 with S1 or S2. The S3 must increase Su-Field controllability or give it needed properties.	1.1.3, 2.4.5M
3.4	The same conditions as above	Restrictions on adding or joining new substances	Completion (synthesis) of Su-Field using the available environment as a substance to be added.	1.1.4, 2.4.6M In particular, if a weight of a moving subsystem needs to change, and it is impossible, the subsystem must be shaped as a wing. Changing the angle of wing inclination about the movement direction, one obtains the additional upward or downward force.
3.5	The same conditions as above	1.14 + no substances in the environment	Substances can be obtained by replacement of the environment, its decomposition, or addition of new substances into it.	1.1.5
Aim: Increase the Su-Field Efficiency Due to Resources				
4.1	Su-Field is weakly controllable and its efficiency should increase	No restrictions	Transformation of a Su-Field component into independently controlled Su-Field and construction of chain Su-Fields. (Analogies: 2.4.1 for Su_M_Fields and 2.4.11 for Su_E_Fields).	2.1.1, 2.4.1M A chain Su-Field can be obtained by expanding relations in Su-Field. In this case, a new link F2-S1 is integrated into the relation S1-S2.

4.2	The same conditions as above	No restrictions	Increase the degree of dispersion of a substance operating as a tool. Increase the degree of flexibility of the Su-Field.	2.2.2, 2.4.2M, 2.2.4, 2.4.3M, 2.4.8M Standards reflect the technique evolution trends.
4.3	The same conditions as above	No restrictions	Transition from homogeneous fields (substances) or fields (substances) with unordered structure to inhomogeneous fields (substances) or fields (substances) with a certain spatial structure (constant or variable).	2.2.5. For field organization 2.2.6. For substances organization 2.4.9M For ferromagnets and magnetic fields
4.4	The same conditions as above	Su-Field components cannot be replaced (2.1.2) by adding new F and S (2.2.1)	Construct a double Su-Field due to introduction of the second well controllable field. (2.1.2) Replace uncontrollable (or weakly controllable) working field with controllable (well controllable) one (2.2.1).	2.1.2, 4.4.2M, 2.2.1, 2.4.1M For example, a mechanical field can be replaced with an electric one, etc. Analogs are 4.4.2M, 2.4.1M
Aim: Growth of Su-Fields Efficiency by Phase Transitions				
5.1	Contradictory requirements to introduce S and F can be met only by using phase transitions	Restriction to add substances	Change the phase state of the available substance instead of adding a new substance.	5.3.1
5.2		Opposite properties for existing substances	Use the substances capable of transition from one phase state to another one, depending on the operation conditions	5.3.2 The phase transition of the second type is preferable.
5.3	The same conditions	See the conditions	Use phenomena accompanying the phase transition.	5.3.3
5.4	The same conditions	The same restrictions	Replace the single-phase state of a substance with a two-phase.	5.3.4 See Standard 5.4.1.
5.5	The same conditions	The conditions are the restrictions	Introduce an interaction (physical, chemical) between phases of the substance (obtained by 5.3.4).	5.3.5
Aim: Formation of Su-Fields for Measurement				

6.1	Poorly measurable or detectable	No restrictions	Construct a simple or double Su- Field using a field passing through the system and carrying	4.2.1 The synthesis of measuring Su-Fields is distinguished incomplete Su- Field out the information about its state by the fact that they must ensure obtaining a field at output. (Compare Standard 1.1.1.)
6.2	Poorly measurable or detectable complete Su-Field	No restrictions	Change the system in such a way that there will be no necessity for detection and measurement.	4.1.1 PF of some subsystems is measurements and detection. It is desirable to exclude (or minimize) such PF, without prejudice to technique accuracy and performance.
6.3	The same conditions as above	No restrictions	Transition to internal or external complex Su-Field, adding easy-to-detect substances to the system.	4.2.2, 4.4.3M Can be applied to a component of any complete Su-Field.
6.4	The same conditions as above	Standard 4.1.1 cannot be applied	Replace direct operations with a subsystem by operations with its copy or picture.	4.1.2 Such copy (picture) can have the opposite colors to the subsystem's colors.
6.5	The same conditions as above	Standards 4.1.1 and 4.1.2 cannot be applied	Perform the sequential detection of changes.	4.1.3 The change from the indistinct concept "measurement" to the clear model "two sequential detections" simplifies many problems.
6.6	The same conditions as above	No substances can be added	Add the substances generating easy-to-detect and easy-to-measure field to environment.	4.2.3, 4.4.4M The state of the technique can be judged from the state of environment.
6.7	The same conditions as above	Restriction for adding the substances according to Standard 4.2.3	Obtain the substances generating easy-to-detect and easy-to-measure field in the environment itself	4.2.4 Such substances can be obtained by decomposition of environment or change of the aggregate state of matter.
Aim: Substances Management in Su-Fields				

7.1	Complete Su-Field	Restriction to add new substances	1. "Emptiness" and/or a field is used in spite of substance. 2. External addition is used in spite of internal one. 3. Substance is added in the form of chemical compound giving off the needed substance. 4. Particularly active addition in very small doses is used. 5. Usual substance in very small doses is added but only at certain points of a subsystem. 6. Addition is used for a while. 7. Technique model, to which substances can be added, is used in spite of the technique. 8. Addition is obtained from the technique itself, its subsystems, or environment by decomposing it using, for example, changing the aggregate state of matter.	5.1.1
7.2	Complete Su-Field	Substance's direct production is impossible	Destroy substance of the closest higher ("full" or "excessive") structure level (e.g., molecules) to obtain its parts (e.g., ions).	5.5.1
7.3	Complete Su-Field	Substance's direct production and destruction are impossible	Integrate a substance of the closest lower ("non-full") structure level (for example, ions).	5.5.2
7.4	Complete Su-Field	A technique is unchangeable and tool replacement or addition of substances is not allowed	Separate substance(s) into parts interacting with each other and use them as a tool.	5.1.2 Separation into parts charged positively and negatively. If all substance's parts have the same electrical charge, another substance should have the opposite charge.
7.5	Complete Su-Field	Added substance must disappear after being used	Make additive substance indistinguishable from the technique substance or in environment.	5.1.3
7.6	Add a lot of substance	Much of substance cannot be added	Use "emptiness" substance as inflatable constructions (macrolevel) or foam (micro-level).	5.1.4 Standard 5.1.4 is often used along with other Standards.
Aim: Add Fields in Su-Fields				

8.1	Complete Su-Field	No restrictions	Use already available ("hidden") fields carrying by substances existing in the technique.	5.2.1. Using existing fields
8.2	Complete Su-Field	Standard 5.2.1 is inapplicable	Use fields from an environment.	5.2.2. Fields from environment
8.3	Complete Su-Field	Standards 5.2.1 and 5.2.2 are inapplicable	Use fields that can be generated by the technique's substances or environment.	5.2.3. Substances as sources of fields Utilize magnetism of ferromagnetic substances used in the technique only mechanically for better interaction between subsystems, for revealing information, etc.
Aim: Forcing of Measuring Su-Fields				
9.1	Complete Su-Field	Changes cannot be directly detected or measured. A field cannot be passed via the system	Excite resonance vibrations (in the whole system or its part), and changes in frequency of these vibrations serve as indications of changes taking place in the system itself.	4.3.2
9.2	Complete Su-Field	Same as above + Standard 4.3.2 cannot be applied	Obtain information about the technique from the changes in intrinsic frequency of a subsystem (environment) related/added to the monitored technique.	4.3.3
Aim: Growth of Efficiency for Physical Effects Applications				
10.1	Su-Field's component must be in various states	Periodically, from time-to time, or occasionally	Use reversible physical transformations (e.g., phase transitions).	5.4.1 Transition by the subsystem itself is due to ionization-recombination, dissociation–association, etc. Also Standard 5.3.4.
10.2	Su-Field has a "weak" input	Cannot increase input, but a "strong" output is needed	Use the substance-transformer into the state close to the critical one. Energy is accumulated in the substance, and an input signal plays a part of "trigger."	5.4.2 Goal here is to obtain a "strong" output, usually in the form of a field.

With this format, a designer can go from the repository to some solution principles through the use of functions and TRIZ solution Principle suggestions. He or she can then arrive at Standard Solutions, as well as a matching problem formulation according to Table 3.6 with a directed course of action.

3.3.2.4 Apply Physical Effects

The TRIZ catalog of Physical Effects contains 30 different required effects and the corresponding phenomenon that can cause the required effect. In addition to these effects and phenomenon, a correlation to the energy transfer function involved in the phenomenon to cause the required effect is listed for each phenomenon. The purpose of this is twofold, 1) to help narrow down the phenomenon by limiting them to those that fit to the established function structure, and 2) to further link the effects to the design repository that is based on the energy transfer functions as developed by Matthias Messer [69]. This table of Required Effects, Phenomenon, and Functional Energy Transformation is listed in Table 3.7.

Table 3.7: Physical Effects and Phenomenon

Required effect		Function(s) (Energy Input → Energy Output)	Phenomenon
1	Measuring Temperature	Magnetostatic → Sound	Barkhausen effect
		Thermal → Electrical	Thermoelectrical Phenomena
		Thermal → Material Properties	Change in optical, electrical, and magnetic properties
		Thermal → Mechanical	Thermal expansion and its influence on natural frequency of oscillations
		Thermal → Pneumatical/Hydraulic	Thermal expansion and its influence on natural frequency of oscillations
2	Lowering Temperature	Electrostati→ Thermal	Peltier, Seebeck, and Thomson effects
			Thermoelectrical Phenomena
		Mechanical →Thermal	Joule-Thomson effect
		Magnetostatic → Thermal	Magnetic calorie effect
		Pneumtical/Hydraulic →Thermal	Joule-Thomson effect
		Thermal → Chemical	Phase Transition
3	Raising Temperature	Chemical → Thermal	Absorption of radiation by the substance
		Electrostatic → Magnetostatic	Eddy Currents
		Electrostatic → Thermal	Dielectrical Heating
			Eddy Currents
			Electrical Charges
			Electromagnetic induction

			Electronic Heating Peltier and Thomson effects Thermal-electrical phenomena
		Mechanical → Thermal	Vortical currents
		Thermal → Material Properties	Surface effect
4	Stabilizing Temperature	Thermal → Chemical	Phase Transition
		Thermal → Thermal	Evaporation
5	Indication of position and location of object	Chemical → Signal	Emission of light Introduction of marker substances Radioactive and Xray radiation
		Eletrostatic → Signal	Changes in electrical field Electrical discharge Emission of light
		Light → Signal	Reflection of light Luminescence
		Magnetostatic → Signal	Changes in magnetic field
		Mechanical → Signal	Deformation
		Mechanical → Sound/Light/Thermal	Doppler effect
6	Controlling location of objects	Electrostatic → Mechanical	Applying electrical field to influence charged object.
		Light → Mechanical	Light pressure
		Magnetosatic → Mechanical	Applying magnetic field to influence an object or magnet linked to object. Applying magnetic field to influence a conductor with DC current going through
		Mechanical → Mechanical	Mechanical oscillations Centrifugal forces
		Pneumatical/Hydraulic → Mechanical	Pressure transfer in liquid or gas
		Thermal → Mechanical	Thermal expansion
		Thermal → Pneumatical/Hydraulic	Thermal expansion
7	Move liquid or gas	Chemical → Material Properties	Toms effect
		Electrostatic → Mechanical	Capillary force
		Mechanical → Mechanical	Wave movement Capillary force Centrifugal forces Weissenberg effect
		Mechanical → Pneumatic/Hydraulic	Bernoulli's effect
		Pneumatical/Hydraulic → Pneum./Hydr.	Bernoulli's effect
		Thermal → Mechanical	Osmosis
		Thermal → Pneumatic/Hydraulic	Osmosis
8	Control of aerosol flow	Electrostatic → Chemical	Electrolysis
		Electrostatic → Mechanical	Applying electrical fields

	(dust, fog, smoke)	Light → Pneumatical/Hydraulic	Pressure of light
		Magnetosatic → Mechanical	Applying magnetic fields
9	Forming Mixtures	Electrical → Electrical	Electrophoresis
		Material properties change	
10	Separation of Mixtures	Material properties change	
11	Stabilization of position of objects	Electrostatic → Mechanical	Applying electrical fields Fixing in liquids which harden in magnetic and electrical fields
		Magnetostatic → Mechanical	Applying magnetic fields
		Mechanical → Mechanical	Reactive Force
		Mechanical → Signal	Gyroscope effect
12	Generation and/or manipulation force	Chemical → Mechanical	Osmosis
		Chemical → Pneumatic	Osmosis
		Chemical → Thermal	Osmosis Use of explosives
		Electrostatic → Material Properties	Changing the hydrostatic forces via influencing pseudo-viscosity of an electro conductive or magnetic liquid in a magnetic field
		Electrostatic → Mechanical	Electro-hydraulic effect
		Magnetostatic → Material properties	Applying magnetic field through magnetic material phase transitions
		Mechanical → Mechanical (Magnetostatic → Magnetostatic)	Effect of a magnetic field via ferromagnetic substance
		Mechanical → Mechanical	Centrifugal forces
		Pneumatical/Hydraulic → Mechanical	Generating high pressure
		Thermal → Mechanical	Thermal Expansion
		Thermal → Pneumatical/Hydraulic	Thermal Expansion
13	Changes in friction	Electrostatic → Mechanical	Johnson-Rhabeck effect
		Material Property Change	Abnormally low friction effect Kragelsky Phenomenon No-wear friction effect Oscillation Radiation Influence
14	Destruction of object	Chemical → Chemical	Induced radiation
		Chemical → Thermal	Induced radiation
		Electrostatic → Mechanical	Electrical discharges Electrohydraulic effect
		Light → Thermal	Use of lasers
		Mechanical → Mechanical	Cavitation Resonance
		Mechanical → Sound	Ultrasonics
		Sound → Mechanical	Resonance Ultrasonics
15	Accumulation	Mechanical → Chemical	Phase Transition

	of mechanical and thermal energy	Mechanical → Mechanical	Elastic deformation Gyroscope
		Pneumatical/Hydraulic → Chemical	Phase Transition
16	Transfer of energy	Chemical → Light	Induced radiation
		Electrostatic → Electrostatic	Superconductivity
		Electrostatic → Mechanical	Electromagnetic induction
		Light → Light	Fiber optics Lasers Light reflection Radiation
		Magnetostatic → Electrostatic	Electromagnetic induction
		Magnetostatic → Magnetosatic	Electromagnetic induction
		Magnetostatic → Mechanical	Electromagnetic induction
		Mechanical → Electrostatic	Electromagnetic induction
		Mechanical → Mechanical	Alexandrov Effect Deformations Oscillations Waves, including shock waves
		Thermal → Electrostatic	Superconductivity
		Thermal → Thermal	Convection Thermal conductivity
17	Influence on a moving object	Electrostatic → Mechanical	Applying electrical fields (no-contact influence instead of physical contact)
18	Measuring a dimensions	Electrostatic → Signal	Applying and reading magnetic and electrical markers
		Mechanical → Signal	Measuring oscillations' natural frequency
19	Changing a dimensions	Electrostatic → Mechanical	Electrostriction (Piezoelectrical effect)
		Magnetostatic → Mechanical	Magnetostriction
		Magnetostatic → Pneumatical/Hydraulic	Magnetostriction
		Magnetostatic → Sound	Magnetostriction
		Mechanical → Electrostatic	Electrostriction (Piezoelectrical effect)
		Mechanical → Magnetostatic	Magnetostriction
		Mechanical → Mechanical	Deformations
		Pneumatical/Hydraulic → Magnetostatic	Magnetostriction
		Thermal → Mechanical	Thermal expansion
		Thermal → Pneumatical/Hydraulic	Thermal expansion
20	Detect surface properties and/or conditions	SIGNAL OUTPUT	
21	Measuring surface properties	Electrical → Signal	Electrical discharge Electronic emission
		Light → Light	Ultraviolet radiation
		Light → Signal	Auger spectroscopy
		Mechanical → Material	Bauschinger effect

		Properties	Diffusion
		Mechanical → Mechanical	Friction Mechanical oscillations
		Sound → Mechanical	Acoustical oscillations
		Sound → Sound	Acoustical oscillations
22	Inspection of state and properties in volume	Chemical → Signal	Introduction of "marker" substances which are capable of transforming an existing field (such as luminophores) or generating their own (such as ferromagnetic materials) depending on structure and/or properties. Nuclear magnetic resonance Ultrasonics, the Moessbauer effect
		Electrostatic → Signal	Changing electrical resistance depending on structure and/or properties' variations Electric optical phenomena Electronic paramagnetic resonance
		Light → Signal	Interaction with light Polarized light X-ray and radioactive radiation
		Magnetostatic → Electrostatic	Hall effect
		Magnetostatic → Mechanical	Magneto-elastic effect
		Magnetostatic → Signal	Magnetic optical phenomena Transition over the Curie point
		Magnetostatic → Sound	Barkhausen effect
		Mechanical → Signal	Measuring inherent frequency of oscillation
23	Changing the volume properties of an object	Chemical → Material Properties	Phase Transition Ultraviolet, X-ray, radioactive radiation. Diffusion
		Electrostatic → Material Properties	Changing the properties of liquids under the action of electrical fields. Ionization under the effect of an electrical field.
		Light → Material Properties	Photochromatic effect
		Magnetostatic → Light	Magnetic-optical effects
		Magnetostatic → Material Properties	Changing the properties of liquids under the action of magnetic fields. Introduction of ferromagnetic substance and action of magnetic field.
		Mechanical → Material Properties	Bauschinger effect Cavitation
		Mechanical → Mechanical	Deformation
		Thermal → Electrostatic	Thermoelectrical effects
		Thermal → Magnetostatic	Thermomagnetic effects
		Thermal → Material Properties	Heating
24	Develop certain structures,	Chemical → Material Properties	Phase Transition
		Magnetostatic → Mechanical	Magnetic waves

	structure stabilization	Mechanical → Material Properties	Cavitation
		Mechanical → Mechanical	Interference waves Standing waves Mechanical oscillations
		Signal Property	Moire effect
		Sound → Mechanical/	Acoustical oscillations
		Sound → Sound	Acoustical oscillations
25	Detect electrical and/or magnetic fields	Chemical → Signal	Nuclear magnetic resonance
		Electrostatic → Pneumatical/Hydraulic	Osmosis (from previous edition, assumed to be Electro-osmosis)
		Electrostatic → Electrostatic	Electrical discharges Electronic emissions
		Electrostatic → Material Properties	Electrification of bodies
		Electrostatic → Mechanical	Electrostriction (Piezoelectrical effect)
		Electrostatic → Signal	Electro-optical phenomena Electrets
		Magnetostatic → Electrostatic/Signal	Gyromagnetic phenomena
		Magnetostatic → Electrostatic	Hall effect
		Magnetostatic → Signal	Magnetic - optical phenomena
		Magnetostatic → Sound	Barkhausen effect
		Mechanical → Electrostatic	Electrostriction (Piezoelectrical effect)
26	Detect radiation	Light → Signal	Luminescence Photoeffect Photoplastic effect
		Thermal → Signal	Thermal expansion
		Sound → Signal	Optical-acoustic effect
27	Generation of electromagneti c radiation	Chemical → Chemical	Induced radiation
		Chemical → Light Energy	Cherenkov effect
		Electrical → Light	Luminescence Gunn effect
		Mechanical → Electrical	Josephson effect
		Mechanical → Mechanical	Tunnel effect
28	Control of electromagneti c fields	Electrical → Electrical	Screening/Farady Cage
		Electrical →Magnetostatic	Screening/Farady Cage
		Magnetostatic → Electrical	Screening/Farady Cage
		CHANGES IN MATERIAL PROPERTIES	Changing properties (i.e. varying electrical conductivity)
			Changing the objects shape
29	Controlling light. Light modulation	Electrostatic → Light	Electrical optical phenomena Gunn effects Kerr effect
		Electrostatic → Magnetostatic	Faraday effect
		Electrostatic → Material Properties	Franz-Keldysh effect
		Light → Light	Refraction and reflection of light

		Light → Signal	Photoelasticity
		Magnetostatic → Electrostatic	Faraday effect
		Magnetostatic → Light	Magnetic optical phenomena Faraday effect
30	Initiation and intensification of chemical changes	Chemical → Material Properties	Ultraviolet, X-ray, radioactive radiation. Micellar catalysis
		Electrostatic → Material Properties	Electrical discharges
		Mechanical → Material Properties	Cavitation Shock waves
		Sound → Chemical	Ultrasonics
		Sound → Mechanical	Ultrasonics

Scanning through the Table 3.7 for the most applicable option, we come across Physical Effect #12, "Generation and or manipulation of force", which has the corresponding phenomenon for Mechanical → Mechanical energy transformation of applying a magnetic field via ferromagnetic substance.

So there are a number of sources within the application of Standards as well as the Effects table that suggest magnetic forces. Indeed, adding a magnetic force even separates the conflict in time by allowing the spring force to be weaker at one time and stronger at another. First, depending on the substance that the spring is pushing on, the surface and the spring could be magnetized to repel each other, but this surface is unknown so the solution cannot be used. Another solution would be to magnetize the windings of the spring in such a way as to create a supplementary repellant force upon compression. Such a solution would not require the spring to be changed in any material or geometric fashion, so this could be approaching the Ideal Final Result.

3.3.2.5 Apply the 40 Principles.

The technical contradictions (both forward and reverse) described in Section 3.3.1.4 are correlated to solution principles using the TRIZ contradiction matrix, Table A.6. The matrix correlates the conflict of 2 of 39 design characteristics with a few (between 1 and 4 usually) general solution principles that have worked in past solutions.

There are 40 of these solution principles, and they are numbered 1-40 (see Appendix Table A.7-Table A.9). The following Table 3.8-Table 3.10 are lists of the suggested solution principles with explanations and solution ideas following the conflict that is correlated to these solution principles.

Table 3.8: Solution Principles from TRIZ Matrix-Force vs. Complexity

Technical Conflict: **Improving the force, worsens complexity**
26[3]. Copying
▪ Instead of an unavailable, expensive, fragile object, use *simpler and inexpensive copies.*
35. Parameter changes
▪ Change an object's *physical state* (e.g. to a gas, liquid, or solid.)
▪ Change the *concentration or consistency*.
▪ Change the *degree of flexibility*.
What if the material is hardened through annealing or using a thicker wire?
▪ Change the *temperature.*
10. Preliminary action
▪ *Perform, before it is needed, the required change* of an object (either fully or partially).
What if the spring is a pre-compressed spring?
▪ *Pre-arrange objects* such that they can come into action from the most convenient place and without losing time for their delivery.
18. Mechanical vibration
▪ Cause an object to *oscillate or vibrate.*
▪ Increase its *frequency* (even up to the ultrasonic).
▪ Use an object's *resonant frequency.*
▪ Use *piezoelectric vibrators* instead of mechanical ones.
▪ Use *combined ultrasonic and electromagnetic field oscillations*.

Table 3.9: Solution Principles from TRIZ Matrix-Complexity vs. Force

Improving *complexity*, worsens *force*
16. *Partial or excessive actions*
• If 100 percent of an object or force is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.

[3] This numbering corresponds to the assigned numbering for the 40 inventive principles in TRIZ, and is used in the contradiction matrix.

Table 3.10: Solution Principles from TRIZ Matrix-Force vs. Shape

Improving *force*, worsens *shape*
40. Composite materials
• Change from uniform to composite (multiple) materials.
What if the spring is dipped into a metallic material to coat it which would make it stiffer?
34. Discarding and recovering
• Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.
• Conversely, restore consumable parts of an object directly in operation.

3.3.2.6 Iterations

If a sufficient solution is not found by going through the previous steps, it should be helpful to repeat steps now that more information has been gained by progressing through them once already and gaining insight from some of the 40 principles. This iteration includes the following steps:

3.3.2.6.1 Apply Su-Field Analysis.
3.3.2.6.2 Apply Standard Solutions.
3.3.2.6.3 Change the mini-problem
3.3.2.6.4 Revisit your conflict (Analyze the Conflict)
3.3.2.6.5 Chose the "other" version of the conflict.
3.3.2.6.6 Reformulate another conflict after the mini-problem

3.3.3 Select Suitable Combinations of Concept Variants or Solutions (Preliminary selection)

Upon completion of the solution search for this problem, a table was populated containing all of the viable solution possibilities generated from the solution search, shown in Table 3.11. This table is categorized by the level on which the problem was solved (Physical or Technical), and in the case of the technical contradictions, the contradiction that yielded that particular solution. Also contained in the table is the specific aspect from TRIZ that triggered this solution and possible shortcomings or lack of information associated with that solution.

Table 3.11: Concept Variants with Source and Problematic Features

Physical level solution	Solution Principle/Solution Trigger	Problematic features/ Information required
1) Depending on the substance that the spring is pushing on, the surface and the spring could be magnetized to repel each other.	Su-Field Modeling →Standard Solution → Physical Effects→"effect of magnetic field via ferromagnetic substance"	Material interacting with spring, force required, magnetization required
2) Magnetizing the spring such that internal forces are created when the spring is compressed. (Perpendicular magnetization)	Su-Field Modeling →Standard Solution →Physical Effects→"effect of magnetic field via ferromagnetic substance" OR "separating opposite physical states in time or space"	Material of spring, force required, magnetization required, non-linear force
Technical Level Solution		
Improving the force worsens complexity		
3) Use another spring inside the existing spring	Copying	Availability of new spring, supporting structures, clearance
4) Heat treatment	Parameter changes	Current state of spring, effect heat treatment has, insufficient force
5) Pre-compression	Preliminary action	Amount of pre-compression required, clearance in spring, reduced clash allowance, means of pre-compression, higher initial force
Improving the complexity worsens force		
6) Higher initial displacement	Partial or excessive actions	Higher initial force, clearance in spring, reduced clash allowance, total increased force
Improving the force worsens shape		
7) Coating the spring in a metallic or stiff-elastic material.	Composite materials	Determining suitable material and thickness, cracking, controlling thickness, not damaging heat treatment
8) Cutting spring to increase spring rate	Discarding and recovering	End conditions of spring, spring clash

To compare the results of this study, some of the most promising solutions are selected for calculations to determine, quantitatively, their feasibility and preference. To determine which concepts should be considered for further design, potential solutions are analyzed in terms of minimizing problematic effects of using a spring out of its intended design parameters and/or minimizing required information and design variables. Weighting factors displayed in the top portion of Table 3.12 are applied to the design problems to quantify their relative importance through the discretion of the designer.

These weighting factors are then applied to the solution variants with rationale to allow for the variants to be compared to each other and to a control example of a complete redesign, as shown in the lower portion of Table 3.12 under the heading View

Points. A complete redesign is defined as an undesirable solution, yet helpful as a base from which a worst-case scenario can be built. Solutions falling short of this measure in terms of problematic features and required information are obviously discarded, while the remainders are ranked in order of the distance from this scenario. For reference, an entirely new spring would rank as a 3 because the benefit of not having to replace the spring is nullified by the act of replacing it. In Table 3.12, the numbers next to each of the viewpoints correspond to the design variants from the previous Table 3.11.

Table 3.12: Weighting Factors for Selection and View Points

Assessment	**Factor**
Required information unattainable	3
Required information unreliable/variable from design to design	2
Required information difficult to obtain	1
Problematic feature nullifies benefit	3
Problematic feature breaks a design requirement	2
Problematic feature lessens/interferes with benefit	1
View Points	
1) The surface the spring acts on is unknown. Required information unattainable:3	3
2) The magnetization may not be strong enough, and the force might not be linear: Problematic feature lessens/interferes with benefit: 1	1
3) Spring may not be able to be positioned reliably inside of spring, and may need extra parts: Problematic feature lessens/interferes with benefit: 1 + Required information difficult to obtain: 1	2
4) If the spring is not already annealed, doing so might not be sufficient, therefore not fulfilling a design requirement: Problematic feature breaks a design requirement: 2	2
5) Pre-compression, by means of clips or straps for example, would be comparable to increased initial displacement, see below: Problematic feature nullifies benefit: 3	3
6) There is a designed 15% clash allowance in the spring, and any increased initial displacement would eliminate that, furthermore, and additional compression still would not amount to the full required force even at shut height and would increase the lower end. Problematic feature nullifies benefit: 3	3
7) There is a possibility of cracking the coating if applied incorrectly, and the difficulty in applying it evenly. Problematic feature lessens/interferes with benefit: 1	1
8) Cutting a spring will increase the spring rate, however the spring would clash at the required displacement. Problematic feature breaks a design requirement: 2	2

The results of this assessment are displayed visually in Figure 3.11. Since there are two concepts that scored a 1, and the minimization of problematic features is desired, this leads to 3 design scenarios:

Scenario 1) The “control” or redesign of the spring.

Scenario 2) Magnetization of the spring, as this causes the least disturbance to the original system. (#2)

Scenario 3) Coating the spring in another metal to thicken the wire. (#7)

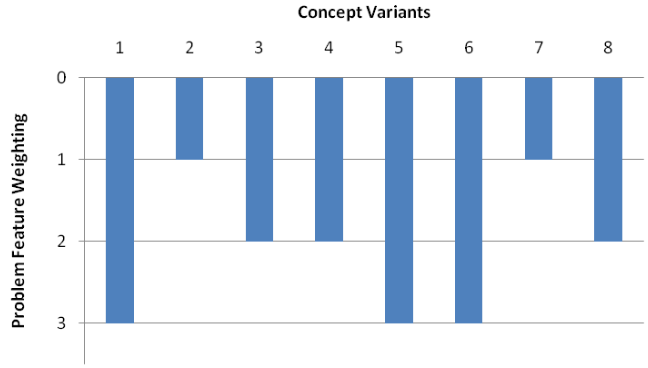


Figure 3.11: Preliminary Selection: Minimization of Problematic Features

3.3.4 Analysis of Design

Of the three design scenarios identified, one must be selected as the principal solution. To do this, the solutions are analyzed in more detail, both quantitatively and qualitatively.

3.3.4.1 Quantitative analysis of design

Scenario 1: Redesign of the Spring

Maintaining the same overall geometric constraints of the spring (spring index C=7) with no additional modifications required an increased wire thickness from 0.207 inches to 0.217 inches based on the following equation [74]:

$$d = \left[\frac{8 \cdot C \cdot N_{fs}}{0.67 \cdot \pi \cdot A} \cdot \left[K_s \cdot F_m - \frac{N_{fs} - 1}{N_{fs}} \cdot K_s \cdot F_{\min} + \left(\frac{0.67}{0.5} \cdot \frac{A \cdot d^b}{S_{ew}} - 1 \right) \cdot K_w \cdot F_a \right] \right]^{\frac{1}{2+b}}$$

The terms in this equation are found in the process outlined in Norton, pages 768-773 [74]. This means that a new spring would need to be manufactured and is therefore undesirable.

Scenario 2: Magnetization (solution #2)

In order for the spring to have an increased force due to magnetism, the magnetic field must be oriented perpendicular to the axis of the spring so that poles become closer to their same poles on adjacent coils, as shown in Figure 3.12. The arrow represents the magnetic field (B), and the S and N represent the corresponding South and North poles. This magnetization is obviously performed on an existing spring, making it simple to implement.

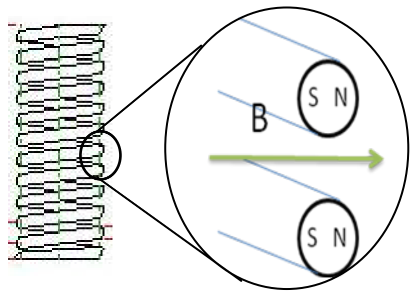


Figure 3.12: Cross Section of Magnetized Spring

To determine the amount of magnetization required, knowing the required maximum force for the 1 inch deflection, the following formula was used:

$$F_r(\vec{r}, \alpha, \beta) = -\frac{3\mu_0}{4\pi}\frac{m_2 m_1}{r^4}\left[2\cos(\phi-\alpha)\cos(\phi-\beta) - \sin(\phi-\alpha)\sin(\phi-\beta)\right]$$

Where α =0, φ= 90^{O}, β=0, m_1=m_2,F_r = 44.48 N, and the coil distance, r=2.54 $x10^{-4}$. This yields a required magnetic moment of 2.484 $x10^{-4}$ Am^2 for each coil. Dividing by the volume of a coil, the required magnetization is 990 A/m, which is an achievable goal, as iron can have a magnetization of up to 1 million A/m.

Scenario 3: Spring Coating (solution #7)

To specify the thickness on the coating of the spring, the coating itself is modeled as a hollow spring and calculated in a similar fashion to a normal spring, yet with a different moment of inertia. This allows for the coating to be modeled separately from the main spring, so they are treated as two parallel springs, therefore the spring rates are added. The reason for doing this and not just using the calculations for the new spring thickness is that the materials will have different elastic properties, and it is not possible to coat the spring with the same material it is made of. Equations to determine the stress within the material and also the spring rate remain the same when arranged to be a function of the moment of inertia.

Bronze was selected as a suitable coating material due to the lower melting temperature it has in comparison to the spring steel. Bronze also adheres to steel well and does not need an intermediary metal. Assuming a coating of bronze, with a shear modulus of 5.90E+06 psi and an ultimate stress of 100,000 psi, the required thickness came to be 0.011 inches. This is a feasible thickness because it is not too thick, i.e. it will not cause the spring to clash. When a polymer was investigated, the thickness required caused the spring to clash.

To further analyze which solution should be selected, the design with the minimal usage of energy and/or material should be selected. An entirely new spring would certainly require the most material and energy to manufacture. A coated spring would require the coating material and a sufficient amount of energy to coat the spring. This could be done through a number of processes ranging from simply melting the metal on to the spring in a process similar to brazing, or by some form of vapor deposition or sputtering. Recall that the thickness required is only 0.011 inches, so whatever means are available could be employed. The final design suggestion, that of magnetizing the spring, would not require any material at all, and only the energy required to sufficiently magnetize the spring. Therefore the most accessible solution seems to be magnetizing the spring.

Principal Solution: Magnetized spring.

3.3.4.2 <u>Qualitative analysis of design</u>

To review the worth of the proposed solution, the principal variant is analyzed qualitatively by posing the following questions [94] [65] :

- *Does your solution meet the requirements of the IFR?*
- *Which contradiction has been eliminated by the solution?*
- *Is the solution suitable for real manufacturing or one-time production?*
- *If you can't use the solution for satisfying the entire problem, can you use the solution for part of the system or cycles of the system?*
- *Are there any other problems as a result of your solution?*
- *What is the maximum usage of the solution?*
  - *What needs to be changed in the supersystem for this solution?*
- *Can the changed system (changed, due to your solution) have new and different applications?*
- *Can you solve other problems with this solution?*

Using the qualitative analysis of the design for spring magnetization, the solution does in fact *satisfy the Ideal Final Result* because "the spring is improved to specifications (very nearly) without using any material resources. The solution also *removes the physical contradiction* because "the spring is not changed in [geometrical] complexity so that it is easy to implement the solution, yet the spring is changed in order to increase the force." The *solution can also be implemented in the world of practice* because the calculations show that the required magnetization is not excessive, i.e., the level of magnetization does not require a magnet stronger than what would be readily available. One of the problems is that the force isn't linear, but over the short range and limited force required, it is reasonable to conclude that this is not a prohibitive problem for a spring that is not being replaced with one specifically designed for the new conditions. A maximal usage of the problem would be that a spring manufacturer would magnetize all of their springs after manufacture, as a matter of course, much in the way that springs are annealed after being formed. This is one of the key ways that the system promotes innovation. Without this question, the solution stays confined to the individual problem, and the state of the art in that particular field is not advanced. With this question comes topics for further investigation: If long term use were intended, a more thorough analysis would have to be done to determine how failure modes would be affected by magnetizing the spring. Also, if the coating were chosen, what other properties would be affected?

Can the changed system have new and different applications? One that comes to mind is for using the magnetic field set up in the spring to make a force curve that is not linear. In this example we were not concerned with the spring remaining linear in force profile, however, it is certainly possible to use this effect to create a exponential force profile if one so desired. This is the key question to ask to promote research; it basically asks what have we learned in the design of this product that hasn't been done in other fields. If it hasn't been done, why not? Why science must we do to advance the field? Going back to the spring, another problem that might be potentially solved is that a positive side effect of having a magnetized spring is that it would collect iron shavings circulating in a machine if it were placed in such an environment. All in all, the point of this exercise is to pull as much out of the design as possible to push the technology forward.

3.4 CHAPTER CLOSURE

Presented in this thesis is an approach for design that augments the systematic process of Pahl and Beitz with TRIZ, structured through ARIZ. This approach is intended to equip designers with an approach that covers the design process starting from the task, through to the detail design phase, while having a detailed emphasis on conceptual design. This focus was chosen because it is in the conceptual design phase where problems are framed and a direction is set for the entire process. It is also in this phase that there is the possibility to work across domains by using the TRIZ tools that abstract the problems to the essential problem, and suggest general solution principles that can be applied in a new domain. Previous combinations of TRIZ and Pahl and Beitz have been explored [64], however, those only intended to make use of the problem solving techniques. To be sure, this is gained, however much more can be gained with the possibility of transferring solution principles (or things that trigger a solution in the mind of a designer) to a domain that better serves the solution of the design. The potential utility in this work is that designers, especially those familiar with a combined method, can consider how the solution principles encountered are applicable in sub-domain design by analogy.

In this work, the sub-domain was the materials domain, and this was seen on two length scales (molecular and micro scale) in the final design variants; the alignment of magnetic poles within the material and the coating of the material with a new substance. While these solutions may not be altogether unique, or even found only through this process, the structure of this process is presented to promote the possibilities of transfer between domains. This transfer from product to material is simply a type of transfer, and can represent other possible transfers that the use of an abstracted, analogical design process allows. It is very possible that this notion is also applicable between even mechanical and electrical or biological domains. This is due to the fact that the problems and solutions are abstracted and generalized, yet the designer does not need to specify in what domains the transfer will take place.

The importance of being able to design across domains concurrently is seen in the broadening of the design space. In the conceptual design phase it is beneficial to broaden the design space so that it is more likely to find a suitable final design. Also, TRIZ gains functionality towards broadening the design space by being united with Pahl and Beitz due to the function structure, requirements list, and general setting in a comprehensive design process. The link to the design repository further broadens the design space, as this allows a designer to cover previous designs so that a design isn't redesigned if it doesn't need to be.

With a broad design space comes the necessity to trim the results down to select a final solution. While preliminary selection can be approached a variety of ways, what is particularly helpful in the approach presented is the steps offered by TRIZ to analyze the solution. The Pahl and Beitz approach goes as far as to provide the designer with a requirements list to evaluate the solution, and TRIZ extends that by assisting the designer define what is the ideal solution and not just the required solution. This increases the likelihood of designing good solution in a shorter amount of time and helps the designer aim for an innovative solution through the process.

3.5 VERIFICATION AND VALIDATION – THEORETICAL STRUCTURAL VALIDITY

In this chapter, theoretical structural validation as one aspect of the validation square is addressed. An overview of the validation strategy is presented in Section 1.2.3. A graphical representation of how this chapter fits into that overall strategy is displayed in Figure 1.11. Theoretical structural validation refers to accepting the validity of individual constructs used in the systematic approach and accepting the internal consistency of the way the constructs are assembled. Theoretical structural validation is performed in this chapter using a procedure consisting of 1) defining the method's range of applicability, *b)* reviewing the relevant literature to identify the strengths and limitations of the constructs contained therein, and *c)* identifying the gaps in the existing literature resulting from those weaknesses, and *d)* determining which constructs are to be used in the approach over the defined range of application. The internal consistency of the individual constructs is checked by a critical review of the literature, and by things such as flow charts. The question is asked, Is the information out of one step sufficient information for the next? If there is a mismatch in information flow, the structure is not valid, but as is the case presented here, the flow charts are used to show the internal consistency.

CHAPTER 4

PRODUCT AND MATERIALS DESIGN CATALOGS INTEGRATED WITH SYSTEMATIC PROBLEM SOLVING TOOLS

In this chapter, the question of - "How should function structures and problem formulation be connected to solution triggers at the appropriate length scales for materials design?" – is addressed through a description of the tools implemented in APTCD method. These tools and catalogs addressed are implementations of the design method constructs presented earlier. Where in Chapter 3 the conceptual design tools are used with the emphasis on explaining the method as a whole during the illustrative example, in this chapter, the conceptual design tools and their constructs are expounded. These constructs namely are the design catalogs for phenomena and associated solution principles together with the TRIZ attention and process directing tools to facilitate systematic conceptual materials and product design.

4.1 AIDING SYSTEMATIC CONCEPTUAL DESIGN BY IMPLEMENTING PROBLEMS SOLVING TOOLS AND FUNCTION BASED CATALOGS - OVERVIEW OF DESIGN CATALOGS BY MATTHIAS MESSER

Matthias Messer argued, "In order to systematically map phenomena to a functional relationship and associated solution principles to the most promising phenomena during function-based systematic design, identifying and determining multiscale phenomena and associated solutions principles is crucial. Hence, use of a classified collection of phenomena and associated solutions principles facilitates function-based systematic design of product and material concepts from a systems perspective in an integrated fashion to avoid "reinventing the wheel". [69] Therefore Messer developed classification schemes that incorporate phenomena and associated solution principles from multiple disciplines to support the designer in identifying and determining phenomena and associated solution principles at the material and product levels. These two constructs, phenomena and associated solution principles must first be understood before building on them. They make up the foundation of the Messer catalogs due to the notion of bounded rationality. Bounded rationality is the concept that individuals are limited in their cognitive abilities, information available, and time allowed to making decisions. [118] When this limitation is applied to the task of conceptual design, particularly at the intersection of materials and products, it becomes apparent that in order to capture the widest range of expert knowledge to make available to a bounded designer, that information must be digested in some fashion and presented in a meaningful and useable way. Thus, the focus is placed on phenomena and associated solution principles that cause particular affects so as to provide solutions to a variety of problems. "Phenomena and associated solution principles can thus help designers as creatures of bounded rationality incapable of dealing with the world in all of its complexity to form simplified pictures of the world." [101]

4.1.1 Phenomena

This section (4.1.1 and all subsections), serving as one of the building blocks for this thesis, is leveraged from Matthias Messer's dissertation (Chapter 4 Section 3) with some modification. [69]

Phenomena are described quantitatively by means of laws governing the quantities involved. In other words, phenomena can be described by the laws of physics and mathematics. For example, the operation of a bi-metallic strip is the result of a combination of two phenomena, namely thermal expansion and elasticity. A sub-function can often be fulfilled by one of a number of phenomena. For example, a force can be amplified by the mechanical lever phenomenon, fluid-mechanical hydraulic lever phenomenon, or electromagnetic phenomena. Messer's focus in the creation of his catalogs was on developing classification schemes for integrated product and materials design, providing phenomena and associated solution principles for embodying the most prominent functional relationships of changing, storing and transforming energy. These generally valid functional relationships were chosen to support eliciting and providing the most product-independent solutions.

Since energy change, storage and transformation phenomena are governed by underlying energy forms, mechanical, pneumatic/hydraulic, electrostatic, magnetostatic, sound, light, thermal as well as chemical, biological and nuclear forms of energy are used as classifying criteria. Considering these forms of energy as system in- and out-puts, phenomena are classified in Table 4.1. Since whenever an entity – from an atom to an ecosystem – undergoes any kind of change, energy must transfer and/or change energy form, this energy-based classification scheme captures the majority of phenomena at a designer's disposal. In essence, this open-ended classification of phenomena is intended to support a designer in identifying underlying phenomena that may lead to generating and designing novel concepts from a systems perspective on multiple levels and scales with enhanced performance and for functionality. For each phenomenon, more detailed associated solution principles may be derived as addressed in Section 4.1.2.

Illustrative examples of novel concepts that can be derived from the phenomena design catalog in the context of integrated product and materials design are described in greater detail in the following sections. It is shown how enhanced system performance and/or functionality can be achieved based on identifying and determining underlying phenomena.

4.1.1.1 Striction and Rheology

Photo-(Electro-, Magneto-)striction is a phenomenon that refers to the application of an optical (electrical, magnetic) energy that alters the inter-atomic distance through polarization. A change in this distance changes the energy of the molecule, which produced elastic energy (strain). This strain deforms or changes the shape of the material. One particular application of electrostriction are *piezoelectric materials*. In piezoelectric materials an input of elastic energy (strain) produces an electrical current. Most piezoelectric materials are bi-directional in that the inputs can be switched and an applied electrical current will produce a deformation (strain).

The piezoelectric effect forms the underlying basis for products as diverse as some types of microphones and speakers or even motors as illustrated in Figure 4.1 b). Also, gas grill fire starters, vibration reducing skis, doorbell pushers and an endless number of position sensors and small actuators are derived from this phenomenon. Photoactuators for example are used in power plants and other commercial and scientific areas such as light-source chasing for devices that would follow light sources. Another interesting example are Zinc oxide nanowires that produce an electrical current and omit light from applied strain as shown in Figure 4.1 a).

Another particular example of electrostriction is a new class of acrylic-based polymers, i.e., *electro-elastomers*, exhibiting phenomenal strains under the influence of applied voltages, far exceeding the performance of piezoelectric or shape-memory materials [28]. An important feature of these elctro-active elastomers is that they may be used in reverse, i.e., when compressed they generate a signal (electric field) and can hence be used for sensor applications. Proposed applications for these electro-elastomers include loudspeaker diaphragms, devices for noise cancellation, unusual types of motors and pumps, etc. as well as multifunctional elctro-elastomer rolls that consist of polymer sheets and suitable flexible electrodes rolled into tubes.

Table 4.1: Design Catalog Phenomena [69]

Input \ Output	**Mechanical Energy** (Potential-/kinetic-/strain-energy)	**Pneumatical-/Hydraulical Energy** (Potential-/kinetic-/pneumatic/hydraulic-energy)	**Electrostatic Energy** (Capacitive-energy)	**Magnetostatic Energy** (Inductive-energy)	**Sound Energy** (Kinetic-energy)	**Light Energy** (Quantum-energy)	**Thermal Energy** (Heat-capacity/-enthalpy)	**Chemical/Biological/Nuclear Energy** (Nuclear-/reaction-/oxidation-energy)
Mechanical Energy (Potential-/kinetic-/strain-energy)	- Inertia (translational/rotational) - Elastic/inelastic deformation (tension/compression/bending/shear/torsion/buckling/fracture/cutting/inversion/extrusion/drawing/flow) - Impact (translational/rotational) - Friction (static/dynamic) - Refraction (waves/particles) - Lever-effect (translational/rotational) - Poisson's-effect (positive/negative) - Stress-induced Martensitic transformation - Force field (gravity/surface-tension/contact-force/atomic-force) - Wedge-effect - Boyle-Mariotte-law - Magnus-effect - Lotus-effect - Resonance - Co-/Adhesion - Capillary-effect - Weissenberg-effect - Load spreading (fixed/flexible constraints or unconstrained) - Blocking and bracing - Topology	- Bernoulli-principle - Viscosity - Toricelli's law - Gravitation - Boyle-Mariotte-law - Impact - Buoyancy - (In)compressibility	- Electrostriction - Induction - Electrokinetic-effects - Electrodynamic-effects - Friction - Capacitance-effect - Josephson-effect - Deformation electrical resistance - Impact-ionization - Stewart-Tolman-effect - Lenard-effect	- Magnetostriction - Induction - Aligning magnetical dipoles - Elastic/inelastic deformation - Barnett-effect	- Impact - Stick-slip-effect - Doppler-effect	- Mechanochromics - Dichroic-effect - Mechanolumin-(fluor-, phosphor-)escence - Doppler-effect	- Pressure state change - Friction - Hysteresis - Turbulence - Inelastic deformation - Joule-Thomson-effect - Doppler-effect - Conduction - Convection - Radiation	- Residual stress - Phase transformations
Pneumatical-/Hydraulical Energy (Potential-/kinetic-/pneumatic/hydraulic-energy)	- Lift - Buoyancy - Turbulence - Magnus-effect - Flow resistance - Backpressure - Reaction principle - Compressibility	- Bernoulli-principle - Continuity-law - Conduction - Absorption - Dalton's-law - Lotus-effect - Von Kármán vortex street	- Electrostriction	- Magnetostriction	- Impact	- Friction - Mechanochromics	- Pressure state change - Friction - Inelastic deformation - Joule-Thomson-effect	- Residual stress - Phase transformations
Electrostatic Energy (Capacitive-energy)	- Electrostriction (piezoelectric materials, electroactive polymers) - Capacitance effect - Coulomb's-law - Johnson-Rhabeck-effect - Biot-Savart-law - Electrokinetic-effects - Friction - Induction	- Electrostriction - Electrorheology - Electrophoresis - Cataphoresis - Electro-osmosis	- Interference - (Super-/Semi-) Conduction - Ohm's-law - Farraday's-law - Impedance - Capacitance-effect - Skin-effect - Quantum tunneling	- Eddy current - Biot-Savart-law - Farraday's-law - Hall-effect - Meissner-effect	- Electrostriction	- Photostriction - Kerr-effect - Pockels-effect - Stark-effect - Electrolumin-(fluor-, phosphor-)escence - Electrochromism - Liquid-crystal/sus-pended-particle effect - Incandescence - Laser-effect	- Joule-heating - Eddy current - Electric arc - Peltier-effect - Hysteresis	- Electrochemistry - X-Ray-effect - Electrodialysis - Electrolysis

Table 4.2: Design Catalog Phenomena (Continued) [69]

Output / Input	**Mechanical Energy** (Potential-/kinetic-/strain-energy)	**Pneumatical-/Hydraulical Energy** (Potential-/kinetic-/pneumatic/hydraulic-energy)	**Electrostatic Energy** (Capacitive-energy)	**Magnetostatic Energy** (Inductive-energy)	**Sound Energy** (Kinetic-energy)	**Light Energy** (Quantum-energy)	**Thermal Energy** (Heat-capacity/-enthalpy)	**Chemical/Biological/Nuclear Energy** (Nuclear-/reaction-/oxidation-energy)
Magnetostatic Energy (Inductive-energy)	- Magnetostriction - Ferro-/electro-magnetism - Christofilos-effect - Induction (Lorentz-effect) - Elihu-Thomson effect - Einstein-de-Haas-effect	- Magnetostriction - Magnetorheology	- Farraday's-law - Hall-effect - Induction (Lorentz force) - Magnetoresistivity	- Interference - (Super-/Semi-) Conduction - Reflection - Total reflection - Refraction - Absorption - Induction - Farraday's-law - Ferromagnetism - Saturation - Remanence	- Magnetostriction - Barkhausen-effect	- Farraday-effect - Zeemann-effect - Cotton-Mouton-effect - Magnetolumin-(fluor-, phosphor-)escence	- Eddy current - Hysteresis - Demagnetization - Thermal Hall-effect (Righi effect)	- Ferromagnetism - Electromagnetism
Sound Energy (Kinetic-energy)	- Sound excitation	- Sound pressure	- Electrostriction	- Magnetostriction	- Reflection - Refraction - Interference - Dispersion - Birefringence - Polarization	- Acousto-optic effect	- Eddy current - Hysteresis - Demagnetization - Thermal Hall-effect (Righi effect)	- Elastic deformation
Light Energy (Quantum-energy)	- Photostriction - Electromagetical radiation pressure	- Electromagnetical radiation pressure	- Photostriction	- Photostriction	- Acousto-optic effect	- Reflection - Refraction - Birefringence - Interference - (Super-/Semi-) Conduction - Photonic crystal effect - Fluor-/phosphor-escence - Fermat's principles - Polarization - Photolumin-(fluor-, phosphor-)escence (Photochromics)	- Thermolumin-(fluor-, phosphor-)escence - Radiation	- Photoeffect - Photoresistor-effect - Photochemical-effect

Table 4.3: Design Catalog Phenomena (Continued) [69]

Input \ Output	**Mechanical Energy** (Potential-/kinetic-/strain-energy)	**Pneumatical-/Hydraulical Energy** (Potential-/kinetic-/pneumatic/hydraulic-energy)	**Electrostatic Energy** (Capacitive-energy)	**Magnetostatic Energy** (Inductive-energy)	**Sound Energy** (Kinetic-energy)	**Light Energy** (Quantum-energy)	**Thermal Energy** (Heat-capacity/-enthalpy)	**Chemical/Biological/Nuclear Energy** (Nuclear-/reaction-/oxidation-energy)
Thermal Energy (Heat-capacity/-enthalpy)	- Temperature change of state - Thermal expansion - Steam pressure - Osmotic pressure - Gas laws - Heat-induced martensitic transformations	- Temperature change of state - Thermal expansion - Steam pressure - Osmotic pressure - Gas laws - Thermophoresis (Soret-effect)	- Thermoelectric-effect - Thermionic emission - Pyroelectricity - Thermal-noise-effect - Conductivity - Semiconductivity - Superconductivity - Curie-Weiss-law	- Curie-Weiss-law	- Thermo-optic effect	- Pyroelectricity - Thermolumin-(fluor-, phosphor-)escence - Thermocromics	- Conduction - Convection - Radiation - Insulation - Condensation - Evaporation - Freezing	- Heat capacity - Phase transformations - Heat induced martensitic transformations - Thermoelectric effect - Stefan-Boltzmann-law - Wien's displacement-law - Destillation
Chemical/ Biological/ Nuclear Energy (Nuclear-/reaction-/oxidation-energy)	- Exothermic reactivity - Osmosis - Molecular-velocity - (De)Sorption - Nuclear fission - Nuclear fusion - Isometric/isotonic contraction - Cell growth	- Exothermic reactivity - Osmosis - Adhesion - Cohesion - Nuclear fission - Nuclear fusion - Chromatography - Effusion - Cell growth	- Electrochemistry - Molecular dipole - Ionization - Fermentation - Bioelectromagnetism - Semiconduction (doping)	- Magnetic-dipole-formation - Bioelectromagnetism	- Exothermic reactivity - Nuclear fission - Nuclear fusion	- Cotton-effect - Combustion - Chemochromics - Chemolumin-(fluor-, phosphor-)escence - Exothermic reactivity - Nuclear fission - Nuclear fusion - Di-/Association	- Combustion - Conduction - Exothermic reactivity - Nuclear fission - Nuclear fusion	- Photosynthesis - Endo-/exo-thermic reactivity - Nuclear fission - Nuclear fusion - Radiation - Absorption - Oxidation/Reduction - Ionic transport - Bohr-effect - Di-/Association/(Dis-)Solution - Adsorption - Electrodialysis - Autolysis - Catalysis - Phase separation - Meiosis - (Bio-)Sensing (antibody, DNA, receptor, enzyme, abzyme, (living) tissue, cell, organelle, isotopes, microbes) - Self-replication/-repair/-assembly/-diagnostic/-destruction/-replication

Magneto-(Electro-)rheology is a phenomenon that refers to the application of a(n) magnetic field (electric field) which causes a change in micro-structural orientation, resulting in a change in viscosity of the fluid. The changes in viscosity when electrorheological or magnetorhelogogical fluids are exposed to electric or magnetic fields, respectively, can be startling. A liquid is seemingly transformed into a solid and back again to a liquid as the field is turned off and on. An electrorheological fluid embedded in an automobile tire, for example, can cause the stiffness of the tire to change upon demand; thus making it possible to tune tires for better cornering or more comfortable highway driving. One can also imagine dampers, chairs or beds with smart rheological fluids embedded so that the relative hardness or softness could be electrically adjusted. However, magneto-(electro-)rheology can also be leveraged to design sculptural pieces, as done by Sachiko Kodama [55] through the use of ferro fluid shown in Figure 4.1 c).

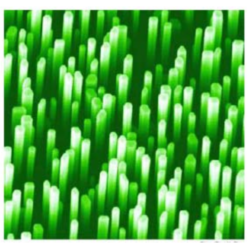
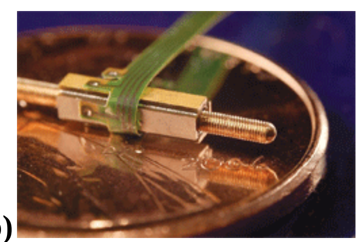
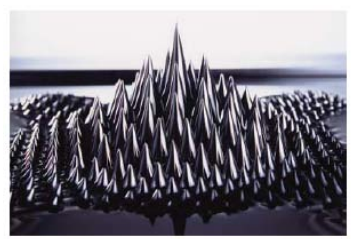
a)  **b)**  **c)** 

Figure 4.1: a) Zinc oxide nanowires [115] b) ultrasonic piezoelectronic motor [107], and c) ferro fluid sculptures[55]. [69]

4.1.1.2 Semi-, and Super-Conductors as well as Meta-Materials

Whereas *conductivity* generally refers to resistivity, *superconductivity* refers to a phenomenon in materials below a certain critical temperature where resistivity almost vanishes. Superconducting magnets for example revolutionized magnetic resonance imaging, power transmission, filters for microwave and cellular base stations, and magnetic field sensor. *Semiconductor materials* (such as silicon) on the other hand are neither good conductors nor good insulators, but, with the addition of small impurities called dopants, they can be tailored to possess many fascinating electrical properties. The addition of these dopants or impurities allows electron movements to be precisely controlled. Exploitation of the resultant properties has allowed a semiconductor to serve the same functions as complicated multipart electronic circuitries or microcontrollers, as illustrated in Figure 4.3 b).

Unlike most metals in which increases in temperatures cause increases in resistance, the conductivity of semiconducting materials increases with increasing temperatures. This property already makes it quite attractive for many applications. It results from a particular type of electron band structure in the internal structure of the materials. A gap exists between bands through which thermally excited electrons cross in particular conditions. The addition of dopants or impurities creates other conditions in affecting the flow of electrons through a material in a controllable way.

Semiconductive devices formed in this way typically consist of p-n junctions. Results are for example phototransistors that convert optical in electrical energy. The same phenomenon is used in photovoltaics where an input of radiation energy from the visible spectrum produces an electrical current, as shown in Figure 4.3 a). Other example include light emitting diodes that convert electrical into optical energy and transistors that can be used as signal amplification or switching devices. Also, semiconductors are now widely used in the low noise receivers of cellular telephone handsets, in addition to the specialized high-speed microwave applications for which they have long been the materials of choice.

Semiconductors are also the basis to create artificial atoms through developing quantum wells, quantum wires, or quantum dots, as illustrated in Figure 4.2 c) through e). The term artificial atom is commonly used to describe objects that have bound, discrete electronic states, as in the case with naturally occurring atoms. Semiconductor *quantum* *dots* – nanometer-sized semiconductor crystals capable of confining a single electron in all three directions – represent the most common example of artificial atoms. They are used as the next generation in luminescent technology as they essentially are quantum light emitting diodes. *Quantum wires* – confining wavelike electrons in two dimension but allowing them to propagate along the third (long) axis in a particle-like manner – are used to produce intense laser beams that can be switched on and off much more rapidly than quantum well lasers can. However, when a p-n-p junction is thin enough to force wavelike behavior along its vertical dimension, it becomes a *quantum well* which traps electrons in the n layer. At the upper p-n interface, large numbers of electrons and holes are brought together at very precise energies, producing photons at characteristics wavelengths. Quantum well hence finds practical use in computers and fiber-optic networks.

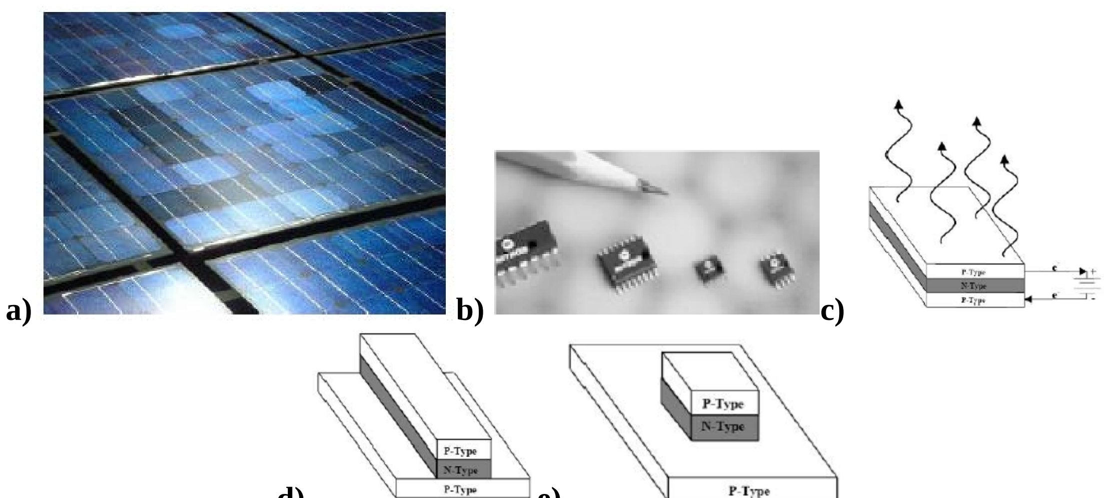


Figure 4.2:) Solar panels [119], b) microcontrollers [53], and c) quantum well, wire, and dot [48]. [69]

Also, *lasers* are one particular application leveraging semiconductivity, as illustrated in Figure 4.3 a). In a laser, light occurs via stimulated emission. An electron can be caused to move from one energy state to another because of an energy input, and, as a consequence, emit a light photon. This emitted photon can in turn stimulate another electron to change energy levels and emit another photon that vibrates in phase with the first. The chain builds up quickly with increasing intensity. Emitted photons vibrate in phase with one another. Hence, the light is phase-coherent. Also, the light is monochromatic, which in turn allows it to be highly focused. Many types of lasers exist that rely on different methods of excitation and use different materials. The most ubiquitous kind of lasers however are typically based on semiconductor technologies. Semiconductor lasers for example made the photonics revolution possible by for example producing beams of light used for transmitting information and reading compact disks in a CD player. Pushing the limits of semiconductor materials technology is thus essential for increasing the speed of transistors and advancing the ability to modulate lasers for high-speed optical information transmission.

Similarly, *thermoelectricity* or Peltier devices, an electronic form of heat pumps as illustrated in Figure 4.3 b), are based on semiconductors. In general, in a thermoelectric material, an input of electrical energy creates a temperature differential on opposite sides of the material. This temperature differential allows thermal energy to be transferred from one junction to the other. A typical Peltier device uses a voltage input to create hot and cold junctions, hence they can be used for heating or cooling. They are found in computers as cooling devices, and in common automotive and household goods as small heaters or coolers.

Semiconductors are also used in many of today's *biosensensing "materials"* where biological systems are highly adept at molecular recognition. In general, a biosensor is considered any sensing device that either contains or responds to a biological element. However, the term biosensor is more appropriately applied to a sensor that contains a biological element. Examples include enzymes, antibodies, cells, microbes and living tissues can be used as biosensing "materials" through efficient recognition procedures [93].

The key requirement in choosing the biological element has to do with its ability to provide a selective response through binding to the analyte at the expected concentrations, regardless of the other chemicals that may be present or of an inhospitable environment. When binding occurs, the biosensing element may respond in several ways, from conversion to another chemical or release of a chemical, but the most useful manner is if the response result in a change of one of its electronic or optical properties. Hence, semiconductors may be used as transducer elements responsible for converting the element's response into a measurable signal. The biological element is deposited on the semiconductor surface and thus electron flow is directly affected when binding to an analyte occurs [113]. Practical applications are for example the web-based "Exmocare" Bluetooth-enabled biosensor wristwatch service for augmenting proper medical supervision of the elderly, as illustrated in Figure 4.3 c). Other applications include sensing blood glucose levels for diabetics, food process control and inspection, molecular recognition, etc.

Electromagnetic multifunctional material systems include structural material systems serving as antennas and transmitters, sometimes referred to as *metamaterials or photonic crystals*. These systems rely primarily on their feature arrangement or topology to induce unique electromagnetic properties. Whether used as passive structural members or structural antennas, transmitters, and/or reflectors, an important attribute of the material is their interaction with electromagnetic radiation over the entire spectrum. This interaction is dictated by the way atoms and electrons in the solid interact with the electric and magnetic field of the wave. More specifically, the incident energy leads to excitation of electronic and ionic dipoles that, in turn, radiate energy that interferes with the incoming energy as described by Maxwell's equations. Thus, electronic diploes determine the optical properties of solids and ionic dipoles determine the infrared and microwave properties. A critical parameter that describes this interaction is the permeability which, along with the permittivity, determines the index of refraction potentially resulting in desired bandgaps and negative indices of refraction. A fascinating finding is that the properties arise as a result of the periodic morphological and topological arrangement of the features rather than their specific composition [52].

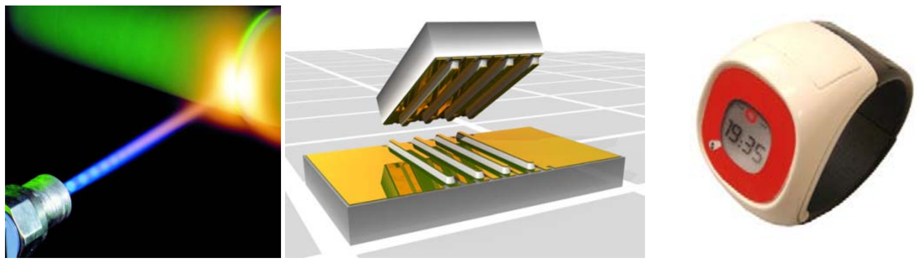


Figure 4.3: a) lasers[50], b) Peltier device [70], and c) Exmocare Bluetooth-enabled biosensor wristwatch service for augmenting proper medical supervision of the elderly [62]. [69]

4.1.1.3 Luminescence, Tropism and Chromism

(Electro-, magneto-, photo-, thermo-, chemo-, mechano-, bio-) lumi-(fluor-, phosphor-)escence is a phenomenon where a material emits light in response to incident (electrical, magnetical, optical, thermal, chemical, mechanical, biological) energy. The light is caused by the re-emission of energy in wavelength in the visible spectrum and is associated with the reversion of electrons from a higher energy state to a lower energy state. A classic example of a material that is luminescent due to a chemical action is the well-known chemoluminescent “light-stick”. If the emission of light occurs more or less instantaneously, the term *fluorescence* is used. If the emission is slower or delayed to several microseconds or milliseconds, the term *phosphorescence* is used. Many compounds are either naturally phosphorescent or designed to be so. The amount of delay time depends on the particular kind of phosphor used.

For example, common television screens rely on the use of phosphorescent materials. Also, typical fluorescent lamps are based on photoluminescent effects where the incident energy associated with an external light source acts upon a material that then re-emits light at a lower energy level. However, different properties, including the color of the emitted light, can be engineered by varying different compounds and impurity inclusions to yield specific kinds of light-emitting materials. In some situations (afterglow), the light emission can continue long after the source of excitation is removed – the electrons become temporarily trapped because of material characteristics. However, electroluminescent lamps are another application becoming widely used. They draw little power and generate no heat. They provide a uniformly illuminated surface that appears equally bright from all angles. Since they do not have moving or delicate parts, they do not break easily. Another interesting group of materials are optically-active polymers that emit light when excited electrically.

Similarly, *thermo-(photo-, electro-, magneto-)tropic materials* are based on a phenomenon where an input of thermal (optical, electrical, magnetic) energy to the material alters its micro-structure through a phase change. In a different phase, most materials demonstrate different properties, including conductivity, transmissivity, volumetric expansion, and solubility. Examples include thermotropic liquid crystalline compounds as shown in Figure 4.1 a).

The *photo- (thermo-, mechano-, chemo-, electro-) chromic phenomenon* is associated to a material that reversibly changes its color, i.e., optical properties, in response to optical (thermal, mechanical, chemical, electrical) energy. An input of external (optical, thermal, mechanical, chemical, electrical) energy to the material alters its molecular structure. The new molecular structure has a different spectral reflectivity than does the original structure. As a result, the material's optical properties, its reflected radiation in the visible range of the electromagnetic spectrum, changes. For example, electrochromic glass can simultaneously be a glazing material, a window, a curtain wall system, a lighting control system, a thermometer or an automated shading system for buildings or glasses as illustrated in Figure 4.4 c) – hence, it is a multifunctional material.

Similarly, thermochromics is used to describe changes in molecular structure due to an input of thermal energy. Based on this phenomena, thermochromic furniture can be designed that changes its color due to the heat released by the user, as shown in Figure 4.4 e). Another example is the simple water temperature safety device attached to the end of a faucet that changes color with water temperature variation in order to provide a safety warning especially for young children and older adults, as illustrated in Figure 4.4 d).

Related technologies include liquid crystals and suspended particles devices that change color or transparencies when electrically activated, as for example used in television sets as illustrated in Figure 4.4 b). *Liquid crystals* – an intermediate phase between crystalline solids and isotropic liquids – are orientationally ordered liquids with anisotropic properties that are sensitive to electrical fields, and therefore are particularly applicable for optical displays. Liquid crystal displays utilize two sheets of polarizing material with a liquid crystal solution between them. An electric current passed through the liquid causes the crystals to align so that light cannot pass through them. Each crystal is like a shutter, either allowing light to pass through or blocking the light.

Also, *suspended particles* feature opto-electric interactions in that they are electrically activated and can change from opaque to a clear color instantly and vice-versa. A typical suspended particle device consists of multiple layers of different materials. The active layer associated with color change has needle-shaped particles suspended in a liquid. This layer is sandwiched between two parallel conducting sheets. When no voltage is applied, the particles are randomly positioned and absorb light. An applied voltage causes the particles to align with the field. When aligned, light transmission is greatly increased through the composite layers.

Figure 4.4: a) thermotropic liquid crystalline compound [51], b) sharp touts ultra-slim LCD TV [100], c) electrochromic glass [48], d) water temperature safety device, and e) heat chairs. based on thermochromic elements or paint [1]. [69]

4.1.1.4 Phase-Transformations

Phase transformations refer to phenomena through which a change in the temperature, pressure or stress can cause it to change from one state to another, thereby undergoing a phase transformation. Phase change processes invariably involve the absorbing, storing or releasing of large amounts of energy in the form of latent heat. For example, *stress-induced martensitic transformations* give a material the ability to undergo enormous elastic or reversible deformation (pseudo-elasticity), as illustrated in Figure 4.5 b). These stress- or heat-induced martensitic transformations are the underlying phenomenon to shape memory alloys or polymers, used for example in eyeglass frames that are amazingly bendable, medical stents for opening arteries that are implanted in a compressed form and then expand to the right size and shape when warmed by the body, tiny actuators that eject disks form laptop computers, small microvalves and a host of other devices, all share a common material technology.

Also, since phase-changing materials can be designed to absorb or release energy at predictable temperatures, they have naturally been explored for use in architecture as a way of helping deal with the thermal environment in a building (e.g., phase-change wallboards). Furthermore, patented technologies exist for embedding microencapsulated phase-changing materials in a textile as illustrated in Figure 4.5 a) – i.e., as a person exercises and generates heat, the materials undergo a phase change and absorb excess heat, thus keeping the body cooler. As the body cools down, and heat is needed, the phase-changing materials begin to release heat to warm the body.

Thus, phase changing materials are commonly used for thermal energy storage for insulation and electronics and recently as nonvolatile memory in computer microchips (since once a solid state phase changing material reaches a prescribed temperature, it liquefies and absorbs heat without any additional temperature change). Also, these materials are used to control the stress transfer between rigid elements in a matrix material (in the flexible state, a composite material is heated and the phase changing material changes to a liquid state, thus effectively inhibiting stress transfer between the rigid elements in the composite). Another example is the use thermal Velcro fasteners with clasps made from a nickel titanium shape memory alloy that closes through thermal stimuli, as shown in Figure 4.5 c).

Shape change is also exhibited by a variety of interesting materials. For example, shape changing gels or crystals have the capacity to absorb huge amounts of water. When drying out, any increase in form reverts back to original size. Shape changing materials are for example used in dehumidification devices and packaging, or baby diapers and plant watering spikes.

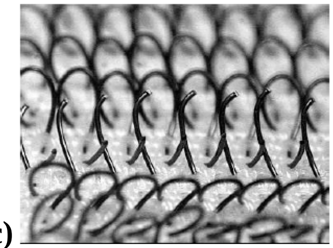
a)  b)  c) 

Figure 4.5: Phase changing materials in: a) textiles[3], b) glasses frames[2] , and c) thermal Velcro fasteners with clasps made from a nickel-titanium shape memory alloy [49]. [69]

4.1.1.5 Multifunctional Composites, Films, Coatings, and Weaves

At the same time, there have been developments that yield even thinner, tougher and versatile films, coatings, and weaves. For example, Plion thin-film batteries by Telcordia used to make powerfoils, i.e., form air-foil surfaces and simultaneously provided a rechargeable power source [28]. Furthermore, there have been other developments that yield even thinner and tougher polymer films that can be designed to have many different properties and exhibit a wide variety of different behaviors, such as radiant color and mirror films, view direction films, image redirection films, Fresnel lens films, polarizing films, photochromatic films, thermochromic films, electroluminescent films, conductive polymeric films, semiconducting light-emitting polymer films, holographically patterned films, piezoelectric films, as well as chemically sensitive color- and shape-changing films. Besides films, analogous paints and coatings, optionally enhanced with nanoparticles, exist. Also, electro-optical, dichroic, photochromic or holographically patterned glasses as well as fiber-optic, electroluminescent, thermochromic, photochromic and phase-changing weaves and fabrics can be designed.

Especially with respect to *carbon-fiber-reinforced thermoplastic materials or hollow structural member* which contain combustible gases, new polymers, or hydrogen-generation materials are proposed to make autophagous (self-consuming) systems that accommodate operational stresses as well as contribute to fuel supply. [28] Also, fiber batteries can be used to make powerfibers, i.e., fiber batteries incorporated into reinforcing architectures as a source of rechargeable power. Furthermore, lightweight laminated material systems containing recesses in which a wide array of feature, including sensors, damping material, and channels for wiring can be incorporated are being realized. An example is the fabrication of laminated materials incorporating cavities to achieve acoustic damping [28].

Moreover, fiber-optic cables can be embedded in different materials to serve as strain or crack detectors in the primary material. Other damage assessment approaches in composites are piezoelectric, magnetostrictive and electric resistance technologies. Fiber-optic strands can however also be used for aesthetic functionality, such as building composites or laminates by waving fiber-optic strands that are lighted by light-emitting diodes. High-performance thermoset matrix composites having unique phase-separated regions that respond to strains by toughening are also under investigation. The proposed repair resin additives are activated by fracture-induced strain and act to arrest propagating matrix cracks and at least partially self-repair crack damage. Candidate resin materials have been synthesized, incorporated into fiber-reinforced composite structures, and are currently undergoing fatigue testing [28].

Examples of such multifunctional composites are incorporated in NASA’s vision of a smart airplane that will “morph” in response to changing environmental conditions, as illustrated in Figure 4.6 a), or in sports equipment, such as the Head i.X3 tennis racquet equipped with piezoelectric fibers in the throat that “transfer more energy to the ball” to deliver a little extra power on all strokes, as illustrated in Figure 4.6 b). Similarly, *superalloys* represent special combination of metals that maintain high strength during prolonged exposure to elevated temperatures.

a)  b) 

Figure 4.6: a) NASA's smart "morphing" airplane [73], and b) Head i.X3[121]. [69]

4.1.2 Associated solution principles

This section (4.1.2), serving as one of the starting points for this thesis, is leveraged from Matthias Messer's dissertation (Chapter 4 Section 4), with some modification. [69]

Having presented a design catalog to identify underlying phenomena in order to enhance system performance and/or functionality and provided motivational examples, a design catalog for associated solution principles that may be mapped to underlying phenomena is developed in the following. The focus of the classification schemes for integrated product and materials design developed in this work is on providing phenomena and associated solution principles for embodying the most prominent functional relationships of changing, storing and transforming energy. Moreover, a design catalog with associated solution principles is provided only for the phenomenon of (in)elastic deformation.

For effective and efficient integrated design of material and product concepts it is crucial to identify phenomena as well as associated governing solution principles on multiple scales in addition to system-level product specific physical effects that can be found in the literature. Leveraging multiscale phenomena and associated solution principles to embody multilevel functional relationships, designers are enabled to determine product and material system concepts that narrow the gap to the desired performance goals when specific more or less advanced materials can not be readily selected from databases or catalogs. Classifying solution principles in terms of length scales is based on the work of Smith [105], who states that structure is best considered by different length scales.

From a *macro-material-level* perspective, examples of phenomena and associated solution principles (provided in brackets) are:

- inertia (translational, rotational, moment of area, radius of inertia, etc.),
- friction (solid-solid, solid-liquid, solid-gas, etc.),
- (in)elastic deformation (monolithic materials, structural elements, composite structures, etc.),
- Poisson's ratio (monolithic materials, composite structures, etc.)
- connections (form, force or material fittings, boundary conditions, etc.),
- size (effect of defects in a volume, dimensions, etc.),
- constituents (composites versus monolithic materials),
- surfaces (form, topologies, coatings, etc.),
- etc.

From a *meso-material-level* perspective, examples of phenomena and associated solution principles (provided in brackets) are:

- friction (granular materials, powders, asperities and actual contact surface, topologies, etc.),
- (in)elastic deformation (honeycomb-core sandwiches, fiber composite materials, etc.),
- Poisson's ratio (chiral structures, fiber composites, etc.),
- size (dimensions relative to reinforcement or second phases or other microstructure features),
- etc.

From a *micro-material-level* perspective, examples of phenomena and associated solution principles (provided in brackets) are:

- (in)elastic deformation (foams, microtruss structures or laminates, particle or dispersion composites, multi-phase or powder mixtures, machine-augmented composites, microstructure composites, etc.),
- Poisson's ratio (foams, microporous polymers, etc.)
- size (dimensions and distributions of phases, etc.),
- constituents (elements, molecular structure, etc.),
- stress or heat induced martensitic transformations as well as solid solutions, such as those obtained by alloying,
- friction (grain or phase boundaries, topologies of phases, crystal systems (cubic, tetragonal, orthorhombic, hexagonal, rhombohedral, monoclinic, triclinic), lattice orientations, etc.),
- etc.

It is emphasized that certain of these latter attributes are amenable to first principles calculations for resulting responses or properties (e.g., elastic constants, thermal conductivity, nucleation of defects, etc.). This list is of course inexhaustive, but is sufficient to convey that multiscale phenomena and associated solution principles at the material level facilitate definition of system sub-functions and related modeling principles. The identification of principal solution alternatives based on phenomena and associated solution principles is facilitated through the use of morphological charts [123]. A systematic approach to creative discovery is thus achieved by enumerating parameters characterizing a subject and combining the parameters in new and different ways.

As illustrated in the qualitative complexity profile for materials design given in Figure 4.7, complexity exponentially increases when phenomena or associated solution principles at lower scales are leveraged. For example, leveraging molecular assemblies on picoscales gives a designer nearly unlimited concept flexibility, but, at the same time exponentially increased complexity (amount of information). In some instances, enhanced product performance may justify such an amount of information and resulting complexity – in others however not. In this context, complexity profiles are attention directing tools introduced by Bar-Yam [11]. A complexity profile counts the number of independent effects at a particular scale and includes the effects that have impact at larger scales. The use of the term complexity reflects a quantitative theory of the degree of difficulty of describing a system's behavior. In its most basic form, this theory simply counts the number of independent effects as a measure of the complexity of a system or amount of information available. Thus, the complexity profile characterizes system behavior by describing the complexity as a function of scale.

A complexity profile can also be interpreted in terms of flexibility. From a design synthesis perspective, phenomena and associated solution principles are leveraged for concept generation. Hence, the more complexity, i.e., amount of information, at a designer's disposal, the higher will be a designer's flexibility. A designer then has to focus on the value of information available. However, from this perspective it becomes clear that growing complexity through integrated product and materials design suggests more responsibility for designers. Because for example materials scientists focusing on specific phenomena or solution principles can not be expected to anticipate all the consequences of designs at a system level when interactions are taken into account, synthesizing phenomena and associated solution principles is a major responsibility of system designers. System designers then need to focus on orchestrating the interaction of complex assemblies.

In the following, a design catalog with associated solution principles is provided for the phenomenon of (in)elastic deformation. The phenomenon of (in)elastic deformation is selected since it is one of the most frequently encountered in materials design. Classifying criteria of associated solution principles are specific length scales at which solutions occur and characteristic generic terms of subsolutions. The design catalog presented in Figure 4.7 is thus intended to provide a classified collection of solution principles associated with (in)elastic deformation supporting a designer to identify and generate integrated material and product system concepts on multiples levels and scales. This collection is of course not exhaustive, but is sufficient to convey that phenomena and associated solution principles at the material level facilitate definition of system sub-functions and related concepts and hence increases a designer's concept flexibility. For example, foaming significantly increases a designer's concept flexibility by extending the range of the properties spanned by conventional solids, creating applications for foams which cannot easily be filled by full dense solids and hence offering potential for engineering ingenuity.

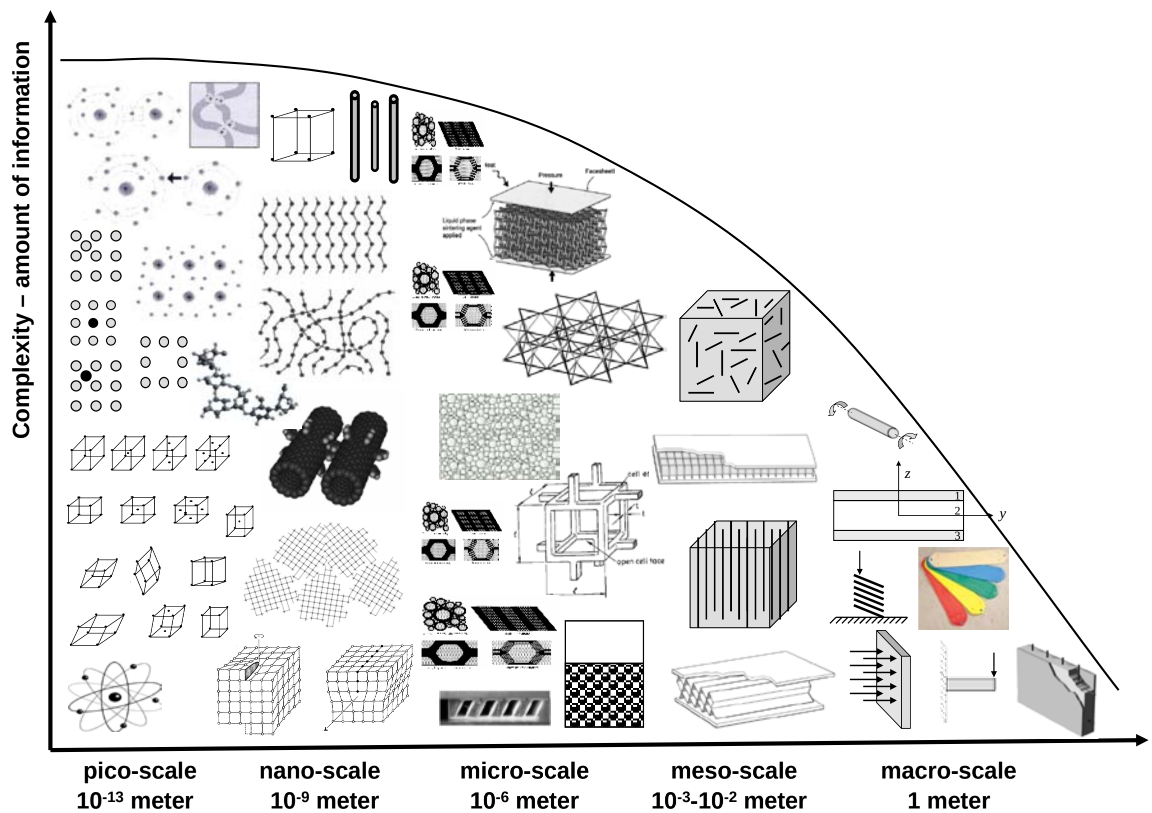


Figure 4.7: Qualitative complexity profile materials design. [69]

In the following, a design catalog with associated solution principles is provided for the phenomenon of (in)elastic deformation. The phenomenon of (in)elastic deformation is selected since it is one of the most frequently encountered in materials design. Classifying criteria of associated solution principles are specific length scales at which solutions occur and characteristic generic terms of subsolutions. The design catalog presented in Table 4.4-Table 4.10 is thus intended to provide a classified collection of solution principles associated with (in)elastic deformation supporting a designer to identify and generate integrated material and product system concepts on multiples levels and scales. This collection is of course not exhaustive, but is sufficient to convey that phenomena and associated solution principles at the material level facilitate definition of system sub-functions and related concepts and hence increases a designer's concept flexibility. For example, foaming significantly increases a designer's concept flexibility by extending the range of the properties spanned by conventional solids, creating applications for foams which cannot easily be filled by full dense solids and hence offering potential for engineering ingenuity.

Table 4.4: Design catalog solution principles associated with (in)elastic deformation. [69]

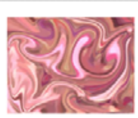
Pheno-menon	Scale	Characteristics: Solution Principle		Characteristics: Properties	Characteristics: Applications
Elastic/inelastic deformation (tension, compression, bending, shear, torsion, buckling, fracture, cutting, inversion, extrusion, drawing, flow) 	Macroscale	**"Monolithic" materials**	From a macroscale, monolithic materials are referred to as matter, i.e., the substance of which physical objects are composed.		
		- Metals		Compared to all other classes of material, metals are stiff, strong and tough, but they are heavy. They have relatively high melting points. Only one metal - gold - is chemically stable as a metal. Metals are ductile, allowing them to be shaped by rolling, forging, drawingn and extrusion. They are easy to machine with precision, and they can be joined in many different ways. Iron and nickel are transitional metals involving both metallic and covalent bonds, and tend to be less ductile than other metals. However, metals conduct electricity well, reflect light and are completely opaque. Primary production of metals is energy intensive. Many require at least twice as much energy per unit weight than commodity polymers. But, metals can generally be recycled and the energy required to do so is much less than that requried for primary production. Some are toxic, others are so inert that they can be implanted in the human body.	- Aluminum-, copper-, magnesium-, nickel-, steel-, titanium-, zinc-alloys - Carbon-, stainles-, ... steels - Amorphous metals, ...
		- Polymers		Polymers feature an immense range of form, color, surface finish, translucency, transparency, toughness and flexibility. Ease of molding allows shapes that in other materials could only be built up by expensive assembly methods. Their excellent workability allows the molding of complex forms, allowing cheap manufacture of integrated components that previously were made by assembling many parts. Many polymers are cheap both to buy and shape. Most resist water, acids and alkalis well, though organic solvents attack some. All are light and many are flexible. Their properties change rapidly with temperature. Even at room temperature many creep and when cooled they may become brittle. Polymers generally are sensitive to UV radiation and to strongly oxidizing environments. They have exceptionally good electrical resistance and dielectric strength as well as low thermal conductivity. - Thermoplastics are quite soft and ductile, can be easily melted and reform into a solid when cooled. This allows them to be molded to complex shapes. As the molecular weight increases, the resin becomes stiffer, tougher, and more resistant to chemicals, but, more difficult to mold. Most accept coloring agents and fillers, an many can be blended to give a wide range of physical, visual and tactile effects. Their sensitivity to sunlight is decreased by adding UV filters and their flammability is decreased by adding flame retardants. - Thermosetting plastics are quite strong, stiff, durable and hard with high temperature resistance and little or no creep. When heated, they do not melt but degrade. Hence, once shaped, thermosetting plastic cannot be reshaped. However, they have greater dimensional stability than thermoplastics, but, can sometimes also be soft and flexible. They cannot be recycled. - Properteis of elastomers lie between those of thermoplastics and thermosets. They remember their shape when stretched (some 5 or more times their original length) and return to it when released. They allow conformability and damping. However, they have a low stiffness and can't be remolded or reshaped, or recycled once shaped. - Semicrystalline polymers (folded chain polymers) can be quite dense, chemically resistant and highly heat resistant, allowing many properties to be imparted to them that are not normally associated with polymers (e.g., conductivity).	- Thermosplastic polymers: ABS, Cellulose, Ionomers, Nylon/PA, PC, PEEK, PE, PMMA, POM, PP, PS, PTFE, tpPVC, tpPU, PET/PETE/PBT - Thermosetting polymers: Epoxy, Phenolic, Polyester, tsPU, tsPVC - Elastomers: Acrylic elastomers, NR, Neoprene, EPDM, EVA, Viton, Isoprene, natural rubber, NBR/BUNA-N, Polybutadiene, Polysulphide, Silicone, SBS, TPE/TPO - Conducting polymers, organic light-emitting diodes
		- Ceramics and glasses		Ceramics and glasses are the most durable materials, particularly at high temperatures. They are not good electric conductors, exceptionally hard and brittle. Ceramics and glasses tend to fail along special cleavage planes and possess high resistance to high temperatures and heating. Often, they are used as refractory materials. Their high melting points give them a low expansion coefficient. They have a high thermal conductivity and low impact resistance.	- Alumina, Boron carbide, Silicon carbide, Tungston carbide, Borosilicate glass, Silica glass, Soda lime glass, tranparent ceramics, sintered corundum, calcium-fluorid crystals, piezo-ceramics, electroceramics, semiconductors, etc.
		- Composite materials		Composites are high-performance materials that are made by combining two or more primary materials, comprising a huge class of materials. Constituent materials have significantly different physical or chemical properties. On the macroscopic level, they remain separate and distinct within the finished structure. In general, there are two constituent phases: matrix and reinforcement/enhancement. At least one portion of each phase is required. The matrix surrounds and supports the reinforcement/enhancement by maintaining relative positions. The reinforcements/enhancement impart their special physical properties to enhance the matrix properties. A synergism produces material properties unavailable from the individual constituent phases.	- Multilayer composites, multiphase composites, multifunctional composites, etc.
		- Fluids		A fluid differs from a solid in that it cannot support a shear stress. In a fluid, shear deformation will continue as long as any shear stress is applied. The constitutive equation for a fluid relates the rate of deformation to the applied stress. A fluid is a subset of the phases of matter and includes liquids, gases, plasmas and, to some extent, plastic solids. Fluids can be characterized as Newtonian fluids, where stress is directly propoertional to the rate of deformation, and Non-Newtonian fluids, where stress is proportional to the rate of deformation, its higher powers and derivatives.	- Newtonian fluids - Non-Newtonian fluids: Kelvin material, anelastic material, rheopectic material, thixotropic material, generalized Newtonian fluids, super-paramgentic liquids, electro-, magneto-rheological fluids, etc.

Table 4.5: Design catalog solution principles associated with (in)elastic deformation (cont'd).[69]

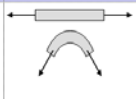
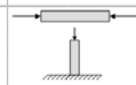
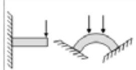
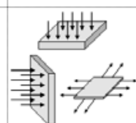
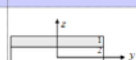
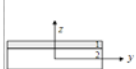
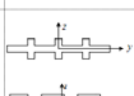
Elastic/inelastic deformation (tension, compression, bending, shear, torsion, buckling, fracture, cutting, inversion, extrusion, drawing, flow) 	Macroscale (continued)	**Fundamental structural elements**	Basic engineering elements on the mocroscale primarily supporting loads are referred to as fundamental structural elements.		
		- Tie, cable, wire or continuous fiber		These structures are capable of carrying tensile loads only. The maximum energy that can be absorbed per unit weight before tensile instability supervenes depends upon the ultimate tensile strength and strain. If tension devices are for example used as a simple type of energy absorber, they suffer from the stroke, i.e., maximum displacement, or maximum strength limitation imposed by the ultimate strain or strength of specific material system.	- Single-, coaxial-, multicore-, ... cables
		- Struts or columns		These structures are capable of carrying compressive loads only. With respect to buckling and plastic collapse the specific ultimate tensile strength is an excellent indicator of the ability of a material to absorb energy. If struts or columns are for example used as energy absorber, the absorbed energy per unit mass in static tests is minimial because of the limited zone of plastic deformation during buckling.	- Hinged-, fixed-, free-, ... columns
		- Beams or archs		Beam and archs (curved beams) are structural elements that carry load primarily in bending (flexure). In general, they are characterized by their profile (the shape of their cross-section), their length, and their material. Beams and archs may for example be used for energy dissiaption or blocking and bracing, i.e., locating supports in contact with stronger parts of a structure, so that imparct forces are directed to these parts.	- Cantilever-, simply-supported-, ... beams
		- Plates/panels, shells, membranes or foils		Plates are initially flat structural elements, having thicknesses much smaller than the other dimensions. Whereas shells only bear in-plane loads, plates bear bending moments as well. Membranes are curved shells. Panels are non-horizontal plates. For example, their load spreading effect (i.e., spreading the forces at impact over a large area so that pressure is reduced) has been used in energy dissipation devices.	- Fixed-, simply-supported-, ... plates and panels - Multifunctional foils: load bearing, aesthetic, etc.
		- Shafts or torsion springs		Shafts or torsion springs are structural elements primarlily loaded in torsion. Besides tension, compression and bending, torsion of bars or tubes, featuring relatively large deceleration strokes, has also been used in energy dissipation devices.	- Tension-, compression-, ... spring
		Structural shape	The external macroscopic outline of structural elements - in costrast to the matter of which it is composed is referred to structural shape. Governing design variables are dimensions and topologies of structures.		
		- Plain-/open-sections		Many structural elements with specifically shaped plain or open sections are standardized. Also, a number of sepcialist and proprietary sections are readily available. However, shape selection or design is based on the moments of inertia: $I=\int_A x_i^2 dA$ or other multifunctional considerations (e.g., heat or fluid flow, etc.).	- Rectangular-, circular-, prismatic-sections - I-, Z-, L-, single/double T-, U-, C-, ... sections - Extruded sections of various shapes
		- Tubes and frustra		Structural elements may also be available in a variety of tubes and frustra. For example, from the point of view of energy absorption capacity it was found that circular tubes and frustra under axial compression provide one of the best devices and hence are the most frequently used components in energy dissipating systems. Circular tubes and frustra provide a high stroke length per unit mass and a reasonably constant operating force, which is in some applications a prime characteristic. Structures based on tubes and frustra generaly have relative densities of 0.2 - 0.3. However, the collapse load and energy absorbing capacity of single tubular components can be increased by using tensile bracing members. - Densification strain open-top tubes: $\varepsilon_D \approx 1-2\frac{d_t}{R_s}=1-\rho_{rel}$ - Relative strength open-top tubes: $\frac{\sigma_y}{\sigma_{ys}} \approx 1.26\ \rho_{rel}^{1.5}$ - Densification strain closed-top frustra: $\varepsilon_D \approx \frac{2}{3}$ - Relative strength closed-top frustra: $\frac{\sigma}{\sigma_{ys}} \approx 0.35(\rho_{rel}\rho_s)^{-1}$	- Rectangular, circular, prismatic tubes and frustra - Open- and closed-top tubes and frustra
		- Bodies		Structural elements may also be shaped in three dimensions in a variety of ways. For example, the mechanisms of spherical shell inversion, i.e., material passing into the central dimple region through a circular knuckle whose radius increases with deformation, is somewhat similar to tube inversion in that it is an efficient method of energy absorption.	- Sphere, cube, cylinder, etc.
		Composite structures	Assemblies or combinations of monolithic materials and structures to enhance structural or functional performance on macroscales while maintaining the properties of each component are referred to as composite structures.		
		- Sheet-structures		Sheet-structures are referred to as composite structrues that consist of an additional layer(s) or outer sheating in a material. Examples include multifunctional clad metals or coated materials featuring coatings that can kill germs, be fire-resistant, self-cleaning, anti-fog, determine appearance, etc. Governing design variables are number, dimensions, configuration, topology and material of constituting layers.	- Clad structures: clad metals, coated or painted materials, bimetals, etc.
		- Sandwich-structures		Structural member made up of two stiff, strong skins separated by a lightweight core are known as sandwich panels. The separation of the skins by the core increases the moment of inertia of the panel with little increase in weight. Therefore, sandwich panels may significantly increase structural stiffness for resisting bending. Also, introducing stabilizing core structures resistance against buckling loads is increased. The mechanical behavior of a sandwich thus depends on the properties of the face and core materials and on its geometry. In general, it is a costly process of assembling a sandwich shell by joining precurved face sheets and core.	- (Un)symmetrical three-, multi-, ...layer sandwich panels
		- Stiffened-structures		On macroscales, structures can be enhanced/reinforced through the addition of stiffeners of various shape or curvatures (inelastic deformation) of the structure itself. Stiffened structures yield a higher moment of inertia and hence increased stiffness. Governing design variables are dimensions and topologies of constituents. For example, hat-stiffened plates are generally regarded to be one of the most efficient light weight constructions for compression panels loaded in direction, waffle-stiffened plates for compression panels loaded in two direction. In general, it is a costly process of joining (precurved) face sheets and stringers or machining.	- Stiffeners of various shapes - Curved structures of various shapes

Table 4.6: Design catalog solution principles associated with (in)elastic deformation (cont'd).[69]

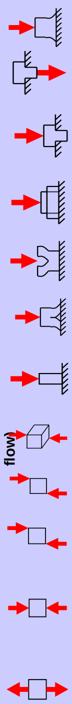
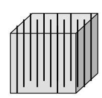
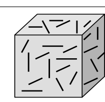
Elastic/inelastic deformation (tension, compression, bending, shear, torsion, buckling, fracture, cutting, inversion, extrusion, drawing, flow) 	Mesoscale	**Honeycomb-core sandwiches**	Honeycomb-core sandwiches take their name from their visual resemblance to a bee's honeycomb. With controllable core dimensions and topologies on mesoscales, they feature relatively high stiffness and yield strength at low density. Large compressive strains are achievable at nominally constant stress (before the material compacts), yielding a potentially high energy absorption capacity. Honeycomb core sandwiches have acceptable structural performance at relatively low costs with useful combinations of thermophysical and mechanical properties. Usually, they provide benefits with respect to multiple use.		
		- In-plane honeycombs		Core cell axes of in-plane honeycomb cores are oriented parallel to the face-sheets. They provide potentials for decreased conductivity and fluid flow within cells. Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D \approx 1 - 1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approximated as: $\frac{E}{E_s} \approx 1\rho_{rel}^3$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.5\rho_{rel}$	- Prismatic-, square-, chiracal-, etc. core in-plane honeycombs
		- Out-of-plane honeycombs		Core cell axes of out-of-plane honeycomb cores are oriented perpendicular to face-sheets. They provide potentials for decreased conductivity. Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D \approx 1 - 1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approximated as: $\frac{E}{E_s} \approx 1\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 1\rho_{rel}$	- Hexagonal-, sqaure-, etc. core put-of-plane honeycombs
		Fiber-composites	The combination of polymers or other matrix materials with fibers has given a range of light materials with stiffness and strength comparable to that of metals. Commonly, resin materials are epoxies, polyesters and vinyls. Fibers are much stronger and stiffer than their equivalent in bulk form because the drawing process by they are made orients the polymer chains along the fiber axis or reduces the density of defects.		
		- Continuous fiber composites		Continuous fiber composites are composites with highest stiffness and strength. They are made of continuous fibers usually embedded in a thermosetting resin. The fibers carry the mechanical loads while the matrix material transmits loads to the fibers and provides ductility and toughness as well as protecting the fibers from damage caused by handling or the environment. It is the matrix material that limits the service temperature and processing conditions. On mesoscales, the properties can be strongly influenced by the choice of fiber and matrix and the way in which these are combined: fiber-resin ratio, fiber length, fiber orientation, laminate thickness and the presence of fiber/resin coupling agents to improve bonding. The strength of a composite is increased by raising the fiber-resin ratio, and orienting the fibers parallel to the laoding direction. Increased laminate thickness leads to reduced composite strength and modulus as there is an increased likelihood of entrapped voids. Environmental conditions affect the performance of composites: fatigue loading, moisture and heat all reduce allowable strength. Polyesters are the most most widely used matrices as they offer reasonable properties at relatively low cost. The superior properties of epoxies and the termperature performance of polyimides can justify their use in certain applications, but they are expensive.	- Glass fibers [high strength at low cost], polymer fibers (organic (e.g., Kevlar) or anorganic (e.g., Nylon, Polyester)) [reasonable properties at relatively low cost], carbon fibers [very high strength, stiffness and low density] - Strands, filaments, fibers, yarns (twisted strands), rovings (bundled strands) - Nonwoven mattings, weaves, braids, knits, other
		- Discontinuous fiber composites		Polymers reinforced with chopped polymer, wood, glass or carbon fibers are referred to as discontinuous fiber composites. The longer the fiber, the more efficient is the reinforcement at carrying the applied loads, but shorter fibers are easier to process and hence cheaper. Hence, fiber length and material are the governing design variables. However, fibrous core composites feature shape flexibility and relatively high bending stiffness at low density.	- Glass fibers, polymer fibers (organic (e.g., Kevlar) or anorganic (e.g., Nylon, Polyester)), carbon fibers

Table 4.7: Design catalog solution principles associated with (in)elastic deformation (cont'd). [69]

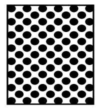
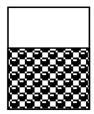
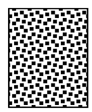
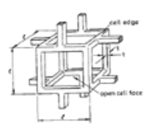
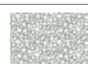
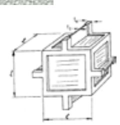
Microscale	**Dispersion-composites**	A multi-component material produced when metal, ceramic or polymer materials provide a macrostructural matrix for the distribution of strengthening agents, such as flakes, throughout the material, increasing its structural or functional performance. Each component however maintains its properties.		
	- Particle-composites		Particle-composites are materials made by reinforcing/enhancing polymers or other matrix materials with particulates (fillers) of for example silica sand, talk. The combination of polymers with fillers has given a range of light materials with stiffness and strength comparable to that of metals as well as enhanced processability. Governing design variables are dimensions, topology and material of fillers as well as matrix material properties. Blending allows other adjustments of properties, e.g., plasticizing additives give polymers leathery behavior or flame retardant additives reduce flammability of polymers. Particle-matrix composites (such as aluminum with silicon carbide) extend the property range of materials, usuallly to make them stiffer, lighter, more tolerant of heat or add other functionality. But, their cost limits their applications.	- Carbide, polymer concerte, …
	- Granular-materials/ powders		A granular material is a conglomeration of discrete solid, characterized by a loss of energy whenever its particles interact mostly through friction. The constituents that compose granular material must be large enough such that they are not subject to thermal motion fluctuations. Governing design variables are filler dimensions, topology and material. For example, filling structures with crushable granular material (sand) is a way of mobilizing membrane stresses at large deformations and increase friction. Axial crushing of filled tubes or honeycombs is focus of current research to increase energy dissipation.	- Granular fill materials, fill powders, ...
	- Solid-/fluid-mixtures/ additives		Solid-/fluid-mixtures are dispersion composites made by adding or mixing and often processing multiple materials with or without additives. Governing design variables are dimensions and materials. Prominent examples are microencapsulation - individually encapsulated small particles or substances to enable suspension in another compound - and sintering - fabrication of metals or ceramics based on powdery educts (starting materials) at high temperatures and pressures - as well as nanoscale additives.	- Metal and/or ceramic composites, ... - Reactive metal powder mixtures, ... - Aerogels, ...
	Foams	In general, polyhedral cells which pack in three dimensions to fill space are referred to as three-dimensional cellular materials foams. Techniques today exist for foaming almost any material.Foams reduce material usage and increase bending stiffness without increasing weight through a relatively high stiffness and yield strength achievable at low density. Large compressive strains can be achieved at nominally constant stress (before the material compacts), yielding a relatively high energy absorption capacity through bending dominated plastic yielding. Foams feature benefits with respect to multiple use and shape flexibility. Governing design variables are the relative density, cell dimensions, topology and material.		
	- Open-cell foams	 	If the solid of which the foam is made is contained in the cell edges only so that the cells connect through open faces, the foam is said to be open-celled. Open-cell foams provide potentials for decreased conductivity (especially for polymer and glass) and fluid flow within cells. Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D = 1-1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approxiamted as: $\frac{E}{E_s} \approx 1\rho_{rel}^2$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.4\rho_{rel}^{1.5}$	- Filatration, thermal insulation, cushioning, packaging, padding, ... devices
	- Closed-cell foams	 	If the faces of open-cell foams are solid too, so that each cell is sealed off from its neighbors, the foam is said to be closed-celled. In closed-cell foams, the fluid within cells is compressed and provides potentials for decreased conductivity (especially for polymer and glass). Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D = 1-1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approxiamted as: $\frac{E}{E_s} \approx 0.33\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.3\rho_{rel}$	- Flotation, thermal insulation, cushioning, packaging, padding, ... devices

Table 4.8: Design catalog solution principles associated with (in)elastic deformation (cont'd).[69]

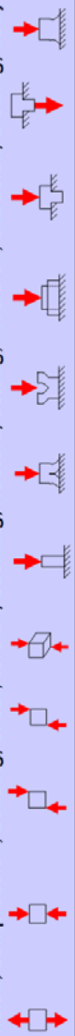
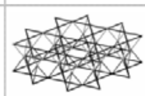
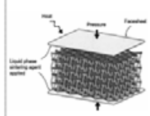
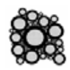
Elastic/Inelastic deformation (tension, compression, bending, shear, torsion, buckling, fracture, cutting, inversion, extrusion, drawing, flow) 	Microscale (continued)	**Microtruss-structures**	Stretching dominated, periodically arranged microtruss-structures, where struts support axial loads, tensile in some, compressive in others when loaded, offer greater stiffness and strength per unit weight than those in which the dominant mode of deformation is by bending. With microtruss-structures, relatively high stiffness and yield strength becomes achievable through stretching dominated plastic yielding at low relative density. They feature a relatively high energy absorption capacity, but, in compression the stretching-dominated materials have a softening post-yield response due to the buckling of the struts. However, they provide benefits with respect to multiple use and fluid flow within cells.		
		- Pyramidal structures		Relative densities for pyramidal microtruss-structures range from 0.01 - 0.1. Their densification strain can be approximated as: $\varepsilon_D = 1-1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approxiamted as: $\frac{E}{E_s} \approx 0.25\,\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.5\,\rho_{rel}$	- Shock-/noise-absorption devices, etc.
		- Tetragonal structures		Relative densities of tetragonal microtruss-structures range from 0.01 - 0.1. Their densification strain can be approximated as: $\varepsilon_D = 1-1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approxiamted as: $\frac{E}{E_s} \approx 0.44\,\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.66\,\rho_{rel}$	- Shock-/noise-absorption devices, etc.
		- Kagome structures		- Kagome structures may mimic random cellular structures as encountered in armadillo shell structures and young suap froths. Their exact behaviour however is currently analyzed.	- Shock-/noise-absorption devices, etc.
		Microtruss-laminates	Periodic microtruss-laminates are synthesized through textile-based approaches based on wire weaves joined using transient liquid phases. They have the compliance and necessary open space for cell collapse, i.e., large compressive strains achievable at nominally constant stress before the material compatcs, thereby absorbing large amounts of energy when compressed. Besides this relatively high energy capacity, they feature relatively high stiffness and yield strength achievable at low density as well as benefits with respect to multiple use.		
		- Textile-based weave (3 dimensional knitting)		Relative densities of tetragonal microtruss-structures range from 0.01 - 0.3. Their densification strain can be approximated as: $\varepsilon_D = 1-1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approxiamted as: $\frac{E}{E_s} \approx 0.5\,\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.5\,\rho_{rel}$	- Shock-/noise-absorption devices, etc.
		Machine-augmented-composites	Machine-augmented composites are formed by embedding mechanisms in a matrix material. Theoretically, these mechanisms may include: - Wheel-gears (friction-/form-locking) - Cam-mechansisms, worm/helical gears, gate geards - Belt-/chain-drives (friction-/form-locking) - 4-bar-turning/sliding-pair linkages, multilink mechanisms Potentially, machine-augmented composites might also be formed by embedding micro-electro-mechanical systems		
		- Microtruss-mechanisms		- Composite formed by embedding simple microtruss-mechanisms, with or instead of fiber or particulate reinforcements, in a matrix material to obtain a multifunctional material with new properties. The mechanisms may take on many different forms and serve to modify power, force, or motion in different ways, hence creating as many different mechanical properties as there are possibilities for the cross-sectional shapes of machines.	- Shock-/noise-absorption devices, etc.
		Microstructure-composites	Microstructure-composites are isotropic cellular materials that attain theoretical upper bounds for the bulk and shear moduli of a voided solid to maximize the stiffness to weight ratio.		
		- Coated spheres assemblages		Coated sphere architectures are differential schemes for constructing composite structures with the extremal Hashin-Shtrikman bulk and shear moduli.	
		- Rank-laminates		Rank laminates attain both the bulk and shear H-S bounds with a finite number of layering directions. Rank laminates are obtained by a sequential process where at each stage the previous laminate is laminated again with a single phase (always the same) in a new direction.	
		- Vigdergauz microstructures		Vigdergauz microstructures are isotropic two-dimensional square symmetric composites feature optimal shape of single inclusions and hence attain theoretical upper bounds for the bulk or shear moduli.	
		- Sigmund microstructures		Sigmund microstructures are statistically isotropic (or at least square symmetric) two-phase microstructure, consisting of disconnected convect polygonal regions with pure phase 1 or 2 material connected by laminated regions of the phases in equal proportions, for which exact solutions for the hydrostatic loading case exist. This composite has bulk modulus equal to either the upper or the lower Hashin-Shtrikman bound if the lamination direction is perpendicular to the stiffer or lower phase respectively. According to Sigmund, an isotropic honeycomb-like hexagonal microstructure belonging to this class of composite has maximum bulk modulus and lower shear modulus than other known composites.	

Table 4.9: Design catalog solution principles associated with (in)elastic deformation (cont’d). [69]

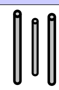
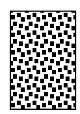
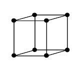
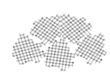
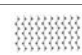
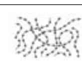
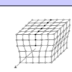
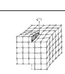
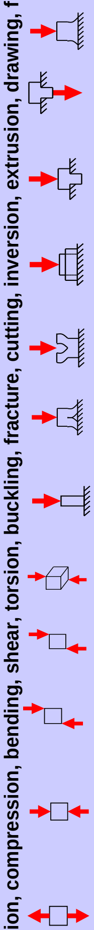
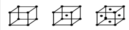
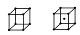
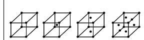
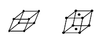
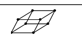
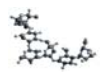
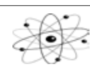
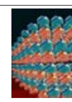
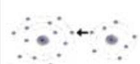
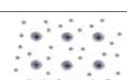
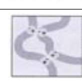
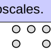
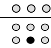
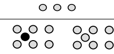
Nanoscale	**Nano-structures**	Nanoscale-structured materials of extraordinaty multifunctional (mechanical, electrical, optical and thermal) properties are referred to as nano-structures.		
	- Microtubes		Microtubes are very small diameter tubes (in the nanometer and micronrange) that have very high aspect ratios and can be made from practically any material in any combination of cross-sectional and axial shape desired. Potential applications are lightweight structural reinforcement or multifunctional composite materials.	- Microtubing, semicon-ductor microtubes as resonators, micro-machines/-devices, etc.
	- Nanotubes		Since carbon-carbon covalent bonds are among the strongest bonds in nature, nanotubes are commonly realized and known as carbon-nanotubes, a structure based on a perfect arrangement of these bonds oriented along the axis of the nanotubes producing a very strong material with an extremely high strength-to-weight ratio. More specifically, a carbon nanotube is a hexagonal network of carbon atoms rolled up into a seamless, hollow cylinder, with each end capped with half of a fullerene molecule. In general, it is only a carbon nanotubes isotropic topology that distinguishes it from other carbon structures and gives it unique properties. Besides extraordinary high tensile strength, low density and high Young’s modulus, the most striking effect is the combination of high flexibility and strength with high stiffness. Thus, nanotubes are very stiff for small loads, but turn soft for larger loads, accommodating large deformations without breaking. Hence, carbon nanotubes have an extraordinary potential in energy dissipation applications. At the same time, they have a unique electronic and optical character	- Single-/multi-walled carbon nanotubes, etc.
	- Nanoparticles		The use of nanoscale filers exploits the advatages that nanometer-sze particulates offer comopared with macro- or microscopic filllers, such as huge surface area per mass, utra-low filler levels required for connectivity through the sample, extremely small interparticle separations, very high aspect ratios. Also, the formation of genuine nanocomposites introduces new physical properties and novel behaiors that are absent in unfilled matrices, effectevly changing their nature.	- Polymer-based nanocomposites, molecular composites, etc.
	Molecular arrangement	Controlling the precise molecular arrangement to be either crystalline, polycrystalline, semicrystalline or amorphous on nanoscales determines material properties on macroscales.		
	- Crystalline		An orderly and repetitive arrangement of atoms and molecules held together with different types of chemical bonding forces is referred as a crystalline molecular arrangement. These patterns form regular lattice structures of which there are many different types with corresponding material structures. A crystalline structure is made up of large number of identical unit cells that are stacked together in a repeated array or lattice.	- Metals and minerals
	- Polycrystalline		A random structure with little if any order as exhibited by a large number of small cyrstals or grains not arranged in an orderly fashion is referred to as a polycrystalline arrangement. For a number of reasons the growth of a crystalline pattern is interrupted and a grain is formed. Particular grains meet one another at irregular grain boudnaries and are normally randomly oriented to one another. Grain size can vary due to multiple reasons (including heat treatment and cold working). Alterations in the grain structure can produce changes in material properties. Governing design variables are grain size, grain boundaries, lattice orientation and phase topology.	- Ceramics and glasses, metals
	- Semicrystalline		Periodic arrangement of chains that are crystalline in nature are referred to as a semicrystalline molecular arrangement. These chains are not cross-linked and have multi-layered structures. Governing design variables are chain length and topology of the multi-layered structure.	- Folded chain polymers
	- Amorphous		A random structure with little if any order as exhibited by interwoven and cross-linked chains is referred to as an amorphous molecular arrangement. Main design variables are chain length, chain interconnectedness, and degree of interweavement.	- Polymers
	Line defects	Line variations from the perfect crystal lattice on the nanoscale typically cause changes in the macroscopic properties of materials, particularly metals.		
	- Edge dislocations		The border of an extra plane of atoms, where the dislocation line identifies the edge of the extra plane, is referred to as an edge dislocation. Edge dislocations include edges of surfaces where there is a relative displacement of lattice planes or rows of missing atoms.	
	- Screw dislocations		Crystals displaced parallel to a cut and finally reconnected into the configuration are referred to as screw dislocations. The dislocation line is the edge of the cut and hence also the border of the displaced region.	

Table 4.10: Design catalog solution principles associated with (in)elastic deformation (cont'd). [69]

Elastic/inelastic deformation (tension, compression, bending, shear, torsion, buckling, fracture, cutting, inversion, extrusion, drawing, flow)



Picoscale

Crystal systems	A crystal structure is a unique arrangement of atoms in a crystal. A crystal structure is composed of crystal unit cells, sets of atoms arranged in a particular way. The characteristics and geometry of crystal unit cells are determined by its basic atomic structure. Basic morphological considerations indicate that there are 14 basic lattice structures (Bravais lattices) that can be made from the seven basic unit cells. Crystal systems can be classified according to the length and angles involved.		
- Cubic		The cubic crystal system has the same symmetry as a cube. Three cubic Bravais lattices exist - the simple cubic, face centered cubic and body centerd cubic.	- Chromium, molybdenum, tungsten - Aluminum, silver, gold, copper
- Tetragonal		Tetragonal crystal lattices result from stretching a cubic lattice along one of its lattice vectors, so that the cube becomes a rectangular prism with a square base and height different from the base length. There are two tetragonal Bravais lattices - the simple tetragonal and the face centered tetragonal.	- Zircon, anatase
- Orthorhombic		Orthorhombic lattices result from stretching a cubic lattice along two of its lattice vectors by two different factors, resulting in a rectangular prism with a rectangular base and height different from both rectangular base length. The three lattice vectors remain mutually orthogonal. Four orthorhombic Bravais lattices exist: simple orthorhombic, base-centered orthorhombic, body-centered orthorhombic, and face-centered orthorhombic.	- Olivine, sulfur
- Hexagonal		The hexagonal crystal system has the same symmetry as a right prism with a hexagonal base and six atoms per unit cell.	- Magnesium, titanium, zinc - Beryll, Nepheline
- Rhombohedral		In the rhombohedral system, the crystal is described by vectors of equal length, of which all three are not mutually orthogonal.	- Quartz, calcite
- Monoclinic		In a monoclinic crystal system, the crystal is described by vectors of unequal length forming a rectangular prism with a parallelogram as base. Two monoclinic Bravais lattices exist - the simple monoclinic and the face centered monoclinic lattices.	- Gypsum, clinopyroxene
- Triclinic		In the triclinic system, the crystal is described by vectore of unequal length where all three vectors are not mutually orthogonal.	- Feldspar
Molecular structures	Control of molecular constituents and structures on the atomic scale affects properties on macroscopic scales in order to achieve given performance requirements.		
- Solid solutions (alloying)		Solid solutions are formed through for example combining various elements or adding alloying elements to a base material to obtain a (base) material with unique and specific characteristics. However, the combination of (alloying) elements in solid solutions may result in constituents which, far from producing a favorable cumulative effect with regard to a certain property, may counteract each other. For example, the mere presence of alloying elments in steel is nothing but a basic condition for the desired characteristic which can be obtained only by propert processing and heat treatment.	- Alloying elements: C, Al, Sb, As, Be, B, Ca, Cr, Co, Cu, H, Pb, Mn, Mo, Ni, N, O, P, Si, S, Sn, V, W
- Atomic elements		Progress in science suggests the feasibility of achieving thorough control of the molecular structure of matter via controlled molecular assembly, i.e., using individual atoms to build molecules precisely as building blocks for bottom-up molecular construction.	- Elements in periodic table: H, Li, Na, K, Rb, Cs, Fr, Be, Mg, Ca, Sr, Ba, Ra, Sc, Y, Ti, etc.
- Subatomic particles		Subatomic particles have less structure than atoms. These include atomic constituents such as electrons, protons, and neutrons, where protons and neutrons are composite particles made up of quarks, as well as particles produced by radiative and scattering processes, such as photons, neutrinos, and muons, as well as a wide range of other particles.	- Electrons, protons, neutrons, photons, neutrinos, muons, etc.
Atomic Bonding	The type of bonding ultimately determines many of the intrinsic properties and major behavioral differences between materials. Bonding forces produce different types of aggregation patterns between atoms to form various molecular and crystalline solid structures. Intermetallic compounds with various types of bonding exist.		
- Ionic		Ionic bonding involves electrostatic forces where one atom transfers electrons to another atom to form charged ions. Multiple ions typically form into compounds composed of crystalline or orderly lattice-like arrangements that are held together by large interatomic forces. Ionic compounds are solid at room temperatures, and their strong bonding force makes the material hard and brittle. In the solid state, all electrons are bonded and not free to move, hence ionic solids are not electrically conductive. Solid materials based on ionic bonding have high melting points and are generally transparent. Many are soluble in water. In the melted or dissolved state, electrical conduction is possible.	Ceramics and glasses
- Covalent		Covalent bonding involves local sharing of electrons and frequently occurs between neighboring non-metallic elements thereby producing localized directions. In some cases, small covalent arragements of atoms or molecules can be formed in which individual molecules are relatively strong, but forces between these molecules are weak. Consequently these arrangements have low melting points and can weaken with increasing heating. They are also poor conductors of electricity. In other cases (such as carbon or diamond), it is possible for many atoms to form a large and complex covalent structure that is extremely strong. These structures are very hard, have very high melting points, will not dissolve in liquids and, because electrons are closely bound and not free to move easily, are typically poor electrical conductors.	Ceramics and glasses, molecules in polymer chains
- Metallic		Metallic bonding involves non-localized sharing of electrons. Outer shell electrons contribute to a common electron cloud, resulting in good electric and heat conducting as well as often ductile deformation characteristics.	Metals
- Secondary		Secondary bonding involves permanent or fluctuating dipole bands. Bonding forces are relatively weak by comparison to ionic, covalent and metallic bonds. They can break easily under stress and they allow molecules to slide with respect to one another.	Polymer chains
Atomic Point defects	Variations from the perfect lattice on picoscales that typically cause changes in the properties of materials, particularly metals, at macroscales.		
- Vacancy impurities		Vacancy impurities involve the absence of an atom at a normally occupied lattice site.	
- Substitutional impurities		Substitutional impurities involve atoms of a different element than the bulk material that occupies a normal lattice site.	
- Interstitial impurities/self		Interstitial impurities/selfs are atoms occupying a position between normal lattice sites. They can be either self (same type of bulk material) or impurity (another type as the bulk material) interstitials atoms.	

4.2 DESIGN CATALOG ADDITIONS

Fundamentally, design catalogs are implemented to help a rationally bounded designer increase concept flexibility within a systematic method by augmenting cognitive abilities. It is therefore practical to include constructs in the catalog that present digested expert knowledge, as phenomena and associated principles do, but in a way that goes beyond classification. Such classification certainly aids easy retrieval of information that is known to be needed. To extend the functionality of the design catalogs beyond safe guarding against reinvention, and further the multi-domain notion, solution triggering and problem solving tools modified from the TRIZ disciple are used in augmenting these catalogs. (In addition to setting the tools in a process that uses TRIZ work flow, as described in the preceding chapters.)

4.2.1 TRIZ Phenomena and Effects

The beginning of the design catalog is the identification of the function of energy transformation involved in the problem. Messer's catalog starts with an expansive chart relating a variety of form of energy to themselves through the phenomena that enables that energy transformation. TRIZ practitioners also use this similar relation, except that it is viewed from the perspective of the required effect (instead of the transformation function) and the phenomena that causes it. Since these are so closely related, it seemed natural to compare them side-by-side to see if there we deficiencies in either. The results of this comparison are displayed in Table 4.12. Not everything that is in the TRIZ literature in terms of phenomena are listed however, as there are some phenomena that are not related to energy-to-energy transformations. The similar phenomena are underlined in each section, and the numbers next to the TRIZ phenomena are the numbers that are assigned to the required effects in the TRIZ literature, as well as found in the table of Physical Effects and Phenomenon Appendix Table A.4. That listing of phenomena and effects also contains the energy transformation functions that categorize the Messer catalog. In this fashion, there are a number of links between the two tables to help a designer locate a phenomenon for further investigation. Categorizing multiple functions based on the effect they can produce gives a designer further insight into what types of functions can be used to solve the problem, thus helping reduce design fixation. Shown in Table 4.11 is a section of the Physical Effect and Phenomenon table that contains the related functions for each effect.

Table 4.11: Physical Effect and Phenomenon with Functions

Required effect		**Function(s)** (Energy Input → Energy Output)	**Phenomenon**
1	Measuring Temperature	Magnetostatic → Sound	Barkhausen effect
		Thermal → Electrical	Thermoelectrical Phenomena
		Thermal → Material Properties	Change in optical, electrical, and magnetic properties
		Thermal → Mechanical	Thermal expansion and its influence on natural frequency of oscillations
		Thermal → Pneumatical/Hydraulic	Thermal expansion and its influence on natural frequency of oscillations
2	Lowering Temperature	Electrostati→ Thermal	Peltier, Seebeck, and Thomson effects
			Thermoelectrical Phenomena
		Mechanical →Thermal	Joule-Thomson effect
		Magnetostatic → Thermal	Magnetic calorie effect
		Pneumtical/Hydraulic →Thermal	Joule-Thomson effect
		Thermal → Chemical	Phase Transition
3	Raising Temperature	Chemical → Thermal	Absorption of radiation by the substance
		Electrostatic → Magnetostatic	Eddy Currents
		Electrostatic → Thermal	Dielectrical Heating Eddy Currents Electrical Charges Electromagnetic induction Electronic Heating Peltier and Thomson effects Thermal-electrical phenomena
		Mechanical → Thermal	Vortical currents
		Thermal → Material Properties	Surface effect

Table 4.12: Messer Function Based Phenomena Catalog [69] Augmented with TRIZ Phenomenon

Output / Input	Mechanical Energy		Pneumatical-/Hydraulical Energy		Electrostatic Energy		Magnetostatic Energy		Sound Energy		Light Energy		Thermal Energy		Chemical/Biological/Nuclear Energy (Nuclear-/reaction-/oxidation-energy)	
Mechanical Energy (Potential-/kinetic-/strain-energy)	- Inertia (translational/rotational) - Elastic/inelastic deformation (tension/compression/bending/shear/torsion/buckling/fracture/cutting/inversion/extrusion/drawing/flow) - Impact (translational/rotational) - Friction (static/dynamic) - Refraction (waves/particles) - Lever-effect (translational/rotational) - Poisson's-effect (positive/negative) - Stress-induced Martensitic transformation - Force field (gravity/surface-tension/contact-force/atomic-force) - Wedge-effect - Boyle-Mariotte-law - Magnus-effect - Lotus-effect - Resonance - Co-/Adhesion - Capillary-effect - Weissenberg-effect - Load spreading (fixed/flexible constraints or unconstrained) - Blocking and bracing - Topology	6. - Mechanical oscillations - Centrifugal forces 7. - Wave movement - Capillary force - Centrifugal forces - Weissenberg effect 11. - Reactive Force 12. - Centrifugal forces - Effect of a magnetic field via ferromagnetic substance 14. - Cavitation - Resonance 15. - Elastic deformation - Gyroscope 16. - Deformations - Oscillations - Waves, including shock waves 19. - Deformations 21. - Friction - Mechanical oscillations 23. - Deformation 24. - Interference waves - Standing waves - Mechanical oscillations 27. - Tunnel effect	- Bernoulli-principle - Viscosity - Toricelli's law - Gravitation - Boyle-Mariotte-law - Impact - Buoyancy - (In)compressibility	7. - Bernoulli's effect	- Electrostriction - Induction - Electrokinetic-effects - Electrodynamic-effects - Friction - Capacitance-effect - Josephson-effect - Deformation electrical resistance - Impact-ionization - Stewart-Tolman-effect - Lenard-effect	16. - Electromagnetic induction 19. - Electrostriction (Piezoelectrical effect) 25. - Electrostriction (Piezoelectrical effect) 27. - Josephson effect	- Magnetostriction - Induction - Aligning magnetical dipoles - Elastic/inelastic deformation - Barnett-effect	16. - Electromagnetic induction 19. - Magnetostriction	- Impact - Stick-slip-effect - Doppler-effect	5. - Doppler effect 14. - Ultrasonics 21. - Acoustical oscillations 24. - Acoustical oscillations	- Mechanochromics - Dichroic-effect - Mechanolumin-(fluor-, phosphor-)escence - Doppler-effect	5. - Doppler effect	- Pressure state change - Friction - Hysteresis - Turbulence - Inelastic deformation - Joule-Thomson-effect - Doppler-effect - Conduction - Convection - Radiation	2. - Joule-Thomson effect 3. - Vortical currents 5. - Doppler effect	- Residual stress - Phase transformations	15. - Phase Transition
Pneumatical-/Hydraulical Energy (Potential-/kinetic-/pneumatic/hydraulic-energy)	- Lift - Buoyancy - Turbulence - Magnus-effect - Flow resistance - Backpressure - Reaction principle - Compressibility	6. - Pressure transfer in liquid or gas 12. - Generating high pressure	- Bernoulli-principle - Continuity-law - Conduction - Absorption - Dalton's-law - Lotus-effect - Von Kármán vortex street	7. - Bernoulli's effect	- Electrostriction		- Magnetostriction	19. - Magnetostriction	- Impact		- Friction - Mechanochromics		- Pressure state change - Friction - Inelastic deformation - Joule-Thomson-effect	2. - Joule-Thomson effect	- Residual stress - Phase transformations	15. - Phase Transition
Electrostatic Energy (Capacitive-energy)	- Electrostriction (piezoelectric materials, electroactive polymers) - Capacitance effect - Coulomb's-law - Johnson-Rhabeck-effect - Biot-Savart-law - Electrokinetic-effects - Friction - Induction	6. - Applying elecrical field to influence charged object. 7. - Capillary force 8. - Applying electrical fields 11. - Applying electrical fields - Fixing in liquids which harden in magnetic and electrical fields 12. - Electrohydraulic effect 13. - Johnson-Rhabeck effect 14. - Electrical discharges - Electrohydraulic effect 16. - Electromagnetic induction 17. - Applying electrical fields (no-contact influence instead of physical contact) 19. - Electrostriction (Piezoelectrical effect)	- Electrostriction - Electrorheology - Electrophoresis - Cataphoresis - Electro-osmosis	9. - Electrophoresis 25. - Electro-osmosis	- Interference - (Super-/Semi-) Conduction - Ohm's-law - Faraday's-law - Impedance - Capacitance-effect - Skin-effect - Quantum tunneling	16. - Superconductivity 25. - Electrical discharges - Electronic emissions 28. - Screening/Faraday Cage	- Eddy current - Biot-Savart-law - Faraday's-law - Hall-effect - Meissner-effect	3. - Eddy currents 28. - Screening/Faraday Cage 29. - Faraday effect	- Electrostriction		- Photostriction - Kerr-effect - Pockels-effect - Stark-effect - Electrolumin-(fluor-, phosphor-)escence - Electrochromism - Liquid-crystal/suspended-particle effect - Incandescence - Laser-effect	27. - Luminescence - Gunn effect 29. - Electrical optical phenomena - Gunn effect - Kerr effect	- Joule-heating - Eddy current - Electric arc - Peltier-effect - Hysteresis	2. - Peltier, Seebeck, and Thomson effects - Thermoelectrical Phenomena 3. - Electromagnetic induction - Eddy Currents - Dielectrical Heating - Electronic Heating - Electrical Charges - Peltier and Thomson effects	- Electrochemistry - X-Ray-effect - Electrodialysis - Electrolysis	8. - Electrolysis
Magnetostatic Energy (Inductive-energy)	- Magnetostriction - Ferro-/electro-magnetism - Christoffos-effect - Induction (Lorentz-effect) - Elihu-Thomson effect - Einstein-de-Haas-effect	6. - Applying magnetic field to influence an object or magnet linked to object. - Applying magnetic field to influence a conductor with DC current going through 8. - Applying magnetic fields 11. - Applying magnetic fields 16. - Electromagnetic induction 17. - Applying magnetic fields (no-contact influence instead of physical contact) 19. - Magnetostriction 22. - Magneto-elastic effect 24. - Magnetic waves	- Magnetostriction - Magnetorheology	19. - Magnetostriction	- Faraday's-law - Hall-effect - Induction (Lorentz force) - Magnetoresistivity	16. - Electromagnetic induction 22. - Hall effect 25. - Hall effect - Gyromagnetic phenomena 28. - Screening/Faraday Cage 29. - Faraday effect	- Interference - (Super-/Semi-) Conduction - Reflection - Total reflection - Refraction - Absorption - Induction - Faraday's-law - Ferromagnetism - Saturation - Remanence	12. - Effect of a magnetic field via ferromagnetic substance 16. - Electromagnetic induction	- Magnetostriction - Barkhausen-effect	1. - Barkhausen effect 19. - Magnetostriction 22. - Barkhausen effect 25. - Barkhausen effect	- Faraday-effect - Zeemann-effect - Cotton-Mouton-effect - Magnetolumin-(fluor-, phosphor-)escence	23. - Magnetic-optical effects 29. - Magnetic-optical effects - Faraday effect	- Eddy current - Hysteresis - Demagnetization - Thermal Hall-effect (Righi effect)	2. - Magnetic calorie effect	- Ferromagnetism - Electromagnetism	
Sound Energy (Kinetic-energy)	- Sound excitation	14. - Resonance - Ultrasonics 21. - Acoustical oscillations 24. - Acoustical oscillations 30. - Ultrasonics	- Sound pressure		- Electrostriction		- Magnetostriction		- Reflection - Refraction - Interference - Dispersion - Birefringence - Polarization		- Acousto-optic effect		- Eddy current - Hysteresis - Demagnetization - Thermal Hall-effect (Righi effect)		- Elastic deformation	30. - Ultrasonics
Light Energy (Quantum-energy)	- Photostriction - Electromagnetical radiation pressure	6. - Pressure of light	- Electromagnetical radiation pressure	8. - Pressure of light	- Photostriction		- Photostriction		- Acousto-optic effect		- Reflection - Refraction - Birefringence - Interference - (Super-/Semi-) Conduction - Photonic crystal effect - Fluor-/phosphor-escence - Phosphorescence - Fermat's principles - Polarization - Photolumin-(fluor-, phosphor-)escence (Photochromics)	16. - Radiation - Lasers - Fiber optics - Light reflection 21. - Ultraviolet radiation 29. - Refraction and reflection of light	- Thermolumin-(fluor-, phosphor-)escence - Radiation	14. - Use of lasers	- Photoeffect - Photoresistor-effect - Photochemical-effect	
Thermal Energy (Heat-capacity/-enthalpy)	- Temperature change of state - Thermal expansion - Steam pressure - Osmotic pressure - Gas laws - Heat-induced martensitic transformations	1. - Thermal expansion and its influence on natural frequency of oscillations 6. - Thermal expansion 7. - Osmosis 12. - Thermal expansion 19. - Thermal expansion	- Temperature change of state - Thermal expansion - Steam pressure - Osmotic pressure - Gas laws - Thermophoresis (Soret-effect)	1. - Thermal expansion and its influence on natural frequency of oscillations 6. - Thermal expansion 7. - Osmosis 12. - Thermal expansion 19. - Thermal expansion	- Thermoelectric-effect - Thermionic emission - Pyroelectricity - Thermal-noise-effect - Conductivity - Semiconductivity - Superconductivity - Curie-Weiss-law	1. - Thermoelectrical Phenomena 16. - Superconductivity 23. - Thermoelectrical effects	- Curie-Weiss-law	23. - Thermomagnetic effects	- Thermo-optic effect		- Pyroelectricity - Thermolumin-(fluor-, phosphor-)escence - Thermocromics		- Conduction - Convection - Radiation - Insulation - Condensation - Evaporation - Freezing	3. - Evaporation 16. - Thermal conductivity - Convection	- Heat capacity - Phase transformations - Heat induced martensitic transformations - Thermoelectric effect - Stefan-Boltzmann-law - Wien's displacement-law - Destillation	2. - Phase Transition 4. - Phase Transition
Chemical/ Biological/ Nuclear Energy (Nuclear-/reaction-/oxidation-energy)	- Exothermic reactivity - Osmosis - Molecular-velocity - (De)Sorption - Nuclear fission - Nuclear fusion - Isometric/isotonic contraction - Cell growth	12. - Osmosis	- Exothermic reactivity - Osmosis - Adhesion - Cohesion - Nuclear fission - Nuclear fusion - Chromatography - Effusion - Cell growth	12. - Osmosis	- Electrochemistry - Molecular dipole - Ionization - Fermentation - Bioelectromagnetism - Semiconducting (doping)		- Magnetic-dipole-formation - Bioelectromagnetism		- Exothermic reactivity - Nuclear fission - Nuclear fusion		- Cotton-effect - Combustion - Chemochromics - Chemolumin-(fluor-, phosphor-)escence - Exothermic reactivity - Nuclear fission - Nuclear fusion - Di-/Association	16. - Induced radiation 27. - Cherenkov effect	- Combustion - Conduction - Exothermic reactivity - Nuclear fission - Nuclear fusion	3. - Absorption of radiation by the substance 12. - Use of explosives 14. - Induced radiation	- Photosynthesis - Endo-/exo-thermic reactivity - Nuclear fission - Nuclear fusion - Radiation - Absorption - Oxidation/Reduction - Ionic transport - Bohr-effect - Di-/Association/(Dis-)Solution - Adsorption - Electrodialysis - Autolysis - Catalysis - Phase separation - Meiosis - (Bio-)Sensing (antibody, DNA, receptor, enzyme, abzyme, (living) tissue, cell, organelle, isotopes, microbes) - Self-replication/-repair/-assembly/-diagnostic/-destruction/-replication	14. - Induced radiation 27. - Induced radiation

4.2.2 TRIZ Solution Principles Integrated with Messer Catalogs

Using the design catalog as it was developed by Messer and presented in section 4.1 is certainly helpful; however this functionality can be extended to varying extents depending on the type of problem (i.e., Technical Contradiction, Physical Contradiction, etc.) Building this functionality into the design catalog is developed then in layers based on the type of problem to solve in mind, and progressing through the different types and subtypes. The most straightforward of types of problems for designers is the Technical Contradiction, so this is the starting point for building the augmentations. Working within the TRIZ method, a designer attempts solving a technical contradiction (in addition to other tasks) by essentially forming the contradiction, and then using the contradiction matrix (Table A.6), finds the associated solution principles to seed concept generation.

Using a function-based design catalog then, while knowing the technical contradiction often related to those functions as well as the effect caused by the TRIZ solution principles, it is natural to draw the relation between what is in the Messer catalogs and the TRIZ solution principles. This is therefore what has been done, and a segment of this potion of the catalog is shown in Figure 4.8. (See Appendix Table A.11-Table A.16 for full catalog). Generally what is being related are the embodiments of the "Messer solution principles" found in the catalog with the generalized "TRIZ solution principles". Using Figure 4.8 as the illustration, the "Messer solution principle" is 'Fundamental structural elements', shown in the top left corner of the figure, and embodiments of this solution principle are shown as the individual rows of the catalog. The TRIZ solution principles related to these embodiments are displayed in the right two columns, classified as strong and weak associations respectively. (These column headings are not shown in Figure 4.8, but can be seen in the full catalog in Appendix Table A.11.) Organized in this fashion, the addition of the TRIZ principles used to solve Technical

Contradictions gives the designer an additional attention directing tool without any additional effort.

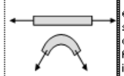
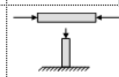
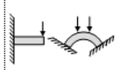
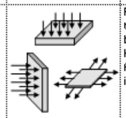
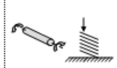
Macroscale	**Fundamental structural elements**	Basic engineering elements on the mocroscale primarily supporting loads are referred to as fundamental structural elements.				
	- Tie, cable, wire or continuous fiber		These structures are capable of carrying tensile loads only. The maximum energy that can be absorbed per unit weight before tensile instability supervenes depends upon the ultimate tensile strength and strain. If tension devices are for example used as a simple type of energy absorber, they suffer from the stroke, i.e., maximum displacement, or maximum strength limitation imposed by the ultimate strain or strength of specific material system.	- Single-, coaxial-, multicore, ... cables	1. Segmentation 3. Local quality	24. Intermediary
	- Struts or columns		These structures are capable of carrying compressive loads only.With respect to buckling and plastic collapse the specific ultimate tensile strength is an excellent indicator of the ability of a material to absorb energy. If struts or columns are for example used as energy absorber, the absorbed energy per unit mass in static tests is minimial because of the limited zone of plastic deformation during buckling.	- Hinged-, fixed-, free-, ... columns	1. Segmentation 3. Local quality	17. Another dimension
	- Beams or archs		Beam and archs (curved beams) are structural elements that carry load primarily in bending (flexure). In general, they are characterized by their profile (the shape of their cross-section), their length, and their material. Beams and archs may for example be used for energy dissiaption or blocking and bracing, i.e., locating supports in contact with stronger parts of a structure, so that imparct forces are directed to these parts.	- Cantilever-, simply-supported-, ... beams	1. Segmentation 3. Local quality	14. Spheroidality - Curvature
	- Plates/panels, shells, membranes or foils		Plates are initially flat structural elements, having thicknesses much smaller than the other dimensions. Whereas shells only bear in-plane loads, plates bear bending moments as well. Membranes are curved shells. Panels are non-horizontal plates. For example, their load spreading effect (i.e., spreading the forces at impact over a large area so that pressure is reduced) has been used in energy dissipation devices.	- Fixed-, simply-supported-, ... plates and panels - Multifunctional foils: load bearing, aesthetic, ...	30. Flexible shells and thin films.	14. Spheroidality - Curvature
	- Shafts or torsion springs		Shafts or torsion springs are structural elements primarlily loaded in torsion. Besides tension, compression and bending, torsion of bars or tubes, featuring relatively large deceleration strokes, has also been used in energy dissipation devices.	- Tension-, compression-, ... spring	15. Dynamics 35. Parameter Changes	11. Beforehand Cushioning 18. Mechanical Vibration

Figure 4.8: Design Repository[69]-- With Associated TRIZ Principles

Unfortunately, not all problems are that straight forward, as the class of problems increases in difficulty to Physical Contradictions. As discussed in Chapter 3, there is a host of tools and a systematic design process they are structured in to help a designer even before one comes to using the design catalog. Recall that for these types of problems, an Su-Field is created to model the problem. From the Su-Field a designer can use the process of the Standard Solutions (Table A.-Table A.3), which may suggest Su-Field modifications or the use of the Physical Effects table (Table A.4), for example. Still, the catalog as a central, systematic, and organized tool, there are augmentations added to the catalog to increase its usefulness for these more difficult problems.

To make the Standard Solutions more accessible and easier to use, depending on the approach that is most suited to the problem (i.e., if the development of the Su-Field through the algorithm isn't as apparent as defining the energy transfer functions), links have been created within the catalog of solution principles. The catalog with this augmentation has another column added on the right side to direct the designer to standard solutions that are relevant. (See Appendix Table A.11) These standard solutions have been related to the embodiments of the "Messer solution principles" in a similar fashion as the TRIZ solution principles; determining what standard solution each of the embodiments resonates with. Doing so creates and interesting coupling within the tools that increases their usability in a way that wasn't originally intended. For instance, a designer can arrive at a particular standard solution by going through the catalog and finding it related to a particular solution principle of interest; or a solution principle can be found by using a standard solution that was found through Su-Field analysis as an entry point into the catalog. Therefore a new 'exit' from the catalog has been created, as well and an 'entry', analogous to a standard and reverse phone book combined.

4.2.3 Electronic/Web Implementation for Concept Generation

Even with a design catalog that has large amounts of information, conveniently classified and categorized for easy retrieval, any archival scheme must be considered as a living document which must be continually maintained, updated, and sometimes even changed in its presentation to adapt to new types and amounts of information. A design catalog organized in this fashion—at the phenomenological level—underscores the multidisciplinary problem solving goals. It allows, in a very pro-TRIZ fashion, for a designer to focus on the contradiction or crux of the problem first, without limiting their design actions to a particular domain. Working then from the phenomenon and associated solution principles, material properties become mingled with the beginning of design activities, rather than being chosen after the completion of the conceptual design phase. Messer stated of his catalogs that, "the design catalogs … represent an open-ended map that enable a designer to identify underlying phenomena and associated solution principles rather than a prescriptive set of directions simply to instruct in the implementation of new materials and technologies is required.” [69] Certainly with the addition of solution triggering tools pulled from many disciplines, it is even truer that the design catalogs represent an open-ended map. This open-endedness is precisely what keeps the designer and the catalogs from being forced into obsolescence, but instead continues with technological evolution as described in TRIZ literature. [6]

The consequence of this though is that the designer must play a very active role in the conceptual design process, and little, if any is left for automation. This fact necessitates that not only is the catalog well organized and classified, but it must be easy to navigate and interact with. To this end, Matthias Messer took the first steps by formatting the catalog into a rudimentary web interface.[69] This web tool is intended to strike a compromise between allowing the document to be living through rapid editing by any user, and making it controllable and manageable. There is significant work at Missouri S&T [17] towards how to implement a design database with these mindsets online. While their foundations are different, focusing on the artifacts rather than phenomenon and solution principles, the structure of multiple connecting nodes to related design information, and the system of management are helpful and steps in the right direction. Future work might include merging the concepts of the advanced database backend with the ease of editing in a wiki style content management system. An interesting direction might also be the direct integration with software similar to the Missouri S&T FunctionCAD. This might be where the designer draws the function, and then selects which area of interest to investigate in the catalog based on a section of the function structure. If this were a success, the next step could be the development of software to give Su-Field modeling a similar treatment as functions, and integrate that with TRIZ standard solutions and the design catalog. The key message in this is that the future work is a continuation of the trend of merging knowledge and technologies.

4.3 VERIFICATION AND VALIDATION – THEORETICAL STRUCTURAL VALIDITY

In this chapter, theoretical structural validation as one aspect of the validation square is addressed. An overview of the validation strategy is presented in Section 1.2.3. A graphical representation of how this chapter fits into that overall strategy is displayed in Figure 1.11. Theoretical structural validation refers to accepting the validity of individual constructs used in the systematic approach and accepting the internal consistency of the way the constructs are assembled. Theoretical structural validation is performed in this chapter using a procedure consisting of 1) defining the method's range of applicability, *b)* reviewing the relevant literature to identify the strengths and limitations of the constructs contained therein, and *c)* identifying the gaps in the existing literature resulting from those weaknesses, and *d)* determining which constructs are to be used in the approach over the defined range of application. The internal consistency of the individual constructs is checked by a critical review of the literature.

Concerning the phenomena and associated solution principles design catalogs, it has been argued why design catalogs are appropriate to facilitate function-based systematic integrated product and materials design from a systems perspective. Based on the existing literature, it is shown that design catalogs have been previously used and validated for facilitating function-based systematic design in different domains successfully. Also, the TRIZ constructs have been used very successfully over a long range of time, validating their usefulness. In this work, previous efforts are extended to include phenomena and associated solution principles of relevance to integrated product and materials design. By focusing on phenomenon and associated solution principles, design tasks are integrated and materials design itself is rendered more systematic and domain-independent. Due to the process of the literature review, gap analysis, the development of tools and augmentation to the design catalogs, the theoretical structural validity of the construct is accepted.

4.4 WHAT HAS BEEN PRESENTED AND WHAT IS NEXT

In this chapter, the focus has been on augmenting design catalogs for with solution triggers to facilitate concept generation for integrated product and material concepts. Theoretical Structural Validation is complete, allowing for the transition to Empirical Structural Validity in the next chapter.

CHAPTER 5

DESIGNING A REACTIVE MATERIAL CONTAINMENT SYSTEM (BLAST RESISTANT PANEL)

Having shown the entire design process and the Theoretical Structural Validity, the motivational example can be examined. In this example it is shown how the problem has been solved in the past and how the solution process is improved. Repeated below is the chart containing information on how each hypothesis is tested in this chapter:

Chapter 5- Design of a blast resistant panel	H1a- supplementing materials selection with materials design to integrate product and material concept generation	Demonstrate material concept generation along side of product concept generation, by showing the outcomes of the method having both.
	H1b - experiential knowledge based problem solving and solution triggering tools to create a systematic and domain-independent method	Demonstrate that the use of the problem solving tools is independent from the domain by applying them to the multiple domains within the blast panel example.
	H2 - problem formulations and solution triggers developed for use in the TRIZ methodology can also be integrated into function based design for multi-scale materials by allowing TRIZ problem modeling (Su-Field models with systems conflicts) to be developed alongside function structures (with the potentially improved performance by using a CAD type software)	Show the use of problem formulations borrowed from TRIZ on the blast panel in conjunction with standard P&B problem formulations, improving the outcome possible in either individually, by having improved outcomes.
	H3 - Mapping pre-existing abstracted problem formulations and solution trigger mappings (TRIZ Matrix) to functions and length scales. Also, analogical techniques found in TRIZ used for the structure of augmentations to a design catalog, utilizing the conflict as the common interface.	Show the solutions from the design repositories (both the length scale considerations for the TRIZ matrix, and the analogical use of conflicts in determining the solution route) for the blast panel.

The reactive material containment system example problem introduced in Section 1.1.5 is used to validate empirically the systematic approach synthesized in this thesis. An overview of empirical structural and performance validation is given in this section and the reactive material containment system is used for those two aspects of validation for the overall systematic approach.

Empirical structural validation involves accepting the appropriateness of the example problems used to verify the performance of the method. In this context, it is to be validated that the examples fall within the scope of integrated product and materials design. Empirical performance validation consists of accepting the usefulness of the outcome with respect to the initial purpose and accepting that the achieved usefulness is related to applying the method.

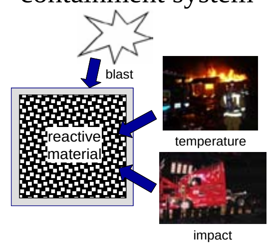
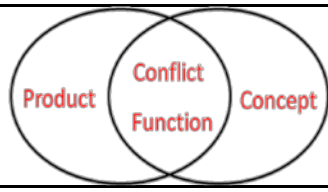
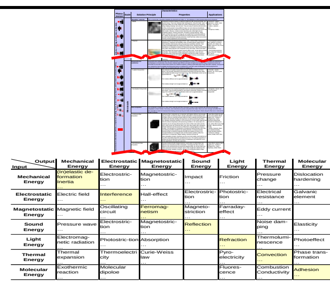
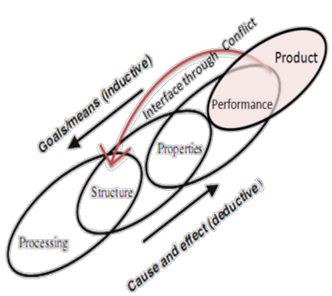
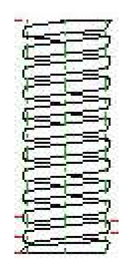
In this chapter, the systematic approach is tested as a whole using the comprehensive example problem of a reactive material containment system. With respect to the reactive material containment system, the example problem, fundamental modeling, material property, and loading assumptions are clarified first. Then, the focus is on applying the systematic approach to the integrated product and material concepts generation and concept exploration to converge to a principal solution. Results are discussed along with verification and validation.

5.1 CONTEXT: VALIDATION OF THE PROPOSED SYSTEMATIC APPROACH

The objective in this chapter is to validate the proposed systematic approach as a whole, using a comprehensive design example. The objective of validation of the proposed systematic approach is accomplished by selecting the design of a reactive material containment system as a reasonably complex design problem that involves design of products and multi-purpose materials. Results from the example presented in this chapter are used for answering, "**How can a designer generate concepts in materials design that supplement concepts in product design to fulfill the design goals of innovative products?**" and "**How should solution principles and problem formulations used in the past mostly for the mechanics domain be integrated into the function based design method to be applicable to multi-scale materials design?**" The constructs of the systematic approach, associated requirements, and hypotheses validated in this chapter are illustrated in Table 5.1.

Since designing a reactive material containment system involves deciding on both material and product design variables, the design problem involves the integrated design of products and materials. The decisions about the product and constituting materials are coupled with each other because both decisions impact achievement of performance requirements and behavior of the product-material system. With respect to the reactive material containment system, the design problem, fundamental modeling, material property, and loading assumptions are clarified in Section 5.2. In Section 5.3, focus is on generating and selecting concepts through function-based analysis, abstraction, synthesis, and systematic variation.

Table 5.1: Constructs of the Systematic Approach to Address the Requirements and Validation Examples

Requirements	Constructs of the Systematic Approach	Hypothesis	Validation Examples
Broaden a designer's conceptual design space	Design catalogs, connecting materials design to product design, TRIZ	***R. H. 1:*** Systematic approach to the integrated design of product and material concepts from a systems perspective. Abstraction, synthesis, and systematic variation.	Reactive material containment system 
Integrating design of product and material concepts		***R. H. 2:*** TRIZ problem modeling (conflicts, Su-Fields) and ARIZ.	
Rendering conceptual design more systematic	Systematic multi-domain mappings	***R. H. 3:*** Systematic, function-based, conceptual materials design mappings	AND
Rendering conceptual materials design more domain-independent	 Design catalogs	***R. H. 1:*** Experiential knowledge based problem solving and solution triggering tools (TRIZ).	Spring Redesign
Accelerate conceptual design	Problem solving tools	***R. H. 2:*** TRIZ problem modeling (conflicts, Su-Fields) and ARIZ.	
Transfer design knowledge (underlying principles) from the product domain to the materials	 Analogy	***R. H. 2:*** The analogy tool helps transfer design knowledge by the use of the system conflict as the common interface.	

5.2 CLARIFICATION OF TASK AND PRODUCT PLANNING

In this section, the reactive material containment system design problem, fundamental modeling, material properties and assumptions are clarified to proceed towards concept generation phase. This design example is built on the work done by Matthias Messer [69] and uses the same design task, but with the process developed in this thesis applied. Doing so allows for a comparison between what is developed using this method to what has previously been possible. Refer to Chapter 3 of this thesis for the details of the individual steps through which this design task is processed. Throughout the text in this chapter, reference will be made to the parallel sections in Chapter 3. The initial phase, that is, up through the requirements list, is a process of clarification whereby a designer defines basic market demands, documents specific technical requirements, performs some speculative forecasting of potential directions for concept generation, presents these design spaces as product proposals, and arrives at a requirements list. This initial phase (all of Section 5.2) is the implementation of the process outlined in Section 3.2.

The design of a reactive material containment system to transport exothermic reactive materials for energetic applications, as shown in Figure 5.1 is selected as a reasonably complex design problem that involves the design of products and materials. Currently, reactive materials are transported to their destinations in enclosures consisting of monolithic panels. Also, the more or less advanced materials of the reactive material containment system are mostly selected from a finite set of available materials. However, in order to minimize adverse economic and environmental effects while ensuring safe handling at satisfactory reactivity, customers pose conflicting requirements such as:

- minimization of reaction probability during transport,
- maximization of reaction probability during usage,
- maximization of collision resistance, and

- minimization of system weight.

The overall system has to be designed in order to ensure satisfactory performance, i.e., reactivity, of the reactive material to be transported as well as its safe handling, i.e., *protection against collisions which may cause impacts, high temperatures and blasts as shown in Figure 5.1, while minimizing overall system weight*. Thus, to solve this design problem, functionalities (and related properties) from the chemical and mechanical domains are required and they are coupled. Also, the reactive material containment system involves decisions on both the product and material level.

On the system level for example, a decision has to be made on configuring the containment system – potentially featuring various panel concepts, ranging from monolithic to composite panels, or unreinforced to stiffened to multilayer sandwich panels. Also, a designer is confronted with material level decisions to better achieve performance requirements. For example, by selecting a sandwich structures to configure the overall containment system, various microscale cellular material or truss structure core configurations can be designed that feature increased energy dissipation per unit mass to better sustain blasts. [69] These material design options, coupled with the overall system level design afford a designer increased flexibility when generating concepts.

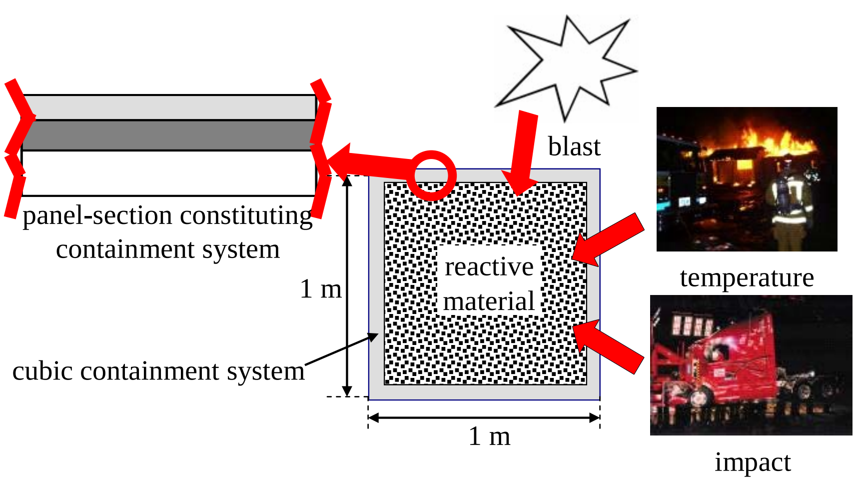


Figure 5.1: Reactive Material Containment System - Messer[69]

The possibilities presented by designing a product in a coupled system level and product level sense are such that the bounds of the concept generation are extended to allow for concepts that are not possible by looking only at each separate domain. An example of this is when the design of a system takes on the TRIZ principle of Homogeneity (Principle #33 of 40) in the sense that a material becomes its own container, or Self-service (Principle #25 of 40) where a material fulfills the function for which it is needed, but also a function for which another supportive material would have been needed. This would be the case if, for example, a system was designed where a reactive material would serve the dual purpose of providing both energy storage and strength to a reactive system; the material would be self-serving. Along the same lines, designers can consider the design of multifunctional panels that compromise the containment system, providing the service of both strength and increased energy absorption per unit mass.

In the following, resistance against impacts and solid fragments of varying size and velocity is not specifically considered, but only blast resistance is considered. In this work, the focus is on generating concepts for the design of a reactive material containment system at minimum weight to sustain blasts by integrating protective measures to sustain blasts at satisfactory reactivity. Specific performance requirements and constraints have been clarified and summarized by Messer [69] in the requirements list shown in Table 5.2, where D stands for demands, and W for wishes, as proposed by Pahl and Beitz [81].

5.2.1 Basic Assumptions

Implementation of process described in Section 3.2.1 Product Planning

The reactive metal powder mixture is considered to be thermite mixture, i.e., a multiphase mixture of metal and metaloxide or intermetallic powders with an Epoxy binder phase. These materials represent an effective means to store energy. When elevated in temperature or subjected to a shock environment, this energy can be released with exothermic, self-sustaining reactions. A certain level of porosity in the mixture is however desirable for shock-induced reaction initiation, as dynamic plasticity and void collapse engender substantial local temperature rise (hot spots).

Table 5.2: Requirements List [69]

Request:		Title: **Reactive Material Containment System**				
Problem statement: Ensure satisfactory performance of a reactive material to be transported as well as its safe handling, while minimizing overall system weight.						
Chan-ges	**Classifi-cation**	**D W**	**Requirements**			**Respon-sible**
			No.	**Description**	**Data, Comment**	
		D	1	Size:	Length: 1 m	
		D	2		Width: 1 m	
		D	3		Height: 1 m	
		D	4	Weight (mass/area):	≤ 900 kg/m^2 (not considering reactive material)	
		D	5	Deformation:	≤ 0.1 m (10% of length)	
		D	6	Protection from:	Blast pressure waves (with peak pressures from 190 to 280 MPa)	
		W	7		Mechanical impacts at varying angle of incidence (solid fragments of varying size and velocity)	
		W	8		High temperatures	
		D	9	Functionalities:	Ensure overall structural stability (strength and stiffness)	
		D	10		Absorb (divert, dissipate and/or store) kinetic energy blast pressure wave (ensure sufficient ductility to dissipate the blast energy without causing collapse or excessive deformation)	
		W	11		Absorb (divert, dissipate and/or store) kinetic energy solid fragments	
		W	12		Stop solid fragments without risking reaction initiation	
		W	13		Absorb (divert, dissipate and/or store) thermal energy without risking reaction initiation	
		D	14		Ensure sufficient reactivity for energetic application	
		W	15	Multifunctional material	Revolutionary structures	
		W	16	features:	Innovative energy absorption mechanisms	
		W	17	Microstructure control:	Control damage evolution of impacted materials	
		W	18	Macrostructure control:	Mitigate shock wave effects (vibration, shock and blast)	
		D	19	Failure modes to be	Low-order buckling	
		W	20	avoided:	Delamination	
		D	21		Rupture	
		D	22		Overall structural collapse	
		D	23	Robustness to:	Uncertainty in loading conditions	
		W	24		Uncertainty in noise factors	
		W	25		Uncertainty in design factors	
		W	26		Uncertainty in simulation models specific for materials design	
		D	27	Safety principle:	Passive	
		W	28	Modular structure:	Exchangable or reusable layers	
		W	29	Scalability:	Scalable in size	
		W	30	Cost	Product life cycle as well as modeling and simulation cost low (specific value and indicators to be specified)	

Material properties relevant to this work are listed in Table 5.3. Most material properties are obtained from Ashby [1]. However, certain properties for specific materials are found in specialized literature [9, 19, 120]. Here, only the most promising materials from a strength/stiffness per unit perspective have been listed, i.e., titanium, ceramic boron carbide, aluminum, magnesium, polymer carbon fiber composite (quasi-isotropic) as well as Nylon (PA). These materials have been identified based on the work of Evans [39]. The strain-hardening stress-strain relationship of materials is assumed to be known. Moreover, the material is assumed to be defined by independent yield strength and density variables. Also, the bounds for material property design variables given in Table 5.3 are determined from the ranges of properties for engineering metals.

Table 5.3: Material properties [9, 19, 120]

Material	***Properties***							
	Density [g/cm^3]	Young's Modulus [GPa]	Poisson's ratio [-]	Strength [MPa]	Elon-gation [%]	Loss factor [-]	Thermal Conductivity [W/mK]	Price [$/kg]
Steel (average)	7.85	210	0.3	370-2850	0.5-70	10^{-3}-10^{-2}	12	0.8
Titanium alloys	4.36 - 4.84	90 - 137	0.32	172-1245 yield	1 – 40	10^{-3}-10^{-2}	3.8 - 20.7	21-28
Ceramic boron carbide	3.7 - 3.8	333 - 350	0.25	175-200 ultimate	0	10^{-4} - 10^{-5}	25 - 30	4-12
Aluminum alloys	2.5 - 2.95	68 - 88.5	0.35	30-510 yield	1 - 44	10^{-3}-10^{-2}	76 - 235	1.3-5.7
Magnesium alloys	1.73 - 1.95	40 - 47	0.29	65-435 yield	1.5 - 20	10^{-3}-0.1	50 - 156	2.6-11.4
Polymer carbon fiber composite (quasi-isotropic)	1.55 - 1.6	230 - 450	0.28	2150-4510 yield	0.3 - 0.35	10^{-3}-10^{-2}	1.3 - 2.6	50-61
Nylon (PA)	1 - 1.42	0.67 - 1.42	0.3	20.7-101.6 ultimate	4 - 1210	10^{-2}-1	0.18 – 0.35	2.9-11.5
Carbon nanotube	1.3	780 - 1800	*	88000-105000	2 - 300	*	*	*
Reactive Metal Powder Mixtures (Al+ Fe_2O_3) and Epoxy binder	*	100	*	800 yield	*	*	*	*

*: not yet available.

5.2.2 Blast Assumptions

The focus in this work is on designing a reactive material containment system to sustain blasts, which for example are caused by explosions occurring in the context of collisions. In general, an explosion is a very fast chemical reaction producing transient air pressure waves called blast waves. High explosives, i.e., explosives in which the speed of reaction is faster than the speed of sound in the explosive (for example 5000 – 8000 m/s [2]), produce a shock wave. The characteristic duration of a high-explosive detonation is measured in microseconds. For a ground-level explosive device, the blast waves will travel away from the source in the form of a hemispherical wavefront if there are no obstructions in its path.

The effects of an explosion are diverse. For explosions close to an object, the pressure-driven effects occur quickly, on the order of microseconds to a few milliseconds. The air-blast loads are commonly subdivided into (1) loading due to the impinging shock front, its reflections, and the greatly increased hydrostatic pressure behind the front, all commonly denoted as overpressure; and (2) the dynamic pressures due to the particle velocity, or mass transfer, of air. When an explosion impinges on a structural element, a shock wave is transmitted internally at high speed; for example, dilatational waves (tension or compression) propagate at speeds of 4900 to 5800 m/s in steel [2]). At these speeds, reflections and refractions quickly occur within the material (within milliseconds), and, depending on the material properties, high-rate straining and major disintegration effects can occur. For example, under extremely high shock pressures, relatively brittle materials like ceramics tend to undergo multiple fractures which can lead to fragmentation. In ductile materials like steels under similar conditions, depending on the material properties and geometry, yielding and fracture can be expected, especially if fabrication flaws are present, with fragmentation occurring in some cases.

The impulse load is assumed to act perpendicular to the surface of the reactive material containment system and be uniformly distributed over the area, as illustrated in Figure 5.2. For the interested reader, Muchnik [72] (page 299) investigated and compared uniform and spherical pressure waves in the context of blast resistant panels. The difference however has appeared to be negligible in the early stages of design.

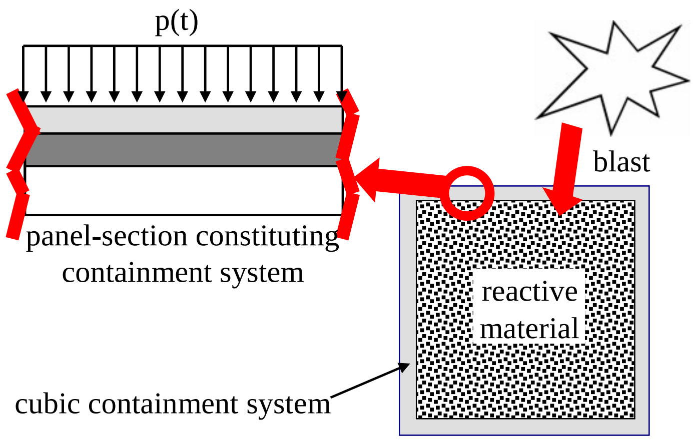


Figure 5.2: Loading Reactive Material Containment System

5.3 CONCEPT GENERATION AND PROBLEM SOLVING

5.3.1 Problem Formulation

Implementation of process described in Section 3.3.1

A process of abstraction, as presented by TRIZ, is used to ensure that a designer avoids fixation. This is also the first step in promoting the transfer to another domain. Beginning with problem formulation, the series of steps prescribed by the Algorithm for Inventive Problem Solving (ARIZ) are used to introduce TRIZ tools into the Pahl and Beitz process. These steps are applied to the Reactive Material Containment System to formulate the problem in accordance with TRIZ standards. First is a process of abstraction to identify the essential problem, or the abstracted solution neutral problem statement:

Ensure satisfactory performance of a reactive material to be transported as well as its safe handling, while minimizing overall system weight.

Once the essential problem is identified, an initial analysis of the problem can be performed by following these steps (TRIZ in italics, Pahl and Beitz in regular font):

- *State the original problem as presented*

  "Ensure satisfactory performance of a reactive material to be transported as well as its safe handling, while minimizing overall system weight."

- State the "overall function" of the system

  "Protect a reactive material from damage during handling and transportation without impeding its energetic use."

- Define any subfunctions

  "Resist deformation caused by blasts and mechanical impacts of solid fragments, resist high temperatures, and when necessary release energy for energetic applications upon receiving a signal to do so. In this exercise, protection against solid fragments and high temperatures is not considered further."

- *Define the system boundaries along with its subsystems*

  "The boundaries around the system level functions of resisting deformation caused by blast and releasing energy for the energetic applications."

- *Identify any supersystem or environment*

  "The product may be susceptible to collisions, blasts, high temperatures, or other harmful transportation/handling environments."

- *Identify any beneficial/detrimental functions of the system*

  "The system will release the stored energy even if a signal to do so hasn't been received if a sufficiently large amount of force or heat penetrates the containment system."

5.3.1.1 Establish function structure

Implementation of process described in Section 3.3.1.2

The creation of function structures on multiple system levels through functional analysis, abstraction and synthesis is based on the clarified problem statement. Concerning the reactive material containment system problem, the system level functionalities that the material-product system should fulfill are to resist deformation caused by blast (kinetic energy E_{kin}) and mechanical impacts of solid fragments (M_{kin}), resist high temperatures (thermal energy $E_{thermal}$), and when necessary, release energy for energetic applications (E_{use}) upon receiving information (signal $S_{release}$) to do so. As mentioned, protection against solid fragments and high temperatures is not considered further. The system level functions of resisting deformation caused by blast and releasing energy for the energetic application are considered only. However, outgoing thermal energy that is not required by energetic applications is lost to the surroundings. The overall system function structure of the reactive material containment system in terms of material, energy and signal flows is shown in Figure 5.3.

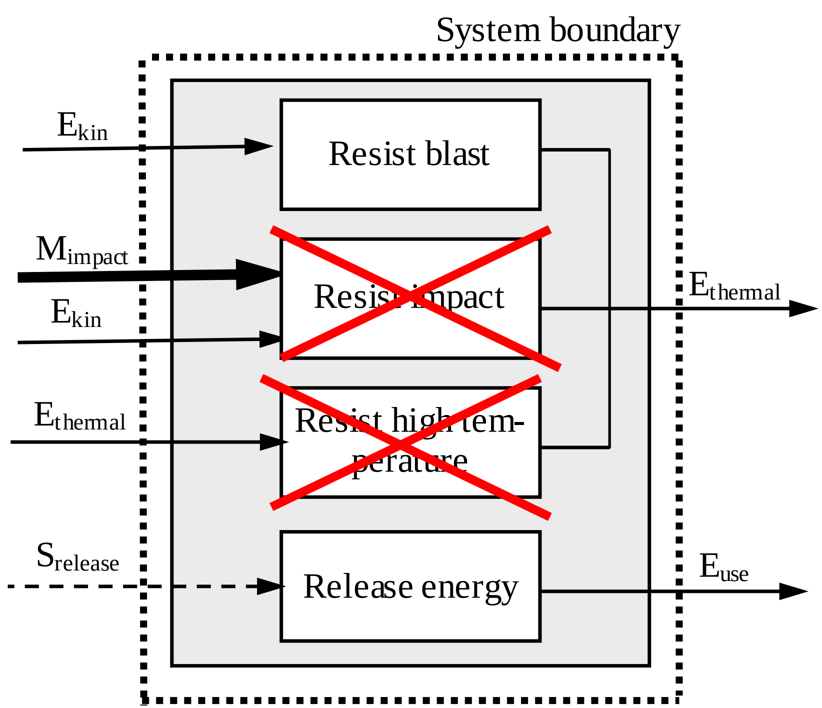


Figure 5.3: System level function structure for reactive material containment system – Messer [69]

Breaking the system level function structure into a component level function structure is shown in Figure 5.4. Though this is a level of closer investigation, material design is still not considered at this stage. Considering the materials level, multiple possible function structures are created at the materials level to expand a designer's flexibility, as shown in Figure 5.5. As can be seen in comparing Figure 5.4 with Figure 5.5, in order to realize the basic component level functionalities of "store energy", "change energy", and "transform energy", significantly more functional relationships are required. This increase in complexity however also increases a designer's concept flexibility. Various function structure alternatives on the materials level are shown in Figure 5.5.

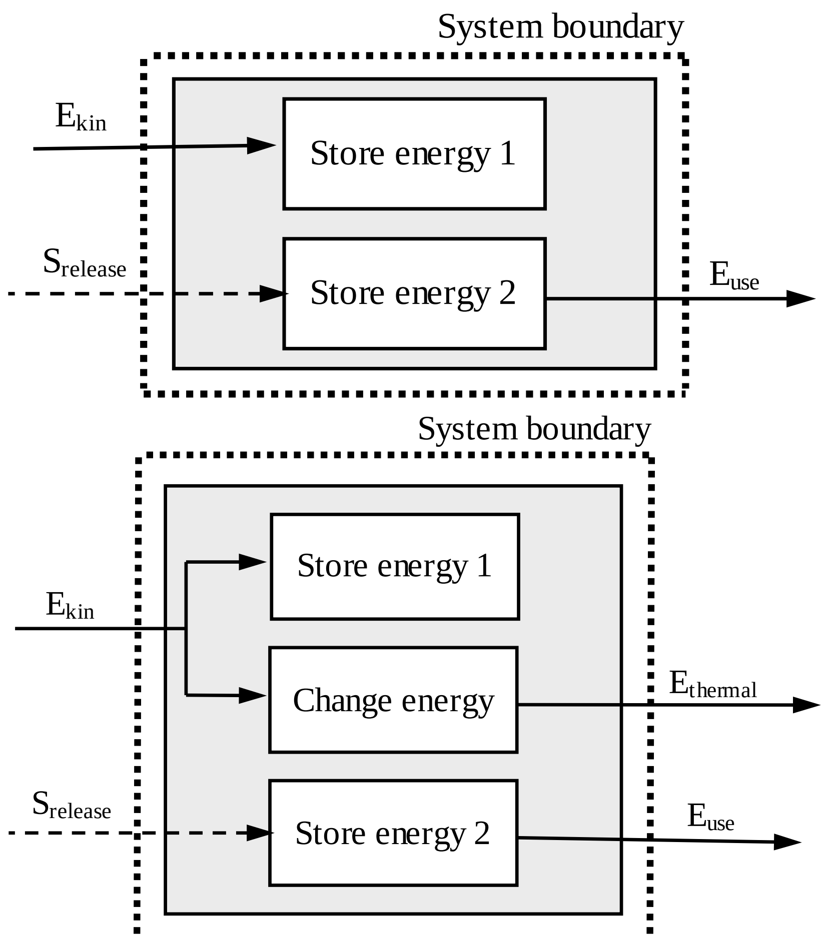


Figure 5.4: Component level function structure for a) storage and release of energy, and b) energy storage, dissipation and release. - Messer[69]

The function structure alternative shown in Figure 5.5 a) – energy transfer, storage, and dissipation – represents the most complex function structure alternative on the materials level. Part of the incoming blast energy is transferred, through for example load spreading or redirecting blast loads, as represented by the material level function "transform energy 1".

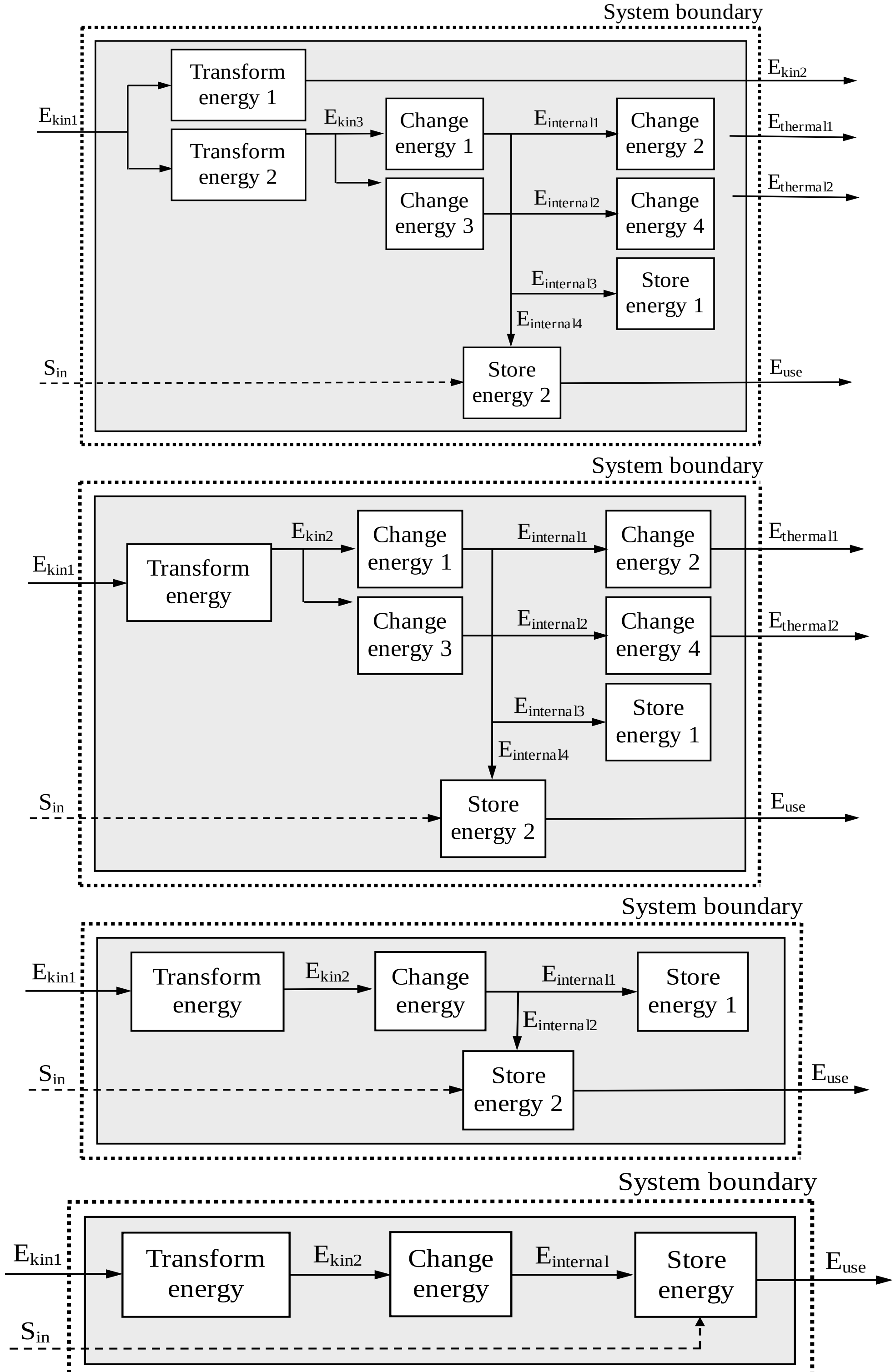


Figure 5.5: Material level function structures alternatives: a) energy transfer, storage, and dissipation, b) energy storage, and dissipation, c) energy storage, and d) multifunctional energy storage – Messer [69]

The remainder of the incoming blast energy is transformed, represented by the function "transform energy 2", and then changed into internal and finally thermal energy through for example *i)* a sandwich panel front face sheet (represented by the functions change energy 1 and 2), and *ii)* a sandwich panel core (represented by the function change energy 3 and 4). The part of internal energy that is not changed into thermal energy is for example stored as internal energy $E_{intnal4}$ (strain energy) in for example a sandwich panel back-face-sheet.[69]

Compared to the function structure alternatives shown in Figure 5.5 a), the function "transform energy 1" to for example spread or redirect blast loads is not considered in the function structure alternatives illustrated in Figure 5.5 b) – energy storage, and dissipation. Hence, Figure 5.5 b) on the materials level is consistent with Figure 5.4 a) on the component level and Figure 5.3 on the system level. In the function structure alternative shown in Figure 5.5 c) – energy storage, only storing incoming blast energy in terms of strain energy and storing energy for the application in the use phase is considered. Hence, Figure 5.5 c) on the materials level is consistent with Figure 5.4 b) on the component level. [69]

On the materials level, a simple function structure alternative is shown in Figure 5.5 d) – multifunctional energy storage. This function structure alternative can for example be realized through the design of a tailor-made reactive metal powder mixture – a multifunctional energetic structural material storing incoming blast energy in terms of strain energy while at the same time storing chemical energy for release during the energetic application in the use phase. On the material level, resistance against deformation is either achieved by storing internal energy, i.e., strain energy, within system boundaries or introducing some means of changing incoming kinetic into thermal energy, such as inelastic deformation that dissipates incoming blast energy. Also, some incoming kinetic energy may be transformed, in other words diverted, to resist further deformation. However, conversion of incoming kinetic energy into internal energy of a material and dissipation at microstructure scales might lead to reaction initiation, which is certainly not intended during transport and handling, but may be required during energetic applications. [69]

5.3.1.2 Description of the Mini-Problem

Implementation of process described in Section 3.3.1.3

The mini-problem is a description of the problem in such a way that there are minimal changes to the existing system. In the case of the reactive material containment system, this takes the form of framing the problem with the goal of minimal weight in mind. Therefore the mini-problem is that the materials in the system are minimized, so as to preserve weight, yet with enough material to maintain safe transportation and handling. In other words, a designer is looking at the problem this time in a way that favors containment structures that use less material and possibly no material at all. The description of the problem in this way allows for a way to search for a more direct solution that may be the easiest to implement, or not explored due to design fixation.

5.3.1.3 System Conflict

Implementation of process described in Section 3.3.1.4

The system conflict is the essence of a problem (and what turns a situation or task into a problem) and its proper formulation provides the key to finding a solution to it. The system conflict, also known as the Technical Contradiction, is a conflict between two aspects of a design such that the improvement of the useful action yields the worsening of the harmful action, or vice versa. As such, the conflict should be stated in both the forward (improvement of the useful action yields the worsening of the harmful action) and reverse (lessening the harmful action yields a degradation of the useful action) sense. Furthermore, in order to standardize the form, the conflict should be described using 2 of the 39 aspects of a design as put forward by Altshuller [6] displayed in Table 5.4.

Thus the Technical Contradictions stated in the forward and reverse sense using parameters from this set are as follows:

- Improving the *Strength/Durability* of the RMCS worsens the *Weight*.
- Decreasing the *Weight* causes the *Strength/Durability* of the RMCS to be lessened.

Table 5.4: Generalized Design Aspects

1. Weight of moving object	21. Power
2. Weight of binding object	22. Waste of energy
3. Length of moving object	23. Waste of substance
4. Length of binding object	24. Loss of information
5. Area of moving object	25. Waste of time
6. Area of binding object	26. Amount of substance
7. Volume of moving object	27. Reliability
8. Volume of binding object	28. Accuracy of measurement
9. Speed	29. Accuracy of manufacturing
10. Force	30. Harmful factors acting on object
11. Tension, pressure	31. Harmful side effects
12. Shape	32. Manufacturability
13. Stability of object	33. Convenience of use
14. Strength	34. Reparability
15. Durability of moving object	35. Adaptability
16. Durability of binding object	36. Complexity of a system
17. Temperature	37. Complexity of control
18. Brightness	38. Level of automation
19. Energy spent by moving object	39. Productivity
20. Energy spent by binding object	

5.3.1.3.1 Intensifying the Conflict

Implementation of process described in Section 3.3.1.4.2

Intensifying the conflict provides another way of understanding the problem, and has the form of: “the harmful action is completely eliminated, but the useful action is not performed at all” and vice versa.

- The strength is increased/durability is increased greatly, but the RMCS cannot fulfill its purpose because it cannot release energy or cannot be effectively transported.
- The weight is decreased maximally by eliminating the containment system, but the device very easily becomes destroyed during handling and transportation.

5.3.1.3.2 Select which intensified conflict version is most helpful for examination

Implementation of process described in Section 3.3.1.4.3

In this scenario, there is no clear preference for either the first or second intensified conflict in being more helpful in generating concepts. As the first conflict is intensified, one beneficial factor is improved (strength) while two negative factors are worsened (weight/material use and primary functionality of the system). As the second conflict is intensified, the weight and material use is reduced while the reductions do not eliminate the primary function of the system, yet it is made more susceptible to damage.

5.3.1.4 Analyze the Resources

Implementation of process described in Section 3.3.1.5

An analysis of the existing resources can often be one of the most crucial steps in solving a problem in a given scenario where only the present resources can be used. It is also helpful in identifying where resources might be able to be used that would have gone to waste otherwise. Analyzing the resources involves the following 3 steps.

5.3.1.4.1 Describe the Operation Zone (space).

Implementation of process described in Section 3.3.1.5.1

This operating zone corresponds to the system boundary in the function structure that is the reactive material, material binding the reactive material together, and any material separating the reactive material from the outside world. What is not included is any system that is used for the transportation or handling of the reactive material, so this excludes the designer from modifying such systems, and forces the designer to consider solutions robust enough to accommodate multiple means of transportation, storage and use.

5.3.1.4.2 Describe the Operating Time

Implementation of process described in Section 3.3.1.5.2

The RMCS must be able to remain effective for at least as long as the shelf life of the reactive material, if not longer. There could be a safety concern if the system remains unused due to a malfunction at the intended time of use and the RMCS degrades to the point of exposing the reactive material to the environment for potential pollution. These concerns lead to an operating time on the order of decades. There is also the operating time of when the device is in proper use, where the system needs to be able to withstand large forces of very short time spans (i.e., blasts and impacts) and when the system must allow for energy release.

5.3.1.4.3 List the internal and external resource of the system and its environment

Implementation of process described in Section 3.3.1.5.3

There are 4 types of resources:

- Substance resources (internal and external)
- Field resources (internal and external)
- Time resources
- Space resources

Assessing the substance resources in terms of the existing system leaves a designer with the actual reactive material itself and the binder. Available to the designer however is any substance that will be reasonable to acquire in manufacturing, which is something that can be assessed after concepts are generated. The other relevant resource is that of space, and the area around the reactive material is the space available for concept generation.

5.3.1.5 Define the Ideal Final Result

Implementation of process described in Section 3.3.1.6

The Ideal Final Result is the goal of the design. If this is achieved, and is feasible, then the design is successful. It is also useful, along with the requirements list, as a measure of assessment for concept selection and final design performance. It is developed in 2 steps:

5.3.1.5.1 State the initial Ideal Final Result (IFR-1).

Implementation of process described in Section 3.3.1.6.1

The Ideal Final Result for the RMCS is that *the containment system is improved to specifications without using any material resources. Stated in other words: The 'resource' used to solve the problem will not impart any additional weight, volume, expense, manufacturing effort, etc. to the device within the system boundary while sufficiently protecting the reactive material. Note* that the aspects of the IFR that are used to limit the resource involved in solving the problem are the aspects that are trying to be minimized in the conceptual design, and the further these are reduced while maintaining requirements, the more 'ideal' the solution is.

5.3.1.5.2 Reinforce the IFR by trying out different statements of the IFR.

Implementation of process described in Section 3.3.1.6.2

This step involves restating the IFR by substituting words for resource such as: tool, object, environment, system, material state, configuration, and so on with as many as are applicable, while focusing on the internal resources. I.e., The 'configuration' used to solve the problem will not impart any additional weight, volume, expense, manufacturing effort, etc. to the device within the system boundary while sufficiently protecting the reactive material.

5.3.1.6 Define the Physical Contradiction

Implementation of process described in Section 3.3.1.7

The Physical Contradiction is the second type of contradiction used in TRIZ. Its formulation is important in understanding how a solution might solve the problem at a physical level (i.e., relying on a physical phenomena or scientific principle) and not merely a technical level. This contradiction is stated such that the conflict is shown to be the result of needing both the presence and absence of an aspect of a design to satisfy the design requirements. There are also two physical contradictions as there are two technical contradictions.

5.3.1.6.1 <u>Define the Physical Contradiction on a Macro Level</u>

Implementation of process described in Section 3.3.1.7.1

The two physical contradictions correspond to the technical contradictions: one for Conflict 1 and one for Conflict 2, the "forward and reverse conflicts" as found in section 5.3.1.3.

1. The walls must be thicker/more massive to make the container stronger, yet the walls must not be thicker/more massive to reduce the weight/increase ease of use.

2. The walls must be made thinner/less massive to make the container lighter, yet the walls must not be made thinner/less massive to protect the reactive material.

The key to the physical contradiction is that there is a property of function that is essentially in conflict with itself in one form or another. The benefit in searching for these sorts of conflicts is that they allow a designer to see the crux of the problem on a physical level (and often material level) and not merely a technical level. Therefore, the solution to these problems is on the physical or material level, and frequently more innovative [4].

5.3.1.6.2 <u>Define the Physical Contradiction on a Micro Level</u>

Implementation of process described in Section 3.3.1.7.2

Transforming the Physical Contradiction defined on the macro level to the micro level can help reveal solutions, particularly of the material design sort. Doing so for the RMCS yields:

The walls must be fashioned in such a way that allows the molecules to move in some fashion to absorb energy in the event of a blast, but not move significantly at other times to protect and support the reactive material.

5.3.1.7 Develop Su-Field Model

Implementation of process described in Section 3.3.1.8

Problem modeling provides a means of representing the problem in a graphical and abstract way, yet in a more concrete and formulated fashion than words alone. Much like how the Function Structure as developed in Pahl and Beitz [82] is an abstracted graphical representation of a problem, the Su-Field model is a graphical representation of a problem as developed by Altshuller [5, 6]. The Su-Field representation also allows a designer to analyze the problem's key elements and, following a procedure, assess what and how something must be changed in order to find a solution through the use of Standards.[94] Shown in Figure 5.6 is the initial development of the Su-Field for the Reactive Material Containment System.

Figure 5.6: Su-Field Models of the Reactive Material Containment System

In the above Su-Field models, the RMCS is developed under two different function assumptions, following from two different function structures as shown in Figure 5.6. In both Su-Fields, the system is represented by three components: two substances (the reactive material and the container) and the field (blast). The different types of arrows signify different things, where the straight arrow represents directed action, a curved arrow represents harmful action, and a double-lined arrow represents a transformation. The first Su-Field on the left is developed for the system at a higher level of abstraction, and the model on the right takes a level closer to the system as the model was developed. For the left model, there is a system of a reactive material surrounded by a container of some sort in direct interaction with the reactive material (hence the straight arrow). The system represents the harmful interaction that a blast has on the containment system, and the subsequent interaction this has on the reactive material. The model on the right represents the same harmful interaction the blast has on the reactive material, but in this model that interaction causes a transformation of the containment substance (a deformation) and then this transformed substance interacts with the reactive material in some lesser extent. Notice that unlike the spring example, there is no interaction directly between the blast and the reactive material, and therefore there is no line directly connecting the two.

With the IFR defined, the Su-Field developed to represent the problem, and all of the varying forms of conflicts and contradictions, the problem formulation phase is complete. Now the design task is ready for a solution search.

5.3.2 Solution Search

Implementation of process described in Section 3.3.2

The first step in the solution search is to attempt to solve the problem at the physical level, which originates from the physical contradiction and the Su-Field modeling, as these solutions tend to be most innovative. To do this, the Design Repository is used first to quickly identify known solutions, followed by a more exhaustive analysis of the Su-field.

5.3.2.1 Interface with Design Repository

Implementation of process described in Section 3.3.2.1

A design repository, as developed by Matthias Messer [72], is a tool intended to increase a designer's ability to explore design options with ease by providing a catalog of solution variants from underlying phenomena that cause a certain behavior. The premise is that a problem is first defined in terms of function, which dictates the behavior required, and therefore can be linked to a repository of solutions that exhibit this behavior. To find the correct repository, the first catalog relating energy transformations to phenomena is used, as shown (partially) in Figure 5.7

In this problem, the input energy of a blast is mechanical, and that is transformed into another form of mechanical energy to absorb the blast. Selecting the input of mechanical energy with the output of mechanical energy yields a list of phenomena as shown in Figure 5.8.

Input \ Output	Mechanical Energy	Electrostatic Energy	Magnetostatic Energy	Sound Energy	Light Energy	Thermal Energy	Molecular Energy
Mechanical Energy	Plasticity Inertia …	Electrostriction …	Magnetostriction …	Impact …	Friction …	Pressure change …	Dislocation hardening …
Electrostatic Energy	Electric field …	Interference …	Hall-effect …	Electrostriction …	Photostriction …	Electrical resistance …	Galvanic element …
Magnetostatic Energy	Magnetic field …	Oscillating circuit …	Ferromagnetism …	Magneto-striction …	Farraday-effect …	Eddy current …	
Sound Energy	Pressure wave …	Electrostriction …	Magnetostriction …	Reflection …		Noise damping …	Elasticity …
Light Energy	Electromagnetic radiation …	Photostric-tion …	Absorption …		Refraction …	Thermoluminescence …	Photoeffect …
Thermal Energy	Thermal expansion …	Thermoelectricity …	Curie-Weiss law …		Pyro-electricity …	Convection …	Phase transformation …
Molecular Energy	Exothermic reaction …	Molecular dipoloe …			Fluorescence …	Combustion Conductivity …	Adhesion …

Figure 5.7: Design Catalog Relating Energy Transformation to Phenomena

Input \ Output	Mechanical Energy (Potential-/kinetic-/strain-energy)	
Mechanical Energy (Potential-/kinetic-/strain-energy)	- Inertia (translational/rotational) - Elastic/inelastic deformation (tension/compression/bending/shear/torsion/buckling/fracture/cutting/inversion/extrusion/drawing/flow) - Impact (translational/rotational) - Friction (static/dynamic) - Refraction (waves/particles) - Lever-effect (translational/rotational) - Poisson's-effect (positive/negative) - Stress-induced Martensitic transformation - Force field (gravity/surface-tension/contact-force/atomic-force) - Wedge-effect - Boyle-Mariotte-law - Magnus-effect - Lotus-effect - Resonance - Co-/Adhesion - Capillary-effect - Weissenberg-effect - Load spreading (fixed/flexible constraints or unconstrained) - Blocking and bracing - Topology	6. - Mechanical oscillations - Centrifugal forces 7. - Wave movement - Capillary force - Centrifugal forces - Weissenberg effect 11. - Reactive Force 12. - Centrifugal forces - Effect of a magnetic field via ferromagnetic substance 14. - Cavitation - Resonance 15. - Elastic deformation - Gyroscope 16. - Deformations - Oscillations - Waves, including shock waves 19. - Deformations 21. - Friction - Mechanical oscillations 23. - Deformation 24. - Interference waves - Standing waves - Mechanical oscillations 27. - Tunnel effect

Figure 5.8: Phenomena Related to a change in Mechanical Energy to Mechanical Energy

In Figure 5.8, the column on the left is the list of phenomena developed by Messer [69] and the column on the right is a similar list using the TRIZ phenomena. The numbers correspond to the numbering system used within TRIZ for physical phenomena, where similar types of phenomena are grouped together. A designer can scan through this list to find a phenomenon that is most relevant to the design task. As there are many mechanisms to convert the generic description of "Mechanical Energy" into another form of mechanical energy, the list is correspondingly large. However, a basic familiarity of physical phenomena and a well developed understanding of the problem go a long way in helping a designer select a suitable phenomenon to explore.

To provide a designer with basic familiarity of physical phenomena, Mathias Messer has complied descriptions of each phenomenon on his web tool that allows a designer to click on a particular phenomenon to read more information about it. This is very helpful, yet could be time consuming when the area within the catalog that is being explored has not been used often by the designer. That is, a designer may become familiar with all of the phenomena within the Mechanical Energy to Mechanical Energy transformation, but not between Magnetostatic and Thermal energy, for example. This deficiency becomes even more pronounced when not only is a designer unfamiliar with the specific phenomena possible for a type of energy transformation, but when the transformation is between energy types that are hard to visualize, or it is not apparent that such a transformation can occur. This of course is not a problem between Mechanical Energy and Mechanical Energy, as we can visualize this transformation in at least a number of the phenomena, even if we are not yet familiar with the particular mechanism. Taking as an example a transformation between two forms of energy that would be hard to visualize, such as Inductive Energy to Thermal Energy, the phenomenon to choose might not be apparent.

So it is evident that here a designer needs more assistance; and it is here and for this reason that the additional column, as shown on the right of Figure 5.8, is added. The purpose in adding this column is twofold; the first is to simply cover any gaps in the first iteration of the catalog. The second purpose is to provide direction and back-linking with TRIZ tools. In terms of direction, a designer can consult the Required Effects Table (Figure 3.7), to look up phenomenon that relate to Required Effects, and see the energy transformations that the associated phenomena fall under. It can however be used in the reverse sense, starting from the phenomenon, and back-linking to the Required Effects Table to see the effects produced and the related phenomena. (Related through the effect produced rather than the energy transformation, realizing that there certainly are many overlaps, but not necessarily so.)

Returning to the Reactive Material Containment System design task, the phenomena that was chosen is (in)elastic deformation, for two reasons. First, intuition leads one to select this phenomenon, and this is also confirmed under the required effects from Figure 3.7 of "Accumulation of mechanical and thermal energy" and "Transfer of energy", where those required effects are associated with (in)elastic deformation. So this decision brings us to the "(in)elastic deformation" design catalog to explore in search of concepts. From here on, any discussion of the design catalog is referring to this specific catalog of (in)elastic deformation, and though that catalog has many layers and components (in fact subdivided by length scale), one should keep in mind that for each of these phenomena, there is a hypothetical catalog behind it. Therefore, general principles of how this catalog is applied can be applied to a catalog constructed for another phenomenon, if it were developed. As one can imagine, if fully developed, the entirety of the design catalog would be vast, and from a practical sense, this must obviously be the case since we see a vast collection of concepts in use. Focusing on just the relevant portion of the catalog as it is encountered at this point in the design process (i.e., without using the TRIZ tools that have been built into the design catalog and that are encountered later), we have the section from it in Figure 5.9 from a simple scan of the entries.

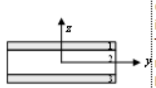
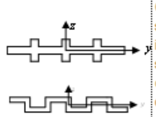
- Sandwich-structures		Structural member made up of two stiff, strong skins separated by a lightweight core are known as sandwich panels. The separation of the skins by the core increases the moment of inertia of the panel with little increase in weight. Therefore, sandwich panels may significantly increase structural stiffness for resisting bending. Also, introducing stabilizing core structures resistance against buckling loads is increased. The mechanical behavior of a sandwich thus depends on the properties of the face and core materials and on its geometry. In general, it is a costly process of assembling a sandwich shell by joining precurved face sheets and core.	- (Un)symmetrical three-, multi-, ...layer sandwich panels	1. Segmentation 7. Nested doll 17. Another dimension 40. Composite materials
- Stiffened-structures		On macroscales, structures can be enhanced/reinforced through the addition of stiffeners of various shape or curvatures (inelastic deformation) of the structure itself. Stiffened structures yield a higher moment of inertia and hence increased stiffness. Governing design variables are dimensions and topologies of constituents. For example, hat-stiffened plates are generally regarded to be one of the most efficient light weight constructions for compression panels loaded in direction, waffle-stiffened plates for compression panels loaded in two direction. In general, it is a costly process of joining (precurved) face sheets and stringers or machining.	- Stiffeners of various shapes - Curved structures of various shapes	1. Segmentation 5. Merging 40. Composite materials

Figure 5.9: Section from the (in)elastic deformation design catalog—without TRIZ selection assistance

Looking at this section, the designer can then begin to generate concepts, which are presented in Figure 5.10.

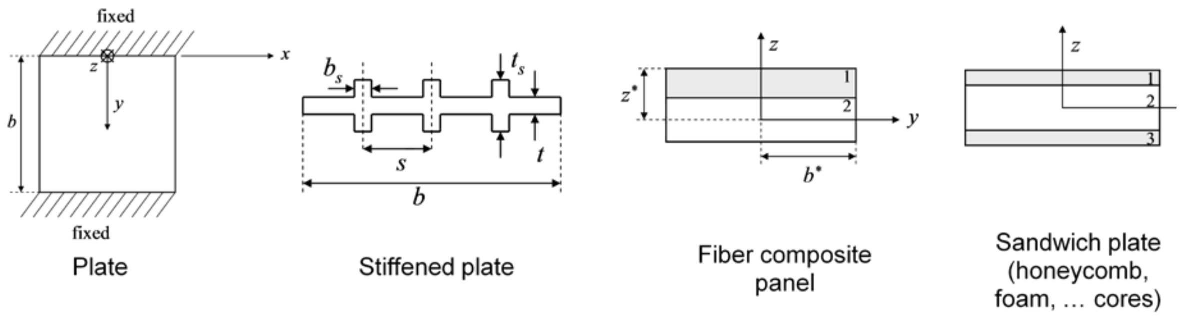


Figure 5.10: Generated concepts from scanning design catalog fitting the function “energy storage”

These concepts are the first concepts generated, and there is a progression of the concepts from fundamental to more sophisticated solutions; starting with just a plate of material, then stiffening it with its own geometry, and then adding other components. These ideas are generated straight from what is found in the Figure 5.9 section of the design catalog.

5.3.2.2 Apply the four Separation Principles

Implementation of process described in Section 3.3.2.2

As with each of the steps in the solution search phase, if the previous procedure does not yield a sufficient solution, or if a further search is desired, the designer progresses to the next step. If a quick scan of the design repository results in a good solution, then no more work is required and the concept generation phase can be concluded. Going forward however, as none of the identified solutions are suitable, an overall attention directing tool from TRIZ is used, in addition to discursive solution search procedures. The overall attention directing tool is the application of the four separation principles to overcome the physical conflict. (*The walls must be thicker/more massive to make the container stronger, yet the walls must not be thicker/more massive to reduce the weight/increase ease of use, or vice versa.*) These separation principles are shown below with sample questions for the Reactive Material Containment System that a designer might ask as the process is progressed through:

- Separate the opposite physical states in time.
    - Can the thickness of the RMCS vary with respect to the time that the energy of the impact would interact with it?
- Separate the opposite physical states in space.
    - Can one location of the RMCS be stiff and the other weak? Can a particular location be strengthened?
- Separate the opposite physical states between the system and its components.
    - Can a component be strengthened apart from the whole system?
- Have both opposite physical states coexist in the same substance.
    - Can there be a heterogeneous mix of strong and weak (or thick and thin) components?

5.3.2.3 Apply Su-Field analysis and Standard Solutions

Implementation of process described in Section 3.3.2.6.1-2

This step is performed after the first development of the Su-Field model and the separation principles, as they can happen sequentially or parallel. Usually, the separation principles listed above will help a designer as a parallel tool as he progresses through this process. This step allows for a solution to be found in the repository, that is, if one exists and is sufficient (as determined by the designer though the use of the requirements list). The 76 Standards that Altshuller developed are difficult to apply and somewhat inhomogeneous in the content of the standards. For example, some of the "standards" are nothing more than an explanation of how to apply certain other standards. To remedy this problem, Savransky [94] presents a systematic method to apply the standards developed by Altshuller [5, 6], shown in Table A.2. Applying that process to the RMCS problem results in the decisions underlined in Table 5.5; a simplified version of Table 3.4 where steps not encountered have been removed. This same process can also be seen graphically in Figure 5.11; a simplified version of Figure 3.8.

In Figure 5.11, the decisions in the flow chart that were selected are circled in red. The areas of the flow chart that consequentially not explored are grayed out, and steps past 5 were omitted because they are not used. Step 5 was included because if a solution is not found, this would be the next step, however, as will be shown, this step is not needed in the case of the RMCS. The outcome, in both Figure 5.11 and Table 5.6 is the use of "Standards", specifically of group 5.1, 5.2, and 5.5. All of these standards are listed in Table 3.5, and the sections of interest (Group 5.1, 5.2 and 5.5) are shown in Table 5.6. To further narrow down which standard solution to use, the designer can use intuition, the 4 separation principles, and the design catalog that TRIZ tools have been integrated into.

Table 5.5: Standard Solutions Algorithm

1.	Construct a model of the problem.
2.	Transform the model of the problem to the Su-Field form. **Note-0:** Complete model should have a product (S1), a tool (S2), and an interaction of a product and tool (F).
3.	Check if it is a measurement problem. If *yes*, go to step 4.1. If *no*, go to step 3.1. **3.1.** Check if a replacement of the initial problem in measurement or detection tasks is accessible. If *yes*, apply the Standards of group 4.1. If *no*, go to step 4. **Note-1:** If the direct transition is too complicated, first transfer the problem to a detection task, and then translate it to a measurement task.
4.	Check the completeness of the Su-Field. If the Su-Field is incomplete (or *no*), complete step 4.1, then go to step 5. If the Su-Field is complete, go directly to step 5. **4.1.** Check presence of harmful links. If present, go to step 4.1.1. If such a link is absent, go to step 4.2. **4.1.1.** Check if the introduction of substances and fields is allowable. If *yes*, apply Standards 1.1.1–1.1.6 or Standards of group 4.2. If *no*, apply the Standards of group 5.1, 5.2, 5.5. **4.2.** Check if introduction of substances and fields is allowable. If *yes*, apply Standards 1.1.7, 1.1.8, 1.2.3. If *no*, apply the Standards of groups 5.1, 5.2, 5.5.
Truncated – See Appendix Table A.1 for full Standard Solutions Algorithm	

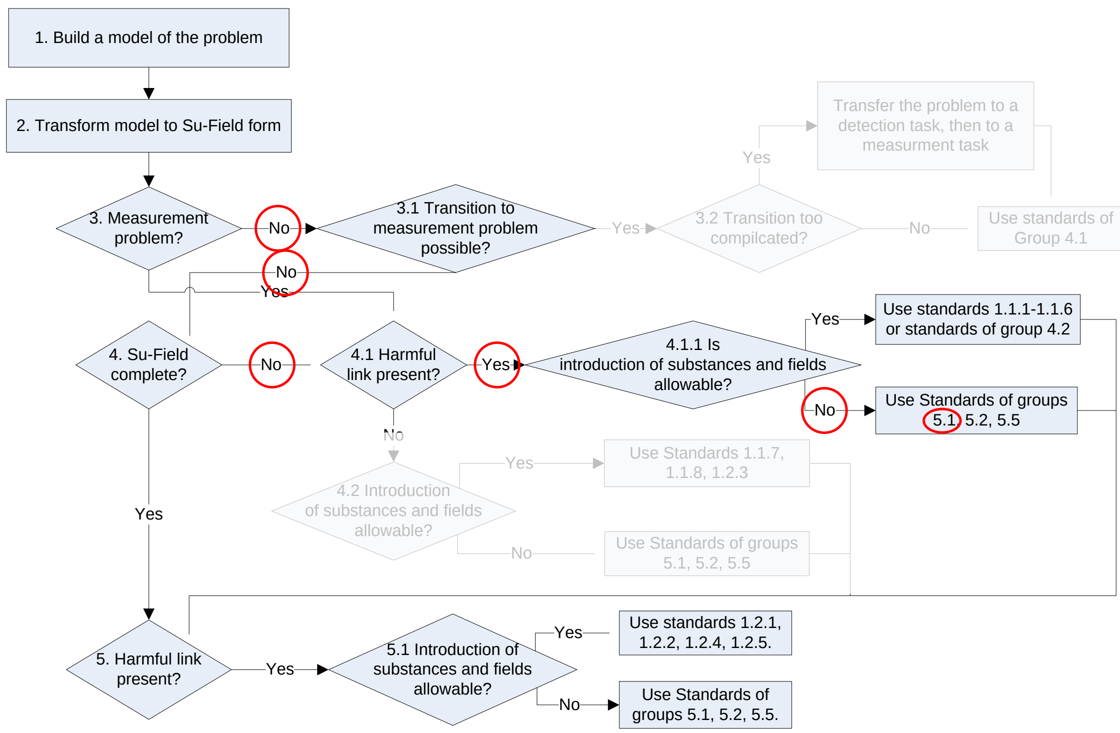


Figure 5.11: Section from Standard Solutions Flow Chart–See Appendix Figure A.1-Figure A.2

Table 5.6: TRIZ Standard Solutions

Altshuller's Standard Solutions of Invention Problems–Section 5 Selection
Class 5. Standards for Using Standards
5.1. Adding substances at construction, reconstruction, and destruction of Su-Fields.
5.1.1. Round-about ways:
5.1.1.1. "Emptiness" instead of substance
5.1.1.2. Field instead of substance
5.1.1.3. External addition instead of internal one
5.1.1.4. Particularly active addition in very small doses
5.1.1.5. Substance in very small doses
5.1.1.6. Addition is used for awhile
5.1.1.7. A copy instead of a subsystem
5.1.1.8. Chemical compound
5.1.1.9. Addition is obtained from the subsystem itself
5.1.2. Substance(s) separation
5.1.3. Substance(s) dissipation
5.1.4. Big additives
5.2. Adding fields at construction, reconstruction, and destruction of Su-Fields
5.2.1. Using existing fields
5.2.2. Fields from environment
5.2.3. Substances as fields sources
5.5. Creation of particles
5.5.1. Substance destroying
5.5.2. Integration of particles

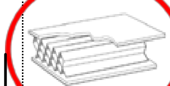
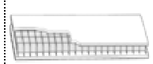
For the RMCS, the design catalog connected to the Standard Solutions was used. Depending on the approach that is most suited to the problem (i.e., if the development of the Su-Field through the algorithm isn't as apparent as defining the energy transfer functions, such as is the case with the RMCS), the use of the links within the catalog of solution principles is helpful. The relevant section of the catalog is shown in Table 5.7. In Table 5.7, the column to direct the designer to standard solutions has been added to the right side of the design catalog by Messer [69]. (Similar to Figure 3.10). The entire catalog can be seen in Appendix Table A.11-Table A.16.

In Table 5.7, the Standard Solution related to the RMCS is **7.1 -5.1.1.1.** This number has two components. The second number (more relevant to the topic at hand than the first), **5.1.1.1,** is the TRIZ Standard Solution number, as it correlates in Table 5.5. Looking 5.1.1.1 up in that table will reveal that this Standard Solution is ""Emptiness" instead of substance". The first number, **7.1**, relates to the categorizations of Su-Fields for use with Standard Solutions per Table 3.6. The format of this table is such that most Standards can be presented in simple IF→THEN form:

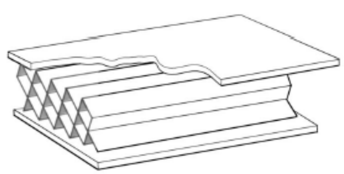
IF a problem of a *goal* is given as Su-Field *conditions* and *constraints* according to the problem circumstances, **THEN** such problems are solved by *action*.[94]

Table 5.8 is a selection form the larger Standard Solutions table, found Appendix Table A.3. With this format, a designer can go from the repository to some solution principles through the use of functions and TRIZ solution Principle suggestions.

Table 5.7: Repository section with Standard Solution Relation Column

Characteristics						Standard Solution of TP Relation (w/ related Altshuller's Numbers)
Solution Principle		Properties	Applications	Associated TRIZ 40 Principle(s): Strong	Associated TRIZ 40 Principle(s): Weak	
Honeycomb-core sandwiches	Honeycomb-core sandwiches take their name from their visual resemblance to a bee's honeycomb. With controllable core dimensions and topologies on mesoscales, they feature relatively high stiffness and yield strength at low density. Large compressive strains are achievable at nominally constant stress (before the material compacts), yielding a potentially high energy absorption capacity. Honeycomb-core sandwiches have acceptable structural performance at relatively low costs with useful combinations of thermophysical and mechanical properties. Usually, they provide benefits with respect to multiple use.					4.3 - 2.2.6 7.1 - 5.1.1.1 7.4 - 5.1.2
- In-plane honeycombs		Core cell axes of in-plane honeycomb cores are oriented parallel to the face-sheets. They provide potentials for decreased conductivity and fluid flow within cells. Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D \approx 1-1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approximated as: $\frac{E}{E_s} \approx 1\rho_{rel}^3$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.5\rho_{rel}$	- Prismatic-, square-, chiracal-, etc. core in-plane honeycombs	3. Local quality 40. Composite materials	31. Porous materials	4.3 - 2.2.6 7.1 - 5.1.1.1 7.4 - 5.1.2
- Out-of-plane honeycombs		Core cell axes of out-of-plane honeycomb cores are oriented perpendicular to face-sheets. They provide potentials for decreased conductivity. Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D \approx 1-1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approximated as: $\frac{E}{E_s} \approx 1\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 1\rho_{rel}$	- Hexagonal-, square-, etc. core put-of-plane honeycombs	3. Local quality 40. Composite materials	31. Porous materials	4.3 - 2.2.6 7.1 - 5.1.1.1 7.4 - 5.1.2

4.3 - 2.2.6
7.1 - 5.1.1.1
7.4 - 5.1.2



5.1.1.1: **"Emptiness" instead of substance.**

Table 5.8: Standard Solutions: IF-THEN Structure [94] - Selection

	Aim/Conditions	Constraints	Action	Altshuller's Numbers and Notes
Aim: Substances Management in Su-Fields				
7.1	Complete Su-Field	Restriction to add new substances	1. "Emptiness" and/or a field is used in spite of substance. 2. External addition is used in spite of internal one. 3. Substance is added in the form of chemical compound giving off the needed substance. 4. Particularly active addition in very small doses is used. 5. Usual substance in very small doses is added but only at certain points of a subsystem. 6. Addition is used for a while. 7. Technique model, to which substances can be added, is used in spite of the technique. 8. Addition is obtained from the technique itself, its subsystems, or environment by decomposing it using, for example, changing the aggregate state of matter.	5.1.1

He or she can then arrive at Standard Solutions, as well as a matching problem formulation according to the table with a directed course of action. In the case of the RMCS, having this link opens up the possibilities shown under the Action column of Table 5.8. Some of these solution possibilities are shown in Figure 5.12, developing from more primitive on the top left, to more advanced on the bottom right.

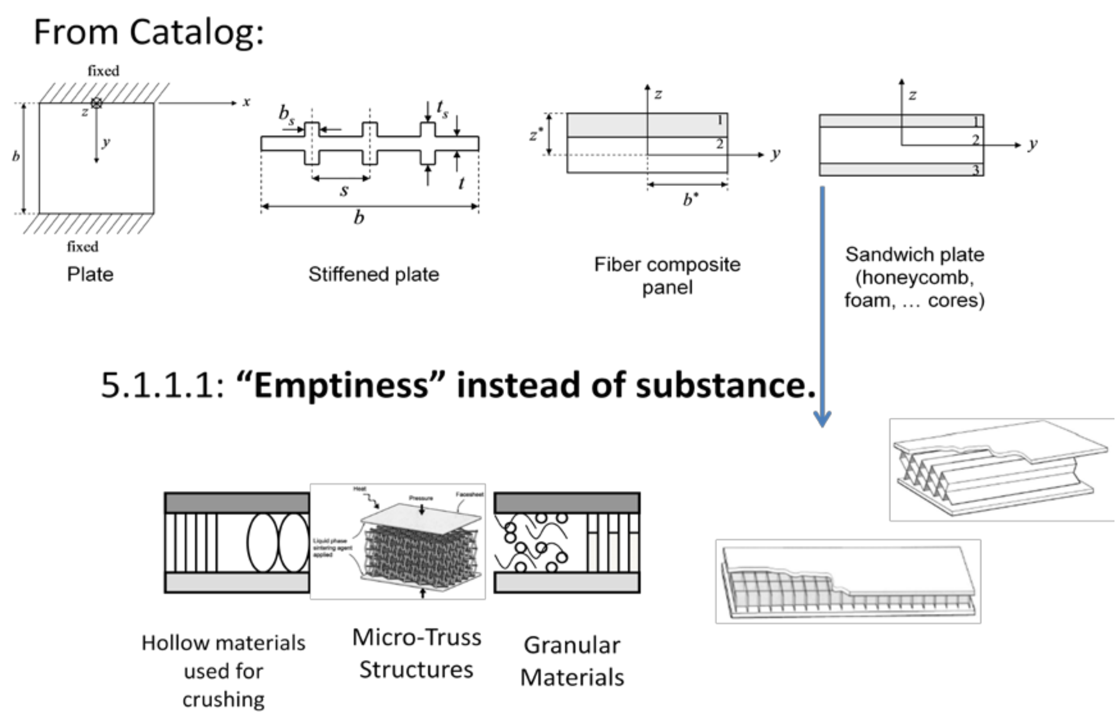


Figure 5.12: Solution possibilities derived from

5.3.2.4 Apply Physical Effects

Implementation of process described in Section 3.3.2.4

The TRIZ catalog of Physical Effects contains 30 different required effects and the corresponding phenomenon that can cause the required effect. In addition to these effects and phenomenon, a correlation to the energy transfer function involved in the phenomenon to cause the required effect is listed for each phenomenon. The purpose of this is twofold, 1) to help narrow down the phenomenon by limiting them to those that fit to the established function structure, and 2) to further link the effects to the design repository that is based on the energy transfer functions as developed by Matthias Messer [69]. This table of Required Effects, Phenomenon, and Functional Energy Transformation is listed in Table 3.7. In the case of the RMCS, as is not surprising, scanning the table for the required effect of accumulation or transfer of energy results in (in)elastic deformation as phenomena. This is shown in Table 5.9.

Scanning through the Table 3.7 for the most applicable option, 2 required effects emerge as possible sources of concepts. “Accumulation of mechanical and thermal energy” and “Transfer Energy”. (The required effect of “Transfer energy” may seem redundant or pre-supposed given the use of a energy transformation based design catalog, but it is not. First, this table is designed with broader applicability in mind and also, there is a difference in a function being centered on a core energy transformation, and the need for a pure energy transformation.) Under the Mechanical to Mechanical function groupings (note that this additional column is not found in lists offered by TRIZ, but is an addition to allow a designer find phenomena more quickly given that this functional relationship has already been established in previous steps) several phenomena are found. These phenomena that are relevant to the RMCS include: elastic deformation, deformations (in this context, inelastic is being referred to), oscillations, waves (including shock waves). This result was both expected and unexpected; the emergence of elastic and inelastic deformation as a phenomena had become obvious by this point, however oscillations and waves was not as obvious.

Table 5.9: Physical Effects and Phenomenon - Section

Required effect		Function(s) (Energy Input > Energy Output)	Phenomenon
15	Accumulation of mechanical and thermal energy	Mechanical > Chemical	Phase Transition
		Mechanical > Mechanical	Elastic deformation Gyroscope
		Pneumatical/Hydraulic > Chemical	Phase Transition
16	Transfer of energy	Chemical > Light	Induced radiation
		Electrostatic > Electrostatic	Superconductivity
		Electrostatic > Mechanical	Electromagnetic induction
		Light > Light	Fiber optics Lasers Light reflection Radiation
		Magnetostatic > Electrostatic	Electromagnetic induction
		Magnetostatic > Magnetosatic	Electromagnetic induction
		Magnetostatic > Mechanical	Electromagnetic induction
		Mechanical > Electrostatic	Electromagnetic induction
		Mechanical > Mechanical	Alexandrov Effect Deformations Oscillations Waves, including shock waves
		Thermal > Electrostatic	Superconductivity
		Thermal > Thermal	Convection Thermal conductivity

Of course a wave is the mechanism by which the blast energy is propagated through the material, but in terms of design, this is a good reminder to consider how the structure of the RMCS might be situated to direct deformation waves in certain directions, or dampen them. Some investigation in this area resulted in finding on-going research by Fraternali et al. [42] on the topic of designing "composite granular protectors". Essentially this type of structure utilizes granular particles of a designed size, location, and pre-stress to divert shock waves from being transmitted straight through the medium. In terms of the RMCS, this is a very interesting future prospect (subjectively it is intellectually interesting; objectively it fulfills some of the separation principles), but due to it still being in the research stage, would not be a viable option immediately for a concept. This concept still makes use of the "emptiness" standard solution, and this is the fundamental principle on which concepts for the RMCS to solve the *physical conflict* are built upon.

5.3.2.5 Apply the 40 Principles

Implementation of process described in Section 3.3.2.5

The technical contradictions (both forward and reverse) described in Section 5.3.1.3 are correlated to solution principles using the TRIZ contradiction matrix (Table A.6). The matrix correlates the conflict of 2 of 39 design characteristics with a few (no more than 4) general solution principles that have worked in past solutions. There are 40 of these solution principles (see Appendix Table A.7-Table A.9). As previously defined, the technical contradiction of the Reactive Material Containment System is: **Improving the *Strength/ Durability* of the RMCS worsens the *Weight.*** The application of this contradiction through the TRIZ matrix results in the 5 solution principles shown in Table 5.10, plus 2 more that are eliminated before generating concepts. The two that were discarded were #16 "partial or excessive actions" and #19 "periodic action" as there is no action or movement involved in the solution; a non-passive device would not meet requirements.

The solution principles summarized in Table 5.10 are coupled with the questions or line of thought that follows from a designer being introduced to these, effectively "concept generation seeds" or "solution triggers". For "Composite Materials", the concepts previously generated fell under this category, and somewhat of an overlap such as this should be expected. Moving to new conceptual territory and beginning with the more distant solution principle of “Copying”, the designer might think along the lines of some sort of wrapping for the RMCS that is replaced when worn out.

Table 5.10: Solution Principles from TRIZ Matrix-Strength/Durability vs. Weight

Technical Conflict: Improving the Strength(14)[4]/ Durability(16) of the RMCS worsens the Weight(2)
40[5]. Composite Materials
Previous solutions fall under this principle.
26. Copying
"Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies." Some sort of wrapping for storage and transport that is replaced if/when it becomes worn out.
27. Cheap Short-living object
Container made of foam core instead of honey-comb?
1. Segmentation
Sandwich plate structure?
6. Universality
Make the container out of the actual reactive material—use a stronger binder on the outside?
Combine above concept with a foam exterior?

This concept doesn’t fit the problem very well however because the system is not expected to withstand multiple blasts, but rather only one and then be decommissioned, so replacement of the protection isn’t of much concern. Moving to the solution principle, “Cheap short living objects”, and coupling this principle with the understanding that the RMCS really only needs to withstand one blast, a designer could make use of foam at a part of the blast resistant panel. “Segmentation” refers to a more discrete, macro version of composite materials, and again most of the previous concepts fall into this category; many by using the idea of a sandwich-type structure.

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[4] This numbering corresponds to the assigned numbering for the 39 design parameters used for generic technical contradictions in the TRIZ contradiction matrix that relates conflicts to inventive principles.
[5] This numbering corresponds to the assigned numbering for the 40 inventive principles in TRIZ used in the contradiction matrix mentioned in the previous footnote.

Perhaps the most interesting and divergent idea developed using this tool is triggered from the solution principle, “Universality”. This solution principle generally means that a concept should make use of a material that will fulfill all or most of the requirements in itself, promoting homogeneity and part reduction. Applying this principle to the RMCS initiates ideas concerning the use of the reactive material itself to act as its own container (not barring modifications of course). Given that the reactive material of interest is thermite, it is conceivable that a modified binder used on the outer surface of the material to allow it to be more resilient to shock could serve as a container. This might even be more effective overall if the binder improved the ignition resistance of the material from heat and shock. If it is expected that the reactive material only be exposed to either relatively small disturbances (rough handling) or very large blasts (close proximity explosion) that would destroy any of the systems, this option is viable. (Not a likely scenario as the RMCS should protect against impacts due to transportation accidents.) Fortunately however, designers are not limited to working within on one principle, and this concept can be combined with any of the other principles, perhaps segmentation to create a RMCS that has a plate and foam sandwich construction surrounding reactive material with an improved outer binder.

The remaining steps in the concept generation process are iterations, listed below and are implementations of Sections 3.3.2.6 - Section 3.3.2.6.6:

5.3.2.6 Iterations

5.3.2.6.1 Apply Su-Field Analysis.

5.3.2.6.2 Apply Standard Solutions.

5.3.2.6.3 Change the mini-problem

5.3.2.6.4 Revisit your conflict (Analyze the Conflict)

5.3.2.6.5 Chose the "other" version of the conflict.

5.3.2.6.6 Reformulate another conflict after the mini-problem

5.3.3 Select Suitable Combinations of Concept Variants or Solutions (Preliminary selection)

Implementation of process described in Section 3.3.3

Upon completion of the solution search for this problem, a table was populated containing all of the viable solution possibilities generated from the solution search and discussed thus far, shown in Table 5.11. This table also contains judgments on whether or not the concepts meet requirements and the viewpoints behind those decisions.

5.3.4 Analysis of Design

Implementation of process described in Section 3.3.5

5.3.4.1 Qualitative analysis of design

To compare the results of this activity, some the most promising solutions are investigated in more depth. The quantitative portion of this work then is context specific, and not integral to the presented concept generation method. What is more general and qualitative is relevant to this method, and this comes in the form of some questions. What must be kept in mind is that the motivation for all of this method development is concept generation, so even through the analysis of the design, there is a focus on concept generation, even if it is for a future need.

- Does your solution meet the requirement of the IFR?
- Which Physical Contradiction has been eliminated by the solution?
- Is the solution suitable for real manufacturing or one-time production?
- If you can't use the solution for satisfying the entire problem, can you use the solution for part of the system or cycles of the system?
- Are there any other problems as a result of your solution?

Table 5.11: Potential Solution Variants observed against requirements

Concepts	Preliminary Requirements?	Viewpoints
1) Bending of Plate	**Y**	Kinetic energy of an incoming blast impinging on a plate can be dissipated by bending and stretching.
2) Stiffened Plate	**Y**	Same advantages as bending plate, but made stiffer by increased bending moment of inertia
3) Fiber Composite Panel	**Y**	Crushing of textile-based weaves exhibits high energy dissipation characteristics at relatively low weight.
4) Sandwich Plate	**Y**	Energy absorption advantage of bending plate plus sandwich core.
5) Hollow Materials (crushing)	**N**	Inversion of circular structures provides energy absorption, but difficulties in securing axial loading.
6) Micro Truss Structures	**N**	Absorb a high amount of energy, but can be difficult to manufacture, and not necessarily better.
7) Granular Filler	**N**	Transmits too much energy because the material cannot disperse easily. Use of size, placement, and pre-stressed granular filler not fully developed yet.
8) Honey comb structure	**Y**	Both in and out of plane honeycomb absorb a high amount of energy by deforming plastically.
9) Foam and single panel	**Y**	Foams have good energy dissipation characteristic during bending collapse. Properties can be adjusted over a wide range. Cost effective.
10) Stiffened binder	**N**	Largest reduction in weight, but very little energy absorption; only a stiffened exterior
11) Stiffened binder plus foam	**Y**	High weight reduction, plus the benefits of a foam energy absorption barrier. May not last up to wear, but could also utilize a metal skin.

5.4 VERIFICATION AND VALIDATION

In this Chapter, two aspects of the validation square introduced in 1.2.3are addressed – Empirical Structural Validation and Empirical Performance Validation – illustrated in Figure 1.11 and discussed in the following.

5.4.1 Empirical Structural Validation

Empirical Structural Validation involves accepting the appropriateness of the example problems used to verify the performance of the method. It is believed that the reactive material containment system example is a reasonably complex domain design problem. Also, the design problem discussed in this chapter allows significant increase in system performance by exercising systematic conceptual design not only on various system levels down to the component level, but, also on the multi-domain level. Moreover, the problem is suitable because many aspects of integrated product and materials design can be demonstrated through the exploration of this example. The main goal in this method is to be able to generate applicable concepts across the material and product domain, and as was shown in this chapter, the problem was more than sufficiently appropriate in a being an apt problem to generate concepts for.

5.4.2 Empirical Performance Validation

Empirical Performance Validation consists of accepting the usefulness of the outcome with respect to the initial purpose and accepting that the achieved usefulness is related to applying the method. The empirical performance validation in this chapter is carried out in the validation of systematic, integrated generation of multi-domain (material and product) concepts. The creation of function structures, Su-Field models as well as subsequent analysis, abstraction, synthesis, and systematic application of solution triggering tools and design catalogs for phenomena and associated solution principles has shown a significant increase in a designer's concept flexibility by exercising systematic conceptual design not only on various system levels down to the component level, but, also on the materials level. Solution principles were identified on the multiscale materials level through function-based and analogy-based analysis, abstraction and synthesis, systematically combining those into concepts and further exploring the most promising concepts. The lack of concrete information at these early stages of design is acknowledged. For this reason, not one, but multiple promising concepts are presented to provide the designer with sufficient design flexibility after the concept generation stage.

The results obtained (i.e., the concepts generated) by applying the method to the reactive material containment system have been evaluated with respect to Ideal Final Result indicators. An evaluation of the concepts in this light allows for a designer to assess the general worthiness toward further exploration and future design flexibility. This evaluation promotes Empirical Performance Validation by showing that the usefulness of the results is linked to applying the method. Having demonstrated utility of the systematic approach through the example, the observed usefulness is linked to the constructs developed in this thesis by the observation that the results shown are a direct result of the actions taken within the method, logically connected, as shown in Theoretical Structural Validation. Therefore it is asserted that Empirical Performance Validity is achieved.

5.5 WHAT HAS BEEN PRESENTED AND WHAT IS NEXT

In this chapter, an integrated product materials design problem example – the reactive material containment system – is presented for validation of the design method and solution triggers developed in Chapters 2, 3, and 4. Concepts generated from the multi-domain process presented in this chapter indicate the usefulness of the proposed systematic approach.

CHAPTER 6

CLOSURE

6.1 SUMMARY OF THE WORK

Presented in this work is an approach for design that augments the systematic process of Pahl and Beitz with TRIZ, structured through ARIZ. This approach is intended to equip designers with an approach that covers the design process starting from the task, through to the detail design phase, while having a detailed emphasis on conceptual design. This focus was chosen because it is in the conceptual design phase where problems are framed and a direction is set for the entire process. It is also in this phase that there is the possibility to work across domains by using the TRIZ tools that abstract the problems to the essential problem, and suggest general solution principles that can be applied in a new domain. Previous combinations of TRIZ and Pahl and Beitz have been explored [64], however only to make use of the problem solving techniques. To be sure, this is gained, however much more can be gained with the possibility of transferring solution principles (concepts that trigger a solution in the mind of a designer) to a domain that better serves the solution of the design. The potential utility in this work is that designers, especially those familiar with a combined method, can consider how the solution principles encountered have the applicability in sub-domain design by analogy.

In this thesis, the sub-domain was the materials domain, and this was seen on multiple length scales in the final design variants of the examples. While the solutions may not be altogether unique, or even found only through this process, the structure of this process is presented to promote the possibilities of transfer between domains. This transfer from product to material is simply a type of transfer, and can represent other possible transfers that the use of an abstracted, analogical design process allows. It is very possible that this notion is also applicable between even mechanical and electrical or biological domains. This is due to the fact that the problems and solutions are abstracted and generalized, yet the designer does not need to specify in what domains the transfer will take place.

The importance of being able to design across domains concurrently is seen in the broadening of the design space. In the conceptual design phase it is beneficial to broaden the design space so that it is more likely to find a suitable final design. Also, TRIZ gains functionality towards broadening the design space by being united with Pahl and Beitz due to the function structure, requirements list and general setting in a comprehensive design process. The link to the design repository further broadens the design space, as this allows a designer to cover previous designs so that a design isn't redesigned if it doesn't need to be.

With a broad design space comes the necessity to trim the results down to select a final solution. While preliminary selection can be approached a variety of ways, what is particularly helpful in the approach presented are the steps offered by TRIZ to analyze the solution. The Pahl and Beitz approach goes as far as to provide the designer with a requirements list to evaluate the solution, and TRIZ extends that by assisting the designer define what is the ideal solution and not just the required solution. This increases the likelihood of designing good solution in a shorter amount of time, and helps the designer aim for an innovative solution through the process.

6.2 EXPLORATORY QUESTIONS

In this thesis there are three gaps addressed that correspond each to a question and a hypothesis. These gaps are presented in **Error! Reference source not found.**

Table 1.1: Research gaps in conceptual design approaches.

Research Gaps	
Gap 1	Systematic approaches to make use of the potential in materials design for concept generation.
Gap 2	Methods and tools to increase a designer's concept flexibility in the context of integrating multi-domain design, specifically product and materials design.
Gap 3	Methods and tools to extend existing systematic conceptual product and systems design approaches to the materials level.

The following is an evaluation of the research questions in the context of the validation square. The first three quadrants in the Validation Square is a framework that allows for the provision of necessary evidence to build confidence in the extension of the proposed method on other similar example problems. Based on the internal consistency of the proposed method, the degree to which the selected example problems adequately address the hypotheses tested, and the effective implementation of the proposed method in solving the example problems to show the validity in the claims of the hypotheses tested, one should then be able to judge if it is reasonable that applying the proposed method to similar example problems will produce practical and desirable results.

6.2.1 Research Question 1

Corresponding to the first gap, the first research question is, "**How can a designer generate concepts in materials design that supplement concepts in product design to fulfill the design goals of innovative products?**" This relates to:

i) the integration of product and material concept generation, and

ii) the rendering of a systematic and domain-independent method to support a wide range of products. The hypothesis to address these two points of the first question has two components:

Hypothesis 1a) The first component is supplementing materials selection with materials design to integrate product and material concept generation. This provides capabilities for synthesizing customized materials with specific performance characteristics by involving phenomena and associated solution principles on the multi-scale materials level (i.e., the multiple ovals found in Figure 1.7) to drive concept generation[70].

Hypothesis 1b) The second component is experiential knowledge based problem solving and solution triggering tools to create a systematic and domain-independent method (TRIZ). This allows a designer to better define problems and find solution principles (or things that trigger a solution in a designer's mind) that have worked in the past regardless of domain.

Theoretical Structural Validation

Theoretical structural validation refers to accepting the validity of individual constructs used in the systematic approach and accepting the internal consistency of the way the constructs are assembled. Theoretical structural validation is performed in this chapter using a procedure consisting of 1) defining the method's range of applicability, *b)* reviewing the relevant literature to identify the strengths and limitations of the constructs contained therein, and *c)* identifying the gaps in the existing literature resulting from those weaknesses, and *d)* determining which constructs are to be used in the approach over the defined range of application. The internal consistency of the individual constructs is checked by a critical review of the literature.

The part of the hypothesis that is relevant to TSV is that of supplementing materials selection with materials design to integrate product and material concept generation. In order to do that and satisfy TSV, materials design itself has to be valid as well as product design. Obviously product design, in a systematic sense, is a valid construct to build on. Typically within product design there is material selection, and this has been shown to work, but it can clearly be improved—the gap for this thesis.

Materials design takes the advantages of product design (as opposed to product selection) and builds that into materials. This is a valid construct so long as sufficient information is used, and for this method there is a wide body of information to work with. So the availability of information to design materials defines the range over which this method is applicable. This expert knowledge base is also itself a fundamental construct and it is in two forms: 1) generalized knowledge in the form of TRIZ which on its own has been used extensively with good effect, and 2) the multi-scale design catalog of solution principles and phenomena, which has also been established.

Empirical Structural Validation

Empirical Structural Validation is closely linked to an example problem. After Theoretical Structural Validation, an example problem is solved through the method. However, to show the appropriateness of the example problem, and satisfy Empirical Structural Validation, the applicability of the example to the method must be substantiated by showing that the method is indeed relevant to that problem. The example must also be representative of actual problem and the examples can support the hypotheses. In relation to the first hypothesis, supplementing materials selection with materials design to integrate product and material concept generation, it is shown in the context of ESV by choosing a problem that has previously been solved with materials selection (blast resistant panel) and then applying materials design to it. Also the problem is of a type that can actually have a designed material.

In the example, a blast resistant panel is designed with more design parameters and considerations than the simple spring example. An example with a complex nature is needed to show that the problem can be used to exercise the details of the method that only become applicable when complexity of the problem is introduced and to show the depth of possible solutions. These details come about from the second half of the first hypothesis--experiential knowledge based problem solving and solution triggering tools to create a systematic and domain-independent method. In order to test the knowledge base, and if the solution triggering tools can work on a difficult design task, a more complex problem is needed. The Reactive Material Containment System is in fact complex enough to fit with this method.

Empirical Performance Validation

Empirical Performance Validity is established by using the representative example problem to evaluate the outcome of the proposed design methodology in terms of its usefulness. Results obtained by applying the method to the reactive material containment system are evaluated with respect to concept flexibility indicators. To accept that usefulness is linked to applying the method, usefulness will is evaluated by looking at a collective group of indicators. In terms of the first hypothesis, EPV is achieved by demonstrating material concept generation along side of product concept generation, and by demonstrating that the use of the problem solving tools is independent from the domain by applying them to the multiple domains within the blast panel example. As a point for comparison, the prior design of plate steel is used, and the concepts generated for the same problem using the method stripped on TRIZ augmentations in used. It was shown that there were more varied and innovative (in terms of solution principles involved) using the method.

6.2.2 Research Question 2

The second research question is, "**How should solution principles and problem formulations used in the past mostly for the mechanics domain be integrated into the function based design method to be applicable to multi-scale materials design?**" This relates to problem solving and solution triggering tools (TRIZ) integration.

Hypothesis 2) The hypothesis is that problem formulations and solution triggers developed for use in the TRIZ methodology can also be integrated into function based design for multi-scale materials by allowing TRIZ problem modeling (Su-Field models with systems conflicts) to be developed alongside function structures, and used to inform later design process steps.

Theoretical Structural Validation

As mentioned, and illustrated earlier in Figure 1.7 with the curved arrow, the mechanism for transfer between the product and materials domain is an analogy tool, making use of the system conflict the chief common interface, and the various TRIZ tools to complete the analogy. To apply TRIZ in a systematic process, and therefore fulfill the requirements of TSV, the Algorithm of Inventive Problem Solving (ARIZ) is used [6] [94]. ARIZ has been developed over a number of years, and is a detailed, sequential process that systematizes the individual TRIZ heuristics. Using this structured process ensures that the information flow is correct and it has been tested extensively over the years so there is confidence that the construct is good.

Empirical Structural Validation

In relation to the second hypothesis, problem formulations and solution triggers developed for use in the TRIZ methodology are also be integrated into function based design for multi-scale materials by allowing TRIZ problem modeling (Su-Field models with systems conflicts) to be developed alongside function structures. To be able to test this hypothesis with the example, the example needs to be appropriate for it. This means that the example problem must be able to be modeled with both Su-Field models and contradictions. Some problems only lend themselves to one type of problem, but the RMCS is complex enough to allow both types. Also the example problem must be able to contain multiple length scales (a nano scale problem would not be applicable) and be modeled in the form of an energy transformation function structure.

Empirical Performance Validation

To show that the use of problem formulations borrowed from TRIZ is applicable in the function based design method in the multi-scale mode, it needs to be shown that formulating the problem in the new fashion, first does not harm the use of the existing function based constructs, and then also augments them to improve the design process. One of the key notions in the Pahl and Beitz Systematic Design process is the concept of abstraction. Early in the design process it is necessary to identify the crux of the problem so that it can be abstracted to find what is essential to the problem. This construct is the same fundamental principle in the TRIZ problem formulations and so at the root level they are compatible. TRIZ departs from P&B by not leaving the steps to locate the crux, and the exactly how to abstract ambiguous. To show that this is desirable and therefore satisfy EPV, it was shown that the key elements in the P&B process do not need to be replaced, (such as function structures) and in fact it was shown that the use of the TRIZ problem formulations not only help the design task further along in the TRIZ steps, but also helped in the completion of P&B steps. For example, identifying the Ideal Final Result greatly helps in being able to continually check the concepts being generated against the requirements list, as the IFR serves as a succinct goal of the requirements list.

6.2.3 Research Question 3

The third research question is, "**How should function structures and problem formulations be connected to solution triggers at the appropriate length scales for materials design?**"

Hypothesis 3) This hypothesis involves mapping pre-existing abstracted problem formulations and solution trigger mappings (TRIZ Matrix) to functions and length scales, creating an additional dimension for the pre-existing mappings. The TRIZ matrix relates two design characteristics that are in conflict to possible solution triggers to create innovative solutions, and with an additional dimension, the tool is better suited to materials design due to increased flexibility. Also, analogical techniques found in TRIZ can be used for the structure of augmentations to a design catalog, using the conflict as the common interface.

Theoretical Structural Validation

Theoretical Structural Validation for the third hypothesis rests on the existing commonality (the conflict) between the two sets of tools, and using that as the bridge to connect them. Previously established is that the individual problem formulations, solution triggers and function structures are all valid constructs on which to build a design method. To establish TSV for this hypothesis however, the key thing is that the information transferred between the constructs have a sensible link. In Chapter 4 this link was explained and shown to allow for the 2 sets of tools to seem together in a logical and consistent way, creating a unified tool that is more valuable than the sum of the parts. The commonality between them is the phenomena that often overlap, and where they do not, other clues from the associated elements can be used to deduce how it should be linked.

Empirical Structural Validation

The hypothesis is that this existing process is improved by modifying the first portion of the design repository to include the analogical tool of an analogy and the second portion of the tool is applied to TRIZ tools, i.e. the TRIZ Technical Contradiction matrix (Table A.6). A problem is first defined in terms of function, which dictates the behavior required, and therefore can be linked to a repository of solutions that exhibit this behavior. In order for the problem to accommodate testing this hypothesis, it needs to be able to be defined in terms of a function, which the RMCS does. The example should also be a candidate for the full use of the catalog to show how each way that the designer can interface with it is valid. In order for this to be the case the example must be able to be defined in terms of both a technical and physical contradiction, which the RMCS does.

Empirical Performance Validation

To show that these constructs do indeed produce the desired result, the concepts generated should come from the design repositories for the blast panel, not discounting other sources of solution triggers however. Also not only should some solutions come from the repository, but they should have a level of quality that would promote them to the level of serious consideration. In fact this was found to be the case as shown in Chapter 5, and that many of these solutions could be found by the different routes into the repository that the unified tools allowed for.

6.3 CONTRIBUTION

The proposed integrated conceptual design of products and materials by facilitating the transfer of problem formulations and solution principles in these multi-domain systems is the contribution to the development of a systematic design approach. This multi-domain approach is based on the understanding of the phenomena and associated solution principles at multiple levels and scales. This understanding built into a systematic approach includes the following key contributions:

1) A new relation between problem formulation and corresponding solution triggers and materials structure property relations and their classification in length scale specific design repositories, to facilitate conceptual design of materials in a systematic function based way. TRIZ focuses on the design conflict and builds analogies from that, and the intent here is to position TRIZ in the broader (i.e., Pahl and Beitz) function based design process.

2) Structure for a repository that contains expert design knowledge as well as problem formulation and tools.

This work has impacts on the Materials Design domain, the Product Design domain, and also on the broader usage of TRIZ. Under the Materials Domain, the method and tools developed in this thesis can be used even when the designer's only concern is to tailor a material to a specific set of performance requirements. This is due to there being structure property relations built into the design catalog, as well as a method to support it that include solution triggering tools from other domains to assist in generating concepts and reducing design fixation. The same is true of the product design domain, and even if to only have designers become more aware of the possibility to design both the material and the product in the conceptual phase with the appropriate method and tools.

The most interesting impact is the impact this work can have on the TRIZ body of knowledge. Many of the TRIZ tools are used similar to the way they typically are, but in new contexts. A few of them still function on the same principles, but have been torn apart and reconstructed in new forms, namely the integration of the Standard Solutions with the design catalog. Previously there was a intricate process of going through the Standard Solutions to find solution principles or phenomena, and with this work that is still in place, but now there is also the possibility of getting to those standard solutions by using the aid of the design catalog with its function-based categories and length scale classification—something that certainly isn't focused on in TRIZ literature.

6.4 CRITICAL REVIEW OF THE WORK

6.4.1 Limitations

The most obvious limitation, which also corresponds to the most obvious area of future work is that of the extremely limited scope of the design catalog. The catalog looks large when working within one particular area for one problem, but stepping back from it, it is only an extremely small fraction. This of course is a necessity though in developing the structure of the catalog. To give an idea of what the potential is for expanding the design catalog, a look at Table A.10 will reveal that each of those phenomena can represent a design catalog much large the one used in this thesis. So as it is now, the design catalog, and consequently the augmentation to it, can only be used for a problem dealing with mechanical to mechanical energy transformation of the (in)elastic deformation sort. Because the TRIZ tools are built into this type of catalog that only handles energy to energy transformation, there are TRIZ phenomena and effects that cannot be related. Table A.4 displays this limitation in some of the function representations of the required effects by having a transformation that might be something like ‘energy to signal’, or anything that is not an energy to energy transformation.

There are practical use application limitations as well. Although it is intended to reduce designer confusion and the learning curve, it might be intimidating at first not knowing the history behind two different schools of thought being merged together. As a consequence, some of the simpler constructs may become stumbling blocks, just for the fact that it would need to be followed from a guide at first, so it would be advisable to have a good reference at hand for both of TRIZ and P&B.

6.4.2 Future work

To address these two main limitations, lack of information and the need for high organization skills, there are two main areas for future work: expanding the catalog and computerizing the processes.

Obviously the design catalog needs to be expanded to become widely useable, but it cannot just be done in a haphazard way. Therefore the academic interest in future work would be the development of an system to handle managing and encouraging expansion of the design catalog. This seems straightforward until domains that are wildly different from the current domain should be added tot eh catalog, and example being bio materials. True everything pretty much falls into the category of either a product or a material, but introducing something that doesn't seem compatible on the surface would require an additional layer of organization. There is however no limitation that the analogical tools wouldn't be applicable in such a cross domain mode, as that is the gain from using this method. It is based on multi-domain analogies, so these analogies can be used in domains that a designer hasn't explored before.

In conjunction with the method of expanding a catalog, is the process of how it should be interacted with on a computer. Matthias Messer made the first step in putting some of the repository on a hyperlinked website; however this would not be a sustainable structure. There is potential then for unifying computer implementation even beyond the catalogs into possible Su-Field CAD modeling software as previously mentioned. The main thrust of research in this field would be finding ways of uniting tools, methods and processes to be better able to handle multi-domain design.

APPENDIX A: TRIZ TOOLS: TABLES AND FLOW CHARTS

Table A.1, The Standard Solutions Algorithm, is the full version of Table 5.5, which appears in truncated form in Chapter 5.

Table A.1: Standard Solutions Algorithm

1.	Construct a model of the problem.
2.	Transform the model of the problem to the Su-Field form. **Note-0:** Complete model should have a product (S1), a tool (S2), and an interaction of a product and tool (F).
3.	Check if it is a measurement problem. If *yes*, go to step 4.1. If *no*, go to step 3.1. **3.1.** Check if a replacement of the initial problem in measurement or detection tasks is accessible. If *yes*, apply the Standards of group 4.1. If *no*, go to step 4. **Note-1:** If the direct transition is too complicated, first transfer the problem to a detection task, and then translate it to a measurement task.
4.	Check the completeness of the Su-Field. If the Su-Field is incomplete (or *no*), complete step 4.1, then go to step 5. If the Su-Field is complete, go directly to step 5. **4.1.** Check presence of harmful links. If present, go to step 4.1.1. If such a link is absent, go to step 4.2. **4.1.1.** Check if the introduction of substances and fields is allowable. If *yes*, apply Standards 1.1.1–1.1.6 or Standards of group 4.2. If *no*, apply the Standards of group 5.1, 5.2, 5.5. **4.2.** Check if introduction of substances and fields is allowable. If *yes*, apply Standards 1.1.7, 1.1.8, 1.2.3. If *no*, apply the Standards of groups 5.1, 5.2, 5.5.
5.	Check presence of harmful links. If *yes*, go to step 5.1. If *no*, go to step 6. **5.1.** Check if the introduction of substances and fields is allowable. If *yes*, apply Standards 1.2.1, 1.2.2, 1.2.4, 1.2.5. If *no*, apply the Standards of groups 5.1, 5.2, 5.5.
6.	Check presence of ferromagnetic substances in the Su-Field. If *yes*, go to step 7. If *no*, go to step 8. ***Note-2***: Check presence of any ferromagnetic substance in subsystems which could be included in the Su-Field under consideration.
7.	Check if introduction of a magnetic field is allowable. If *yes*, go to step 17.

	If *no*, go to step 8.
8.	Check if formation of the complex Su-Fields is allowable. If *yes*, apply the Standards of group 2.1. If *no*, go to step 9. **Note-3:** If the complication of the system is not restricted in conditions of the problem, it is often possible to solve the problem by formation of complex Su-Fields.
9.	Check if replacement of the Su-Field is allowable. If *yes*, apply Standard 2.2.1. If *no*, go to step 10. **Note-4:** Replace any field except magnetic and electrical. **Note-5:** Replacement of a field is inadmissible if the replacing field is a source of hindrances.
10.	Check if the system is dynamic. If *yes*, go to step 11. If *no*, apply Standards 2.2.2–2.2.4. **Note-6:** Remember the principle of increased dynamism of the technique.
11.	Check if the structure of components of the Su-Field is coordinated. If *yes*, go to step 12. If *no*, apply Standards 2.2.5, 2.2.6, or 4.3.1 and of groups 5.3 and 5.4. **Note-7:** Remember duality of this law! It may be necessary to misbalance consciously the components.
12.	Check if dynamics of components of the Su-Field are coordinated. If *yes*, go to step 13. If *no*, apply Standards 2.3.1–2.3.3 or 4.3.2 and 4.3.3.
13.	Check if introduction of ferromagnetic substances and magnetic fields is allowable in Su-Field instead of current components. If *yes*, apply Standards 2.4.1 or 4.4.1. If *no*, go to step 14.
14.	Check if introduction of the ferromagnetic additives is allowable in available substances. If *yes*, apply Standards 2.4.5 or 4.4.3. If *no*, go to step 15.
15.	Check if introduction of the ferromagnetic additives is allowable in the environment. If *yes*, apply Standard 2.4.6 or 4.4.4. If *no*, go to step 16.
16.	Check if use of electrical fields and/or currents is allowable. If *yes*, apply Standards 2.4.11 and 2.4.12. If *no*, go to step 20.
17.	Check if Su-M_Field is dynamic. If *yes*, go to step 18.

	If *no*, apply Standards 2.4.2, 2.4.3, 2.4.4, 2.4.7, 2.4.8, and 4.4.2. **Note-8:** At step 7 we introduce only a magnetic field, and at step 17 we come to Su-M_Field, making ferromagnetic substance dynamic (Standards 2.4.2–2.4.4) or making all components dynamic.
18.	Check if structure of components Su-M_Field is coordinated. If *yes*, go to step 19. If *no*, apply Standard 2.4.9.
19.	Check if dynamic of components Su-M_Field is coordinated. If *yes*, go to step 20. If *no*, apply Standards 2.4.10, 4.4.5, and of groups 5.3 and 5.4.
20.	Apply the Standards of the third class to the solution of the problem in the following sequence: Standard 3.2.1, and then 3.1.1, 3.1.2, 3.1.3, and 3.1.5. **Note-9:** Standard 3.1.4 can be applied at any stage of development of bi-systems and poly-systems.

Figure A.1 and Figure A.2, The Flow Chart of the Standard Solutions Algorithm, is the full version of Figure 5.11, which appears in truncated form in Chapter 5.

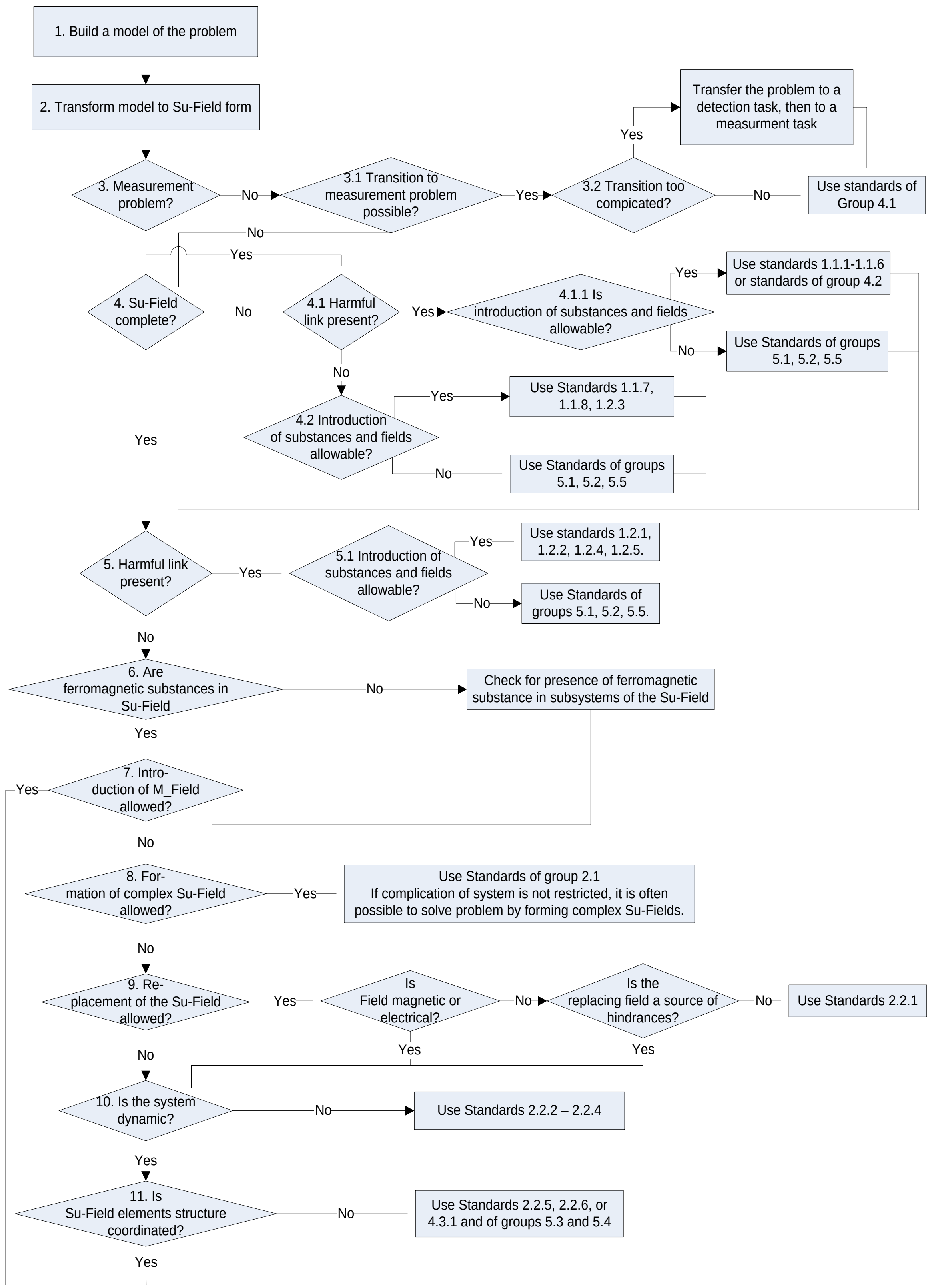


Figure A.1: Flow Chart of Standard Solutions – Part A

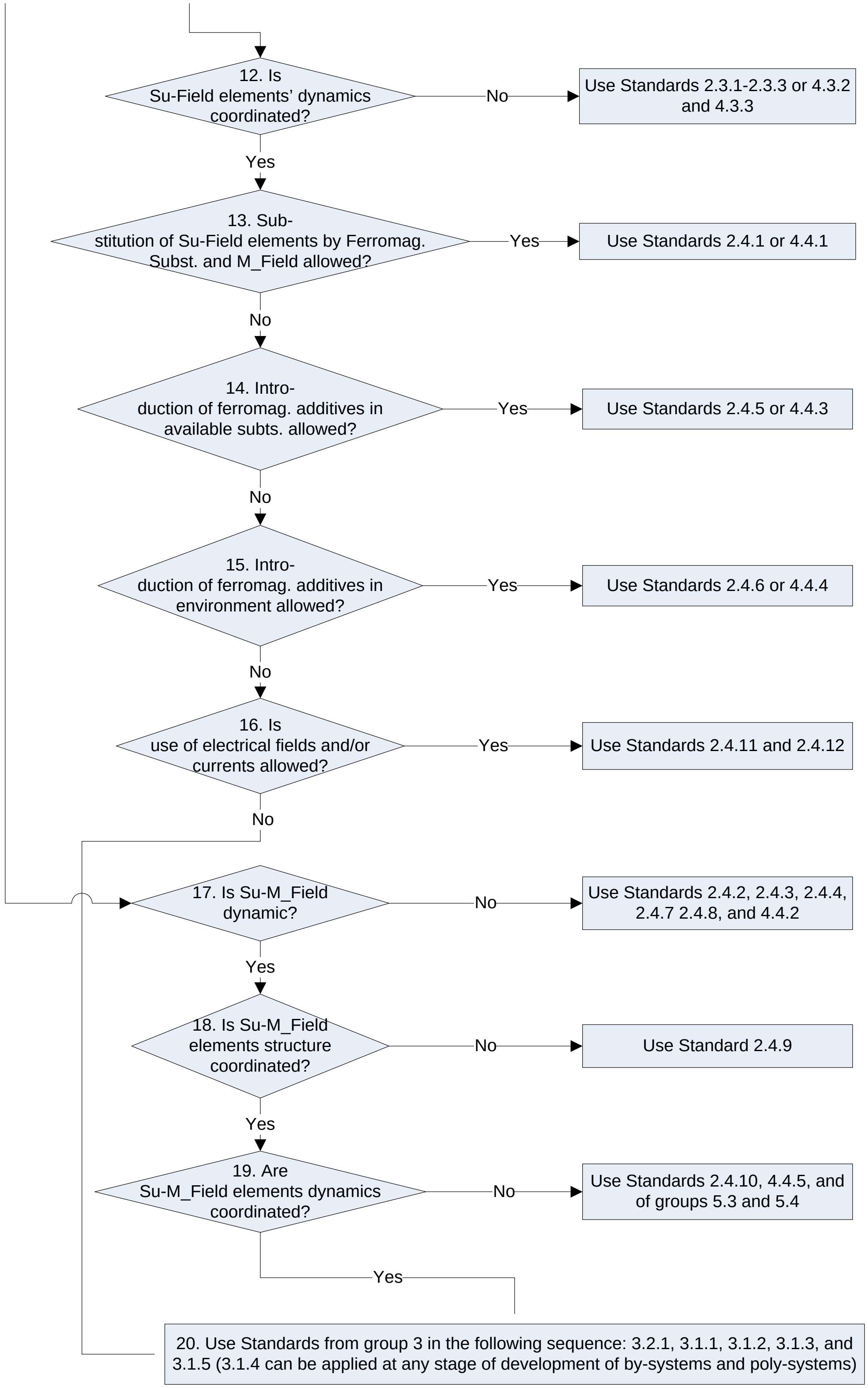


Figure A.2: Flow Chart of Standard Solutions – Part B

Table A.2, The TRIZ Standard Solutions, is the full version of Table 5.6, which appears in truncated form in Chapter 5.

Table A.2: TRIZ Standard Solutions

Altshuller's Standard Solutions of Invention Problems
Class 1. Construction and Destruction of Su-Field Systems
1.1. Synthesis of Su-Fields
1.1.1. Making Su-Field
1.1.2. Inner complex Su-Field
1.1.3. External complex Su-Field
1.1.4. External environment Su-Field
1.1.5. External environment Su-Field with additives
1.1.6. Minimal regime
1.1.7. Maximal regime
1.1.8. Selectively maximal regime
1.2. Destruction of Su-Fields
1.2.1. Removing of harmful interaction by adding a new substance
1.2.2. Removal of harmful interaction by modification of the existing substances
1.2.3. Switching off harmful interaction
1.2.4. Removal of harmful interaction by adding a new field
1.2.5. Turn-off magnetic interaction
Class 2. Development of Su-Fields
2.1. Transition to complex Su-Fields
2.1.1. Chain Su-Field
2.1.2. Double Su-Field
2.2. Forcing of Su-Fields
2.2.1. Increasing of field's controllability
2.2.2. Tool fragmentation
2.2.3. Transition to capillary-porous substances
2.2.4. Dynamization (flexibility)
2.2.5. Field organization
2.2.6. Substances organization
2.3. Forcing of Su-Fields by fitting (matching) rhythms
2.3.1. Field-Substances frequencies adjustment
2.3.2. Field-Field frequencies adjustment
2.3.3. Matching independent rhythms
2.4. Transition to Su-M_Field systems
2.4.1. Making initial Su-M_Field (or "proto-Su-M_Field")
2.4.2. Making Su-M_Field
2.4.3. Magnetic liquids
2.4.4. Capillary-porous Su-M_Field
2.4.5. Complex Su-M_Field
2.4.6. Environment Su-M_Field
2.4.7. Usage of physical effects

2.4.8. Su-M_Field dynamization
2.4.9. Su-M_Field organization
2.4.10. Matching rhythms in Su-M_Field
2.4.11. Su-E_Fields
2.4.12. Electrorheological suspension
Class 3. Transition to Super-System and to Microlevel
3.1. Transition to bi-systems and poly-systems
3.1.1. Creation of bi-systems and poly-systems
3.1.2. Development of links
3.1.3. Increase of difference between system's elements
3.1.4. Convolution
3.1.5. Opposite properties
3.2. Transition to micro-level
3.2.1. Shift to micro-level
Class 4. Standards for System Detection and Measurement
4.1. Roundabout ways to solve problems of detection and measurement
4.1.1. Change instead to measure
4.1.2. Copying
4.1.3. Sequential detection
4.2. Synthesis of Su-Field measurement systems
4.2.1. Creation of measurable Su-Field
4.2.2. Complex measurable Su-Field
4.2.3. Measurable Su-Field at environment
4.2.4. Additives in environment
4.3. Forcing of measuring Su-Fields
4.3.1. Physical effects applications
4.3.2. Resonance
4.3.3. Resonance of additives
4.4. Transition to Su-M_Field systems
4.4.1. Measurable proto-Su-M_Field
4.4.2. Measurable Su-M_Field
4.4.3. Complex measurable Su-M_Field
4.4.4. Environment measurable Su-M_Field
4.4.5. Physical effects related to magnetic field
4.5. Direction of measuring system evolution
4.5.1. Measurable bi- or poly-systems
4.5.2. Evolution line
Class 5. Standards for Using Standards
5.1. Adding substances at construction, reconstruction, and destruction of Su-Fields.
5.1.1. Round-about ways:
5.1.1.1. "Emptiness" instead of substance
5.1.1.2. Field instead of substance
5.1.1.3. External addition instead of internal one
5.1.1.4. Particularly active addition in very small doses
5.1.1.5. Substance in very small doses
5.1.1.6. Addition is used for awhile
5.1.1.7. A copy instead of a subsystem
5.1.1.8. Chemical compound

5.1.1.9. Addition is obtained from the subsystem itself
5.1.2. Substance(s) separation
5.1.3. Substance(s) dissipation
5.1.4. Big additives
5.2. Adding fields at construction, reconstruction, and destruction of Su-Fields
5.2.1. Using existing fields
5.2.2. Fields from environment
5.2.3. Substances as fields sources
5.3. Phase transitions
5.3.1. Change of the phase state
5.3.2. Second type phase transition
5.3.3. Phenomena coexist with phase transition
5.3.4. Two-phase state
5.3.5. Interaction between phases
5.4. Application peculiarities of physical effects
5.4.1. Self-driven transition
5.4.2. Increase of output field
5.5. Creation of particles
5.5.1. Substance destroying
5.5.2. Integration of particles
5.5.3. How to use Standards 5.5.1 and 5.5.2

Table A.3, Standard Solutions: IF-THEN Structure, is the full version of Table 5.8, which appears in truncated form in Chapter 5.

Table A.3: Standard Solutions: IF-THEN Structure [94]

	Aim/Conditions	Constraints	Action	Altshuller's Numbers and Notes
Aim: Optimization of Su-Fields				
1.1	Minimal (dosed, optimal) mode	Hard, or even impossible, to achieve	Use the maximal mode followed by removal of surplus part	1.1.6
1.2	UF maximal mode	Maximal mode is intolerable on one substance (e.g., S1)	Retain maximal mode maintenance but direct it to another substance (e.g., S2) related to the first one (e.g., S1).	1.1.7
1.3	Selective mode	No restrictions on F value	Add a protective substance where minimal mode is needed, and add a substance giving a local field where maximal mode is needed.	1.1.8 F is maximal in some sectors and minimal in other sectors.
Aim: Destruction of Su-Fields				
2.1	Both UF and HF take place between substances in Su-Field	The substances must not necessarily be in direct contact	Add a new, free, or sufficiently inexpensive substance S3 between the substances S1 and S2.	1.2.1 Take S3 from the outside in the finished form or made of substances available under the action of fields; e.g., S3 is bubbles, "emptiness," foam, etc.
2.2	The same conditions as above	1.2.1 + the usage of foreign S3 is barred.	Add a new, free, or sufficiently inexpensive substance S3 between S1 and S2, and this third substance is a modification of the first two.	1.2.2 S3 is already available in a technique; S3 is just modified for performing new functions.
2.3	The same conditions as above	S1 and S2 must be in direct contact	Pass to double Su-Field, where available field F1 retains its UF, and added field F2 neutralizes (compensates) HF (or transforms it into useful one).	1.2.4
2.4	HF of a field on substance exists	No restrictions	Introduce a substance that will eliminate HF itself.	1.2.3, 1.2.5M
Aim: Construction of Su-Fields				
3.1	The given substance is hardly changeable in the needed direction	No restrictions on adding new substances and fields	Completion (synthesis) of Su-Field due to introduction of new (missing) components.	1.1.1 When performing operations with thin, operations with thin, fragile, and easily deformable substance, a subsystem is joined during these operations with a substance making it hard substance making

				it hard (strong). Then this subsystem can be removed by dissolving, evaporation, etc.
3.2	The same conditions as	No restrictions on adding new substances into existing subsystem	Transition (constant or temporal) to internal complex Su-Field, introducing additions into available substances S1 or S2. Such additions must increase Su-Field controllability or add needed properties to it.	1.1.2 Sometimes one and the same solution, depending on the statement of a problem, can be obtained by constructing (complex) Su-Field. S3 is an addition to the tool S2.
3.3	The same conditions as above	Restrictions on adding new substances to available ones S1 or S2	Transition (constant or temporal) to external complex Su-Field, joining outer substance S3 with S1 or S2. The S3 must increase Su-Field controllability or give it needed properties.	1.1.3, 2.4.5M
3.4	The same conditions as above	Restrictions on adding or joining new substances	Completion (synthesis) of Su-Field using the available environment as a substance to be added.	1.1.4, 2.4.6M In particular, if a weight of a moving subsystem needs to change, and it is impossible, the subsystem must be shaped as a wing. Changing the angle of wing inclination about the movement direction, one obtains the additional upward or downward force.
3.5	The same conditions as above	1.14 + no substances in the environment	Substances can be obtained by replacement of the environment, its decomposition, or addition of new substances into it.	1.1.5
Aim: Increase the Su-Field Efficiency Due to Resources				
4.1	Su-Field is weakly controllable and its efficiency should increase	No restrictions	Transformation of a Su-Field component into independently controlled Su-Field and construction of chain Su-Fields. (Analogies: 2.4.1 for Su_M_Fields and 2.4.11 for Su_E_Fields).	2.1.1, 2.4.1M A chain Su-Field can be obtained by expanding relations in Su-Field. In this case, a new link F2-S1 is integrated into the relation S1-S2.
4.2	The same conditions as above	No restrictions	Increase the degree of dispersion of a substance operating as a tool. Increase the degree of flexibility of the Su-Field.	2.2.2, 2.4.2M, 2.2.4, 2.4.3M, 2.4.8M Standards reflect the technique evolution trends.

4.3	The same conditions as above	No restrictions	Transition from homogeneous fields (substances) or fields (substances) with unordered structure to inhomogeneous fields (substances) or fields (substances) with a certain spatial structure (constant or variable).	2.2.5. For field organization 2.2.6. For substances organization 2.4.9M For ferromagnets and magnetic fields
4.4	The same conditions as above	Su-Field components cannot be replaced (2.1.2) by adding new F and S (2.2.1)	Construct a double Su-Field due to introduction of the second well controllable field. (2.1.2) Replace uncontrollable (or weakly controllable) working field with controllable (well controllable) one (2.2.1).	2.1.2, 4.4.2M, 2.2.1, 2.4.1M For example, a mechanical field can be replaced with an electric one, etc. Analogs are 4.4.2M, 2.4.1M
Aim: Growth of Su-Fields Efficiency by Phase Transitions				
5.1	Contradictory requirements to introduce S and F can be met only by using phase transitions	Restriction to add substances	Change the phase state of the available substance instead of adding a new substance.	5.3.1
5.2		Opposite properties for existing substances	Use the substances capable of transition from one phase state to another one, depending on the operation conditions	5.3.2 The phase transition of the second type is preferable.
5.3	The same conditions	See the conditions	Use phenomena accompanying the phase transition.	5.3.3
5.4	The same conditions	The same restrictions	Replace the single-phase state of a substance with a two-phase.	5.3.4 See Standard 5.4.1.
5.5	The same conditions	The conditions are the restrictions	Introduce an interaction (physical, chemical) between phases of the substance (obtained by 5.3.4).	5.3.5
Aim: Formation of Su-Fields for Measurement				
6.1	Poorly measurable or detectable	No restrictions	Construct a simple or double Su- Field using a field passing through the system and carrying	4.2.1 The synthesis of measuring Su-Fields is distinguished incomplete Su- Field out the information about its state by the fact that they must ensure obtaining a field at output. (Compare Standard 1.1.1.)

6.2	Poorly measurable or detectable complete Su-Field	No restrictions	Change the system in such a way that there will be no necessity for detection and measurement.	4.1.1 PF of some subsystems is measurements and detection. It is desirable to exclude (or minimize) such PF, without prejudice to technique accuracy and performance.
6.3	The same conditions as above	No restrictions	Transition to internal or external complex Su-Field, adding easy-to-detect substances to the system.	4.2.2, 4.4.3M Can be applied to a component of any complete Su-Field.
6.4	The same conditions as above	Standard 4.1.1 cannot be applied	Replace direct operations with a subsystem by operations with its copy or picture.	4.1.2 Such copy (picture) can have the opposite colors to the subsystem's colors.
6.5	The same conditions as above	Standards 4.1.1 and 4.1.2 cannot be applied	Perform the sequential detection of changes.	4.1.3 The change from the indistinct concept "measurement" to the clear model "two sequential detections" simplifies many problems.
6.6	The same conditions as above	No substances can be added	Add the substances generating easy-to-detect and easy-to-measure field to environment.	4.2.3, 4.4.4M The state of the technique can be judged from the state of environment.
6.7	The same conditions as above	Restriction for adding the substances according to Standard 4.2.3	Obtain the substances generating easy-to-detect and easy-to-measure field in the environment itself	4.2.4 Such substances can be obtained by decomposition of environment or change of the aggregate state of matter.
Aim: Substances Management in Su-Fields				

7.1	Complete Su-Field	Restriction to add new substances	1. “Emptiness” and/or a field is used in spite of substance. 2. External addition is used in spite of internal one. 3. Substance is added in the form of chemical compound giving off the needed substance. 4. Particularly active addition in very small doses is used. 5. Usual substance in very small doses is added but only at certain points of a subsystem. 6. Addition is used for a while. 7. Technique model, to which substances can be added, is used in spite of the technique. 8. Addition is obtained from the technique itself, its subsystems, or environment by decomposing it using, for example, changing the aggregate state of matter.	5.1.1
7.2	Complete Su-Field	Substance’s direct production is impossible	Destroy substance of the closest higher (“full” or “excessive”) structure level (e.g., molecules) to obtain its parts (e.g., ions).	5.5.1
7.3	Complete Su-Field	Substance’s direct production and destruction are impossible	Integrate a substance of the closest lower (“non-full”) structure level (for example, ions).	5.5.2
7.4	Complete Su-Field	A technique is unchangeable and tool replacement or addition of substances is not allowed	Separate substance(s) into parts interacting with each other and use them as a tool.	5.1.2 Separation into parts charged positively and negatively. If all substance’s parts have the same electrical charge, another substance should have the opposite charge.
7.5	Complete Su-Field	Added substance must disappear after being used	Make additive substance indistinguishable from the technique substance or in environment.	5.1.3
7.6	Add a lot of substance	Much of substance cannot be added	Use “emptiness” substance as inflatable constructions (macrolevel) or foam (micro-level).	5.1.4 Standard 5.1.4 is often used along with other Standards.
Aim: Add Fields in Su-Fields				

8.1	Complete Su-Field	No restrictions	Use already available ("hidden") fields carrying by substances existing in the technique.	5.2.1. Using existing fields
8.2	Complete Su-Field	Standard 5.2.1 is inapplicable	Use fields from an environment.	5.2.2. Fields from environment
8.3	Complete Su-Field	Standards 5.2.1 and 5.2.2 are inapplicable	Use fields that can be generated by the technique's substances or environment.	5.2.3. Substances as sources of fields Utilize magnetism of ferromagnetic substances used in the technique only mechanically for better interaction between subsystems, for revealing information, etc.
Aim: Forcing of Measuring Su-Fields				
9.1	Complete Su-Field	Changes cannot be directly detected or measured. A field cannot be passed via the system	Excite resonance vibrations (in the whole system or its part), and changes in frequency of these vibrations serve as indications of changes taking place in the system itself.	4.3.2
9.2	Complete Su-Field	Same as above + Standard 4.3.2 cannot be applied	Obtain information about the technique from the changes in intrinsic frequency of a subsystem (environment) related/added to the monitored technique.	4.3.3
Aim: Growth of Efficiency for Physical Effects Applications				
10.1	Su-Field's component must be in various states	Periodically, from time-to time, or occasionally	Use reversible physical transformations (e.g., phase transitions).	5.4.1 Transition by the subsystem itself is due to ionization-recombination, dissociation–association, etc. Also Standard 5.3.4.
10.2	Su-Field has a "weak" input	Cannot increase input, but a "strong" output is needed	Use the substance-transformer into the state close to the critical one. Energy is accumulated in the substance, and an input signal plays a part of "trigger."	5.4.2 Goal here is to obtain a "strong" output, usually in the form of a field.

Table A.4: Physical Effects and Phenomenon Related to Energy Transformation Function, is the full version of Table 5.9, which appears in truncated form in Chapter 5.

Table A.4: Physical Effects and Phenomenon Related to Energy Transformation Function

Required effect		Function(s) (Energy Input → Energy Output)	Phenomenon
1	Measuring Temperature	Magnetostatic → Sound	Barkhausen effect
		Thermal → Electrical	Thermoelectrical Phenomena
		Thermal → Material Properties	Change in optical, electrical, and magnetic properties
		Thermal → Mechanical	Thermal expansion and its influence on natural frequency of oscillations
		Thermal → Pneumatical/Hydraulic	Thermal expansion and its influence on natural frequency of oscillations
2	Lowering Temperature	Electrostati→ Thermal	Peltier, Seebeck, and Thomson effects
			Thermoelectrical Phenomena
		Mechanical →Thermal	Joule-Thomson effect
		Magnetostatic → Thermal	Magnetic calorie effect
		Pneumtical/Hydraulic →Thermal	Joule-Thomson effect
		Thermal → Chemical	Phase Transition
3	Raising Temperature	Chemical → Thermal	Absorption of radiation by the substance
		Electrostatic → Magnetostatic	Eddy Currents
		Electrostatic → Thermal	Dielectrical Heating Eddy Currents Electrical Charges Electromagnetic induction Electronic Heating Peltier and Thomson effects Thermal-electrical phenomena
		Mechanical → Thermal	Vortical currents
		Thermal → Material Properties	Surface effect
4	Stabilizing Temperature	Thermal → Chemical	Phase Transition
		Thermal → Thermal	Evaporation
5	Indication of position and location of object	Chemical → Signal	Emission of light Introduction of marker substances Radioactive and Xray radiation
		Eletrostatic → Signal	Changes in electrical field Electrical discharge Emission of light
		Light → Signal	Reflection of light Luminescence
		Magnetostatic → Signal	Changes in magnetic field
		Mechanical → Signal	Deformation
		Mechanical → Sound/Light/Thermal	Doppler effect

6	Controlling location of objects	Electrostatic → Mechanical	Applying electrical field to influence charged object.
		Light → Mechanical	Light pressure
		Magnetosatic → Mechanical	Applying magnetic field to influence an object or magnet linked to object. Applying magnetic field to influence a conductor with DC current going through
		Mechanical → Mechanical	Mechanical oscillations Centrifugal forces
		Pneumatical/Hydraulic → Mechanical	Pressure transfer in liquid or gas
		Thermal → Mechanical	Thermal expansion
		Thermal → Pneumatical/Hydraulic	Thermal expansion
7	Move liquid or gas	Chemical → Material Properties	Toms effect
		Electrostatic → Mechanical	Capillary force
		Mechanical → Mechanical	Wave movement Capillary force Centrifugal forces Weissenberg effect
		Mechanical → Pneumatic/Hydraulic	Bernoulli's effect
		Pneumatical/Hydraulic → Pneum./Hydr.	Bernoulli's effect
		Thermal → Mechanical	Osmosis
		Thermal → Pneumatic/Hydraulic	Osmosis
8	Control of aerosol flow (dust, fog, smoke)	Electrostatic → Chemical	Electrolysis
		Electrostatic → Mechanical	Applying electrical fields
		Light → Pneumatical/Hydraulic	Pressure of light
		Magnetosatic → Mechanical	Applying magnetic fields
9	Forming Mixtures	Electrical → Electrical	Electrophoresis
		Material properties change	
10	Separation of Mixtures	Material properties change	
11	Stabilization of position of objects	Electrostatic → Mechanical	Applying electrical fields Fixing in liquids which harden in magnetic and electrical fields
		Magnetostatic → Mechanical	Applying magnetic fields
		Mechanical → Mechanical	Reactive Force
		Mechanical → Signal	Gyroscope effect
12	Generation and/or manipulation force	Chemical → Mechanical	Osmosis
		Chemical → Pneumatic	Osmosis
		Chemical → Thermal	Osmosis Use of explosives
		Electrostatic → Material Properties	Changing the hydrostatic forces via influencing pseudo-viscosity of an electro conductive or magnetic liquid in a magnetic

			field
		Electrostatic → Mechanical	Electro-hydraulic effect
		Magnetostatic → Material properties	Applying magnetic field through magnetic material phase transitions
		Mechanical → Mechanical (Magnetostatic → Magnetostatic)	Effect of a magnetic field via ferromagnetic substance
		Mechanical → Mechanical	Centrifugal forces
		Pneumatical/Hydraulic → Mechanical	Generating high pressure
		Thermal → Mechanical	Thermal Expansion
		Thermal → Pneumatical/Hydraulic	Thermal Expansion
13	Changes in friction	Electrostatic → Mechanical	Johnson-Rhabeck effect
		Material Property Change	Abnormally low friction effect Kragelsky Phenomenon No-wear friction effect Oscillation Radiation Influence
14	Destruction of object	Chemical → Chemical	Induced radiation
		Chemical → Thermal	Induced radiation
		Electrostatic → Mechanical	Electrical discharges Electrohydraulic effect
		Light → Thermal	Use of lasers
		Mechanical → Mechanical	Cavitation Resonance
		Mechanical → Sound	Ultrasonics
		Sound → Mechanical	Resonance Ultrasonics
15	Accumulation of mechanical and thermal energy	Mechanical → Chemical	Phase Transition
		Mechanical → Mechanical	Elastic deformation Gyroscope
		Pneumatical/Hydraulic → Chemical	Phase Transition
16	Transfer of energy	Chemical → Light	Induced radiation
		Electrostatic → Electrostatic	Superconductivity
		Electrostatic → Mechanical	Electromagnetic induction
		Light → Light	Fiber optics Lasers Light reflection Radiation
		Magnetostatic → Electrostatic	Electromagnetic induction
		Magnetostatic → Magnetosatic	Electromagnetic induction
		Magnetostatic → Mechanical	Electromagnetic induction
		Mechanical → Electrostatic	Electromagnetic induction
		Mechanical → Mechanical	Alexandrov Effect Deformations

			Oscillations Waves, including shock waves
		Thermal → Electrostatic	Superconductivity
		Thermal → Thermal	Convection Thermal conductivity
17	Influence on a moving object	Electrostatic → Mechanical	Applying electrical fields (no-contact influence instead of physical contact)
18	Measuring a dimensions	Electrostatic → Signal	Applying and reading magnetic and electrical markers
		Mechanical → Signal	Measuring oscillations' natural frequency
19	Changing a dimensions	Electrostatic → Mechanical	Electrostriction (Piezoelectrical effect)
		Magnetostatic → Mechanical	Magnetostriction
		Magnetostatic → Pneumatical/Hydraulic	Magnetostriction
		Magnetostatic → Sound	Magnetostriction
		Mechanical → Electrostatic	Electrostriction (Piezoelectrical effect)
		Mechanical → Magnetostatic	Magnetostriction
		Mechanical → Mechanical	Deformations
		Pneumatical/Hydraulic → Magnetostatic	Magnetostriction
		Thermal → Mechanical	Thermal expansion
		Thermal → Pneumatical/Hydraulic	Thermal expansion
20	Detect surface properties and/or conditions	SIGNAL OUTPUT	
21	Measuring surface properties	Electrical → Signal	Electrical discharge Electronic emission
		Light → Light	Ultraviolet radiation
		Light → Signal	Auger spectroscopy
		Mechanical → Material Properties	Bauschinger effect Diffusion
		Mechanical → Mechanical	Friction Mechanical oscillations
		Sound → Mechanical	Acoustical oscillations
		Sound → Sound	Acoustical oscillations
22	Inspection of state and properties in volume	Chemical → Signal	Introduction of "marker" substances which are capable of transforming an existing field (such as luminophores) or generating their own (such as ferromagnetic materials) depending on structure and/or properties. Nuclear magnetic resonance Ultrasonics, the Moessbauer effect
		Electrostatic → Signal	Changing electrical resistance depending on structure and/or properties' variations Electric optical phenomena Electronic paramagnetic resonance

		Light → Signal	Interaction with light Polarized light X-ray and radioactive radiation
		Magnetostatic → Electrostatic	Hall effect
		Magnetostatic → Mechanical	Magneto-elastic effect
		Magnetostatic → Signal	Magnetic optical phenomena Transition over the Curie point
		Magnetostatic → Sound	Barkhausen effect
		Mechanical → Signal	Measuring inherent frequency of oscillation
23	Changing the volume properties of an object	Chemical → Material Properties	Phase Transition Ultraviolet, X-ray, radioactive radiation. Diffusion
		Electrostatic → Material Properties	Changing the properties of liquids under the action of electrical fields. Ionization under the effect of an electrical field.
		Light → Material Properties	Photochromatic effect
		Magnetostatic → Light	Magnetic-optical effects
		Magnetostatic → Material Properties	Changing the properties of liquids under the action of magnetic fields. Introduction of ferromagnetic substance and action of magnetic field.
		Mechanical → Material Properties	Bauschinger effect Cavitation
		Mechanical → Mechanical	Deformation
		Thermal → Electrostatic	Thermoelectrical effects
		Thermal → Magnetostatic	Thermomagnetic effects
		Thermal → Material Properties	Heating
24	Develop certain structures, structure stabilization	Chemical → Material Properties	Phase Transition
		Magnetostatic → Mechanical	Magnetic waves
		Mechanical → Material Properties	Cavitation
		Mechanical → Mechanical	Interference waves Standing waves Mechanical oscillations
		Signal Property	Moire effect
		Sound → Mechanical/	Acoustical oscillations
		Sound → Sound	Acoustical oscillations
25	Detect electrical and/or magnetic fields	Chemical → Signal	Nuclear magnetic resonance
		Electrostatic → Pneumatical/Hydraulic	Osmosis (from previous edition, assumed to be Electro-osmosis)
		Electrostatic → Electrostatic	Electrical discharges Electronic emissions
		Electrostatic → Material Properties	Electrification of bodies
		Electrostatic → Mechanical	Electrostriction (Piezoelectrical effect)
		Electrostatic → Signal	Electro-optical phenomena

			Electrets
		Magnetostatic → Electrostatic/Signal	Gyromagnetic phenomena
		Magnetostatic → Electrostatic	Hall effect
		Magnetostatic → Signal	Magnetic - optical phenomena
		Magnetostatic → Sound	Barkhausen effect
		Mechanical → Electrostatic	Electrostriction (Piezoelectrical effect)
26	Detect radiation	Light → Signal	Luminescence Photoeffect Photoplastic effect
		Thermal → Signal	Thermal expansion
		Sound → Signal	Optical-acoustic effect
27	Generation of electromagneti c radiation	Chemical → Chemical	Induced radiation
		Chemical → Light Energy	Cherenkov effect
		Electrical → Light	Luminescence Gunn effect
		Mechanical → Electrical	Josephson effect
		Mechanical → Mechanical	Tunnel effect
28	Control of electromagneti c fields	Electrical → Electrical	Screening/Farady Cage
		Electrical →Magnetostatic	Screening/Farady Cage
		Magnetostatic → Electrical	Screening/Farady Cage
		CHANGES IN MATERIAL PROPERTIES	Changing properties (i.e. varying electrical conductivity)
			Changing the objects shape
29	Controlling light. Light modulation	Electrostatic → Light	Electrical optical phenomena Gunn effects Kerr effect
		Electrostatic → Magnetostatic	Faraday effect
		Electrostatic → Material Properties	Franz-Keldysh effect
		Light → Light	Refraction and reflection of light
		Light → Signal	Photoelasticity
		Magnetostatic → Electrostatic	Faraday effect
		Magnetostatic → Light	Magnetic optical phenomena Faraday effect
30	Initiation and intensification of chemical changes	Chemical → Material Properties	Ultraviolet, X-ray, radioactive radiation. Micellar catalysis
		Electrostatic → Material Properties	Electrical discharges
		Mechanical → Material Properties	Cavitation Shock waves
		Sound → Chemical	Ultrasonics
		Sound → Mechanical	Ultrasonics

Table A.5: TRIZ Generic Engineering Parameters, is a table listing the 39 Generic Engineering parameters discussed in Chapter 3, specifically Section 3.3.1.4.1.

Table A.5: TRIZ Generic Engineering Parameters

1. Weight of moving object
2. Weight of binding object
3. Length of moving object
4. Length of binding object
5. Area of moving object
6. Area of binding object
7. Volume of moving object
8. Volume of binding object
9. Speed
10. Force
11. Tension, pressure
12. Shape
13. Stability of object
14. Strength
15. Durability of moving object
16. Durability of binding object
17. Temperature
18. Brightness
19. Energy spent by moving object
20. Energy spent by binding object
21. Power
22. Waste of energy
23. Waste of substance
24. Loss of information
25. Waste of time
26. Amount of substance
27. Reliability
28. Accuracy of measurement
29. Accuracy of manufacturing
30. Harmful factors acting on object
31. Harmful side effects
32. Manufacturability
33. Convenience of use
34. Reparability
35. Adaptability
36. Complexity of a system
37. Complexity of control
38. Level of automation
39. Productivity

Table A.6, is the Technical Contradiction Matrix referenced in sections: 1.2.2, 2.3.2, 3.3.2.5, 4.2.2, 5.3.2.5 and 6.2.3.

Table A.6: TRIZ Technical Contradiction Matrix

	Worsening Feature → / Improving Feature ↓	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Speed	Force (Intensity)	Stress or pressure	Shape	Stability of the object's composition	Strength	Duration of action of moving object	Duration of action of stationary object	Temperature	Illumination intensity	Use of energy by moving object	Use of energy by stationary object	Power	Loss of Energy	Loss of Substance	Loss of Information	Loss of Time	Quantity of substance	Reliability	Measurement accuracy	Manufacturing precision	Object-affected harmful factors	Object-generated harmful factors	Ease of manufacture	Ease of operation	Ease of repair	Adaptability or versatility	Device complexity	Difficulty of detecting and measuring	Extent of automation	Productivity
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
1	Weight of moving object	+	-	15, 8, 29,34	-	29, 17, 38, 34	-	29, 2, 40, 28	-	2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39	28, 27, 18, 40	5, 34, 31, 35	-	6, 29, 4, 38	19, 1, 32	35, 12, 34, 31	-	12, 36, 18, 31	6, 2, 34, 19	5, 35, 3, 31	10, 24, 35	10, 35, 20, 28	3, 26, 18, 31	1, 3, 11, 27	28, 27, 35, 26	28, 35, 26, 18	22, 21, 18, 27	22, 35, 31, 39	27, 28, 1, 36	35, 3, 2, 24	2, 27, 28, 11	29, 5, 15, 8	26, 30, 36, 34	28, 29, 26, 32	26, 35 18, 19	35, 3, 24, 37
2	Weight of stationary object	-	+	-	10, 1, 29, 35	-	35, 30, 13, 2	-	5, 35, 14, 2	-	8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40	28, 2, 10, 27	-	2, 27, 19, 6	28, 19, 32, 22	19, 32, 35	-	18, 19, 28, 1	15, 19, 18, 22	18, 19, 28, 15	5, 8, 13, 30	10, 15, 35	10, 20, 35, 26	19, 6, 18, 26	10, 28, 8, 3	18, 26, 28	10, 1, 35, 17	2, 19, 22, 37	35, 22, 1, 39	28, 1, 9	6, 13, 1, 32	2, 27, 28, 11	19, 15, 29	1, 10, 26, 39	25, 28, 17, 15	2, 26, 35	1, 28, 15, 35
3	Length of moving object	8, 15, 29, 34	-	+	-	15, 17, 4	-	7, 17, 4, 35	-	13, 4, 8	17, 10, 4	1, 8, 35	1, 8, 10, 29	1, 8, 15, 34	8, 35, 29, 34	19	-	10, 15, 19	32	8, 35, 24	-	1, 35	7, 2, 35, 39	4, 29, 23, 10	1, 24	15, 2, 29	29, 35	10, 14, 29, 40	28, 32, 4	10, 28, 29, 37	1, 15, 17, 24	17, 15	1, 29, 17	15, 29, 35, 4	1, 28, 10	14, 15, 1, 16	1, 19, 26, 24	35, 1, 26, 24	17, 24, 26, 16	14, 4, 28, 29
4	Length of stationary object		35, 28, 40, 29	-	+	-	17, 7, 10, 40	-	35, 8, 2,14	-	28, 10	1, 14, 35	13, 14, 15, 7	39, 37, 35	15, 14, 28, 26	-	1, 10, 35	3, 35, 38, 18	3, 25	-		12, 8	6, 28	10, 28, 24, 35	24, 26,	30, 29, 14		15, 29, 28	32, 28, 3	2, 32, 10	1, 18		15, 17, 27	2, 25	3	1, 35	1, 26	26		30, 14, 7, 26
5	Area of moving object	2, 17, 29, 4	-	14, 15, 18, 4	-	+	-	7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39	3, 15, 40, 14	6, 3	-	2, 15, 16	15, 32, 19, 13	19, 32	-	19, 10, 32, 18	15, 17, 30, 26	10, 35, 2, 39	30, 26	26, 4	29, 30, 6, 13	29, 9	26, 28, 32, 3	2, 32	22, 33, 28, 1	17, 2, 18, 39	13, 1, 26, 24	15, 17, 13, 16	15, 13, 10, 1	15, 30	14, 1, 13	2, 36, 26, 18	14, 30, 28, 23	10, 26, 34, 2
6	Area of stationary object	-	30, 2, 14, 18	-	26, 7, 9, 39	-	+	-		-	1, 18, 35, 36	10, 15, 36, 37		2, 38	40	-	2, 10, 19, 30	35, 39, 38		-		17, 32	17, 7, 30	10, 14, 18, 39	30, 16	10, 35, 4, 18	2, 18, 40, 4	32, 35, 40, 4	26, 28, 32, 3	2, 29, 18, 36	27, 2, 39, 35	22, 1, 40	40, 16	16, 4	16	15, 16	1, 18, 36	2, 35, 30, 18	23	10, 15, 17, 7
7	Volume of moving object	2, 26, 29, 40	-	1, 7, 4, 35	-	1, 7, 4, 17	-	+	-	29, 4, 38, 34	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4	28, 10, 1, 39	9, 14, 15, 7	6, 35, 4	-	34, 39, 10, 18	2, 13, 10	35	-	35, 6, 13, 18	7, 15, 13, 16	36, 39, 34, 10	2, 22	2, 6, 34, 10	29, 30, 7	14, 1, 40, 11	25, 26, 28	25, 28, 2, 16	22, 21, 27, 35	17, 2, 40, 1	29, 1, 40	15, 13, 30, 12	10	15, 29	26, 1	29, 26, 4	35, 34, 16, 24	10, 6, 2, 34
8	Volume of stationary object	-	35, 10, 19, 14	19, 14	35, 8, 2, 14	-		-	+	-	2, 18, 37	24, 35	7, 2, 35	34, 28, 35, 40	9, 14, 17, 15	-	35, 34, 38	35, 6, 4		-		30, 6		10, 39, 35, 34		35, 16, 32 18	35, 3	2, 35, 16		35, 10, 25	34, 39, 19, 27	30, 18, 35, 4	35		1		1, 31	2, 17, 26		35, 37, 10, 2
9	Speed	2, 28, 13, 38	-	13, 14, 8	-	29, 30, 34	-	7, 29, 34	-	+	13, 28, 15, 19	6, 18, 38, 40	35, 15, 18, 34	28, 33, 1, 18	8, 3, 26, 14	3, 19, 35, 5	-	28, 30, 36, 2	10, 13, 19	8, 15, 35, 38	-	19, 35, 38, 2	14, 20, 19, 35	10, 13, 28, 38	13, 26		10, 19, 29, 38	11, 35, 27, 28	28, 32, 1, 24	10, 28, 32, 25	1, 28, 35, 23	2, 24, 35, 21	35, 13, 8, 1	32, 28, 13, 12	34, 2, 28, 27	15, 10, 26	10, 28, 4, 34	3, 34, 27, 16	10, 18	
10	Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+	18, 21, 11	10, 35, 40, 34	35, 10, 21	35, 10, 14, 27	19, 2		35, 10, 21	-	19, 17, 10	1, 16, 36, 37	19, 35, 18, 37	14, 15	8, 35, 40, 5		10, 37, 36	14, 29, 18, 36	3, 35, 13, 21	35, 10, 23, 24	28, 29, 37, 36	1, 35, 40, 18	13, 3, 36, 24	15, 37, 18, 1	1, 28, 3, 25	15, 1, 11	15, 17, 18, 20	26, 35, 10, 18	36, 37, 10, 19	2, 35	3, 28, 35, 37
11	Stress or pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36	36, 35, 21	+	35, 4, 15, 10	35, 33, 2, 40	9, 18, 3, 40	19, 3, 27		35, 39, 19, 2	-	14, 24, 10, 37		10, 35, 14	2, 36, 25	10, 36, 3, 37		37, 36, 4	10, 14, 36	10, 13, 19, 35	6, 28, 25	3, 35	22, 2, 37	2, 33, 27, 18	1, 35, 16	11	2	35	19, 1, 35	2, 36, 37	35, 24	10, 14, 35, 37
12	Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40	34, 15, 10, 14	+	33, 1, 18, 4	30, 14, 10, 40	14, 26, 9, 25		22, 14, 19, 32	13, 15, 32	2, 6, 34, 14		4, 6, 2	14	35, 29, 3, 5		14, 10, 34, 17	36, 22	10, 40, 16	28, 32, 1	32, 30, 40	22, 1, 2, 35	35, 1	1, 32, 17, 28	32, 15, 26	2, 13, 1	1, 15, 29	16, 29, 1, 28	15, 13, 39	15, 1, 32	17, 26, 34, 10
13	Stability of the object's composition	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	33, 15, 28, 18	10, 35, 21, 16	2, 35, 40	22, 1, 18, 4	+	17, 9, 15	13, 27, 10, 35	39, 3, 35, 23	35, 1, 32	32, 3, 27, 16	13, 19	27, 4, 29, 18	32, 35, 27, 31	14, 2, 39, 6	2, 14, 30, 40		35, 27	15, 32, 35		13	18	35, 24, 30, 18	35, 40, 27, 39	35, 19	32, 35, 30	2, 35, 10, 16	35, 30, 34, 2	2, 35, 22, 26	35, 22, 39, 23	1, 8, 35	23, 35, 40, 3
14	Strength	1, 8, 40, 15	40, 26, 27, 1	1, 15, 8, 35	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	8, 13, 26, 14	10, 18, 3, 14	10, 3, 18, 40	10, 30, 35, 40	13, 17, 35	+	27, 3, 26		30, 10, 40	35, 19	19, 35, 10	35	10, 26, 35, 28	35	35, 28, 31, 40		29, 3, 28, 10	29, 10, 27	11, 3	3, 27, 16	3, 27	18, 35, 37, 1	15, 35, 22, 2	11, 3, 10, 32	32, 40, 25, 2	27, 11, 3	15, 3, 32	2, 13, 25, 28	27, 3, 15, 40	15	29, 35, 10, 14
15	Duration of action of moving object	19, 5, 34, 31	-	2, 19, 9	-	3, 17, 19	-	10, 2, 19, 30	-	3, 35, 5	19, 2, 16	19, 3, 27	14, 26, 28, 25	13, 3, 35	27, 3, 10	+	-	19, 35, 39	2, 19, 4, 35	28, 6, 35, 18		19, 10, 35, 38		28, 27, 3, 18	10	20, 10, 28, 18	3, 35, 10, 40	11, 2, 13	3	3, 27, 16, 40	22, 15, 33, 28	21, 39, 16, 22	27, 1, 4	12, 27	29, 10, 27	1, 35, 13	10, 4, 29, 15	19, 29, 39, 35	6, 10	35, 17, 14, 19
16	Duration of action by stationary object	-	6, 27, 19, 16	-	1, 40, 35	-		-	35, 34, 38	-				39, 3, 35, 23		-	+	19, 18, 36, 40		-		16		27, 16, 18, 38	10	28, 20, 10, 16	3, 35, 31	34, 27, 6, 40	10, 26, 24		17, 1, 40, 33	22	35, 10	1	1	2		25, 34, 6, 35	1	20, 10, 16, 38
17	Temperature	36,22, 6, 38	22, 35, 32	15, 19, 9	15, 19, 9	3, 35, 39, 18	35, 38	34, 39, 40, 18	35, 6, 4	2, 28, 36, 30	35, 10, 3, 21	35, 39, 19, 2	14, 22, 19, 32	1, 35, 32	10, 30, 22, 40	19, 13, 39	19, 18, 36, 40	+	32, 30, 21, 16	19, 15, 3, 17		2, 14, 17, 25	21, 17, 35, 38	21, 36, 29, 31		35, 28, 21, 18	3, 17, 30, 39	19, 35, 3, 10	32, 19, 24	24	22, 33, 35, 2	22, 35, 2, 24	26, 27	26, 27	4, 10, 16	2, 18, 27	2, 17, 16	3, 27, 35, 31	26, 2, 19, 16	15, 28, 35
18	Illumination intensity	19, 1, 32	2, 35, 32	19, 32, 16		19, 32, 26		2, 13, 10		10, 13, 19	26, 19, 6		32, 30	32, 3, 27	35, 19	2, 19, 6		32, 35, 19	+	32, 1, 19	32, 35, 1, 15	32	13, 16, 1, 6	13, 1	1, 6	19, 1, 26, 17	1, 19		11, 15, 32	3, 32	15, 19	35, 19, 32, 39	19, 35, 28, 26	28, 26, 19	15, 17, 13, 16	15, 1, 19	6, 32, 13	32, 15	2, 26, 10	2, 25, 16
19	Use of energy by moving object	12,18,28,31	-	12, 28	-	15, 19, 25	-	35, 13, 18	-	8, 35, 35	16, 26, 21, 2	23, 14, 25	12, 2, 29	19, 13, 17, 24	5, 19, 9, 35	28, 35, 6, 18	-	19, 24, 3, 14	2, 15, 19	+	-	6, 19, 37, 18	12, 22, 15, 24	35, 24, 18, 5		35, 38, 19, 18	34, 23, 16, 18	19, 21, 11, 27	3, 1, 32		1, 35, 6, 27	2, 35, 6	28, 26, 30	19, 35	1, 15, 17, 28	15, 17, 13, 16	2, 29, 27, 28	35, 38	32, 2	12, 28, 35
20	Use of energy by stationary object	-	19, 9, 6, 27	-		-		-		-	36, 37			27, 4, 29, 18	35				19, 2, 35, 32	-	+			28, 27, 18, 31			3, 35, 31	10, 36, 23			10, 2, 22, 37	19, 22, 18	1, 4					19, 35, 16, 25		1, 6
21	Power	8, 36, 38, 31	19, 26, 17, 27	1, 10, 35, 37		19, 38	17, 32, 13, 38	35, 6, 38	30, 6, 25	15, 35, 2	26, 2, 36, 35	22, 10, 35	29, 14, 2, 40	35, 32, 15, 31	26, 10, 28	19, 35, 10, 38	16	2, 14, 17, 25	16, 6, 19	16, 6, 19, 37		+	10, 35, 38	28, 27, 18, 38	10, 19	35, 20, 10, 6	4, 34, 19	19, 24, 26, 31	32, 15, 2	32, 2	19, 22, 31, 2	2, 35, 18	26, 10, 34	26, 35, 10	35, 2, 10, 34	19, 17, 34	20, 19, 30, 34	19, 35, 16	28, 2, 17	28, 35, 34
22	Loss of Energy	15, 6, 19, 28	19, 6, 18, 9	7, 2, 6, 13	6, 38, 7	15, 26, 17, 30	17, 7, 30, 18	7, 18, 23	7	16, 35, 38	36, 38			14, 2, 39, 6	26			19, 38, 7	1, 13, 32, 15			3, 38	+	35, 27, 2, 37	19, 10	10, 18, 32, 7	7, 18, 25	11, 10, 35	32		21, 22, 35, 2	21, 35, 2, 22		35, 32, 1	2, 19		7, 23	35, 3, 15, 23	2	28, 10, 29, 35
23	Loss of substance	35, 6, 23, 40	35, 6, 22, 32	14, 29, 10, 39	10, 28,24	35, 2, 10, 31	10, 18, 39, 31	1, 29, 30, 36	3, 39, 18, 31	10, 13, 28, 38	14, 15, 18, 40	3, 36, 37, 10	29, 35, 3, 5	2, 14, 30, 40	35, 28, 31, 40	28, 27, 3, 18	27, 16, 18, 38	21, 36, 39, 31	1, 6, 13	35, 18, 24, 5	28, 27, 12, 31	28, 27, 18, 38	35, 27, 2, 31	+		15, 18, 35, 10	6, 3, 10, 24	10, 29, 39, 35	16, 34, 31, 28	35, 10, 24, 31	33, 22, 30, 40	10, 1, 34, 29	15, 34, 33	32, 28, 2, 24	2, 35, 34, 27	15, 10, 2	35, 10, 28, 24	35, 18, 10, 13	35, 10, 18	28, 35, 10, 23
24	Loss of Information	10, 24, 35	10, 35, 5	1, 26	26	30, 26	30, 16		2, 22	26, 32						10	10		19			10, 19	19, 10		+	24, 26, 28, 32	24, 28, 35	10, 28, 23			22, 10, 1	10, 21, 22	32	27, 22				35, 33	35	13, 23, 15
25	Loss of Time	10, 20, 37, 35	10, 20, 26, 5	15, 2, 29	30, 24, 14, 5	26, 4, 5, 16	10, 35, 17, 4	2, 5, 34, 10	35, 16, 32, 18		10, 37, 36,5	37, 36,4	4, 10, 34, 17	35, 3, 22, 5	29, 3, 28, 18	20, 10, 28, 18	28, 20, 10, 16	35, 29, 21, 18	1, 19, 26, 17	35, 38, 19, 18	1	35, 20, 10, 6	10, 5, 18, 32	35, 18, 10, 39	24, 26, 28, 32	+	35, 38, 18, 16	10, 30, 4	24, 34, 28, 32	24, 26, 28, 18	35, 18, 34	35, 22, 18, 39	35, 28, 34, 4	4, 28, 10, 34	32, 1, 10	35, 28	6, 29	18, 28, 32, 10	24, 28, 35, 30	
26	Quantity of substance/the matter	35, 6, 18, 31	27, 26, 18, 35	29, 14, 35, 18		15, 14, 29	2, 18, 40, 4	15, 20, 29		35, 29, 34, 28	35, 14, 3	10, 36, 14, 3	35, 14	15, 2, 17, 40	14, 35, 34, 10	3, 35, 10, 40	3, 35, 31	3, 17, 39		34, 29, 16, 18	3, 35, 31	35	7, 18, 25	6, 3, 10, 24	24, 28, 35	35, 38, 18, 16	+	18, 3, 28, 40	13, 2, 28	33, 30	35, 33, 29, 31	3, 35, 40, 39	29, 1, 35, 27	35, 29, 25, 10	2, 32, 10, 25	15, 3, 29	3, 13, 27, 10	3, 27, 29, 18	8, 35	13, 29, 3, 27
27	Reliability	3, 8, 10, 40	3, 10, 8, 28	15, 9, 14, 4	15, 29, 28, 11	17, 10, 14, 16	32, 35, 40, 4	3, 10, 14, 24	2, 35, 24	21, 35, 11, 28	8, 28, 10, 3	10, 24, 35, 19	35, 1, 16, 11		11, 28	2, 35, 3, 25	34, 27, 6, 40	3, 35, 10	11, 32, 13	21, 11, 27, 19	36, 23	21, 11, 26, 31	10, 11, 35	10, 35, 29, 39	10, 28	10, 30, 4	21, 28, 40, 3	+	32, 3, 11, 23	11, 32, 1	27, 35, 2, 40	35, 2, 40, 26		27, 17, 40	1, 11	13, 35, 8, 24	13, 35, 1	27, 40, 28	11, 13, 27	1, 35, 29, 38
28	Measurement accuracy	32, 35, 26, 28	28, 35, 25, 26	28, 26, 5, 16	32, 28, 3, 16	26, 28, 32, 3	26, 28, 32, 3	32, 13, 6		28, 13, 32, 24	32, 2	6, 28, 32	6, 28, 32	32, 35, 13	28, 6, 32	28, 6, 32	10, 26, 24	6, 19, 28, 24	6, 1, 32	3, 6, 32		3, 6, 32	26, 32, 27	10, 16, 31, 28		24, 34, 28, 32	2, 6, 32	5, 11, 1, 23	+		28, 24, 22, 26	3, 33, 39, 10	6, 35, 25, 18	1, 13, 17, 34	1, 32, 13, 11	13, 35, 2	27, 35, 10, 34	26, 24, 32, 28	28, 2, 10, 34	10, 34, 28, 32
29	Manufacturing precision	28, 32, 13, 18	28, 35, 27, 9	10, 28, 29, 37	2, 32, 10	28, 33, 29, 32	2, 29, 18, 36	32, 23, 2	25, 10, 35	10, 28, 32	28, 19, 34, 36	3, 35	32, 30, 40	30, 18	3, 27	3, 27, 40		19, 26	3, 32	32, 2		32, 2	13, 32, 2	35, 31, 10, 24		32, 26, 28, 18	32, 30	11, 32, 1		+	26, 28, 10, 36	4, 17, 34, 26		1, 32, 35, 23	25, 10		26, 2, 18		26, 28, 18, 23	10, 18, 32, 39
30	Object-affected harmful factors	22, 21, 27, 39	2, 22, 13, 24	17, 1, 39, 4	1, 18	22, 1, 33, 28	27, 2, 39, 35	22, 23, 37, 35	34, 39, 19, 27	21, 22, 35, 28	13, 35, 39, 18	22, 2, 37	22, 1, 3, 35	35, 24, 30, 18	18, 35, 37, 1	22, 15, 33, 28	17, 1, 40, 33	22, 33, 35, 2	1, 19, 32, 13	1, 24, 6, 27	10, 2, 22, 37	19, 22, 31, 2	21, 22, 35, 2	33, 22, 19, 40	22, 10, 2	35, 18, 34	35, 33, 29, 31	27, 24, 2, 40	28, 33, 23, 26	26, 28, 10, 18	+		24, 35, 2	2, 25, 28, 39	35, 10, 2	35, 11, 22, 31	22, 19, 29, 40	22, 19, 29, 40	33, 3, 34	22, 35, 13, 24
31	Object-generated harmful factors	19, 22, 15, 39	35, 22, 1, 39	17, 15, 16, 22		17, 2, 18, 39	22, 1, 40	17, 2, 40	30, 18, 35, 4	35, 28, 3, 23	35, 28, 1, 40	2, 33, 27, 18	35, 1	35, 40, 27, 39	15, 35, 22, 2	15, 22, 33, 31	21, 39, 16, 22	22, 35, 2, 24	19, 24, 39, 32	2, 35, 6	19, 22, 18	2, 35, 18	21, 35, 2, 22	10, 1, 34	10, 21, 29	1, 22	3, 24, 39, 1	24, 2, 40, 39	3, 33, 26	4, 17, 34, 26		+					19, 1, 31	2, 21, 27, 1	2	22, 35, 18, 39
32	Ease of manufacture	28, 29, 15, 16	1, 27, 36, 13	1, 29, 13, 17	15, 17, 27	13, 1, 26, 12	16, 40	13, 29, 1, 40	35	35, 13, 8, 1	35, 12	35, 19, 1, 37	1, 28, 13, 27	11, 13, 1	1, 3, 10, 32	27, 1, 4	35, 16	27, 26, 18	28, 24, 27, 1	28, 26, 27, 1	1, 4	27, 1, 12, 24	19, 35	15, 34, 33	32, 24, 18, 16	35, 28, 34, 4	35, 23, 1, 24		1, 35, 12, 18		24, 2		+	2, 5, 13, 16	35, 1, 11, 9	2, 13, 15	27, 26, 1	6, 28, 11, 1	8, 28, 1	35, 1, 10, 28
33	Ease of operation	25, 2, 13, 15	6, 13, 1, 25	1, 17, 13, 12		1, 17, 13, 16	18, 16, 15, 39	1, 16, 35, 15	4, 18, 39, 31	18, 13, 34	28, 13 35	2, 32, 12	15, 34, 29, 28	32, 35, 30	32, 40, 3, 28	29, 3, 8, 25	1, 16, 25	26, 27, 13	13, 17, 1, 24	1, 13, 24		35, 34, 2, 10	2, 19, 13	28, 32, 2, 24	4, 10, 27, 22	4, 28, 10, 34	12, 35	17, 27, 8, 40	25, 13, 2, 34	1, 32, 35, 23	2, 25, 28, 39		2, 5, 12	+	12, 26, 1, 32	15, 34, 1, 16	32, 26, 12, 17		1, 34, 12, 3	15, 1, 28
34	Ease of repair	2, 27 35, 11	2, 27, 35, 11	1, 28, 10, 25	3, 18, 31	15, 13, 32	16, 25	25, 2, 35, 11	1	34, 9	1, 11, 10	13	1, 13, 2, 4	2, 35	11, 1, 2, 9	11, 29, 28, 27	1	4, 10	15, 1, 13	15, 1, 28, 16		15, 10, 32, 2	15, 1, 32, 19	2, 35, 34, 27		32, 1, 10, 25	2, 28, 10, 25	11, 10, 1, 16	10, 2, 13	25, 10	35, 10, 2, 16		1, 35, 11, 10	1, 12, 26, 15	+	7, 1, 4, 16	35, 1, 13, 11		34, 35, 7, 13	1, 32, 10
35	Adaptability or versatility	1, 6, 15, 8	19, 15, 29, 16	35, 1, 29, 2	1, 35, 16	35, 30, 29, 7	15, 16	15, 35, 29		35, 10, 14	15, 17, 20	35, 16	15, 37, 1, 8	35, 30, 14	35, 3, 32, 6	13, 1, 35	2, 16	27, 2, 3, 35	6, 22, 26, 1	19, 35, 29, 13		19, 1, 29	18, 15, 1	15, 10, 2, 13		35, 28	3, 35, 15	35, 13, 8, 24	35, 5, 1, 10		35, 11, 32, 31		1, 13, 31	15, 34, 1, 16	1, 16, 7, 4	+	15, 29, 37, 28	1	27, 34, 35	35, 28, 6, 37
36	Device complexity	26, 30, 34, 36	2, 26, 35, 39	1, 19, 26, 24	26	14, 1, 13, 16	6, 36	34, 26, 6	1, 16	34, 10, 28	26, 16	19, 1, 35	29, 13, 28, 15	2, 22, 17, 19	2, 13, 28	10, 4, 28, 15		2, 17, 13	24, 17, 13	27, 2, 29, 28		20, 19, 30, 34	10, 35, 13, 2	35, 10, 28, 29		6, 29	13, 3, 27, 10	13, 35, 1	2, 26, 10, 34	26, 24, 32	22, 19, 29, 40	19, 1	27, 26, 1, 13	27, 9, 26, 24	1, 13	29, 15, 28, 37	+	15, 10, 37, 28	15, 1, 24	12, 17, 28
37	Difficulty of detecting and measuring	27, 26, 28, 13	6, 13, 28, 1	16, 17, 26, 24	26	2, 13, 18, 17	2, 39, 30, 16	29, 1, 4, 16	2, 18, 26, 31	3, 4, 16, 35	30, 28, 40, 19	35, 36, 37, 32	27, 13, 1, 39	11, 22, 39, 30	27, 3, 15, 28	19, 29, 39, 25	25, 34, 6, 35	3, 27, 35, 16	2, 24, 26	35, 38	19, 35, 16	18, 1, 16, 10	35, 3, 15, 19	1, 18, 10, 24	35, 33, 27, 22	18, 28, 32, 9	3, 27, 29, 18	27, 40, 28, 8	26, 24, 32, 28		22, 19, 29, 28	2, 21	5, 28, 11, 29	2, 5	12, 26	1, 15	15, 10, 37, 28	+	34, 21	35, 18
38	Extent of automation	28, 26, 18, 35	28, 26, 35, 10	14, 13, 17, 28	23	17, 14, 13		35, 13, 16		28, 10	2, 35	13, 35	15, 32, 1, 13	18, 1	25, 13	6, 9		26, 2, 19	8, 32, 19	2, 32, 13		28, 2, 27	23, 28	35, 10, 18, 5	35, 33	24, 28, 35, 30	35, 13	11, 27, 32	28, 26, 10, 34	28, 26, 18, 23	2, 33	2	1, 26, 13	1, 12, 34, 3	1, 35, 13	27, 4, 1, 35	15, 24, 10	34, 27, 25	+	5, 12, 35, 26
39	Productivity	35, 26, 24, 37	28, 27, 15, 3	18, 4, 28, 38	30, 7, 14, 26	10, 26, 34, 31	10, 35, 17, 7	2, 6, 34, 10	35, 37, 10, 2		28, 15, 10, 36	10, 37, 14	14, 10, 34, 40	35, 3, 22, 39	29, 28, 10, 18	35, 10, 2, 18	20, 10, 16, 38	35, 21, 28, 10	26, 17, 19, 1	35, 10, 38, 19	1	35, 20, 10	28, 10, 29, 35	28, 10, 35, 23	13, 15, 23		35, 38	1, 35, 10, 38	1, 10, 34, 28	18, 10, 32, 1	22, 35, 13, 24	35, 22, 18, 39	35, 28, 2, 24	1, 28, 7, 10	1, 32, 10, 25	1, 35, 28, 37	12, 17, 28, 24	35, 18, 27, 2	5, 12, 35, 26	+

Table A.7:40 Principles with Brief Descriptions – Part A

1. Segmentation	**15. Dynamics**	**27. Cheap short-living objects**
Divide an object into independent parts.	Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.	Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).
Make an object easy to disassemble.	Divide an object into parts capable of movement relative to each other.	**28 Mechanics substitution**
Increase the degree of fragmentation or segmentation.	If an object (or process) is rigid or inflexible, make it movable or adaptive.	Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.
2. Taking out	**16. Partial or excessive actions**	Use electric, magnetic and electromagnetic fields to interact with the object.
Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object.	achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.	Change from static to movable fields, from unstructured fields to those having structure.
3. Local quality	**17. Another dimension**	activated (e.g. ferromagnetic) particles.
Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.	To move an object in two- or three-dimensional space.	**29. Pneumatics and hydraulics**
Make each part of an object function in conditions most suitable for its operation.	Use a multi-story arrangement of objects instead of a single-story arrangement.	Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).
Make each part of an object fulfill a different and useful function.	Tilt or re-orient the object, lay it on its side.	**30. Flexible shells and thin films**
4. Asymmetry	Use 'another side' of a given area.	Use flexible shells and thin films instead of three dimensional structures
Change the shape of an object from symmetrical to asymmetrical.	**18. Mechanical vibration**	Isolate the object from the external environment using flexible shells and thin films.
If an object is asymmetrical, increase its degree of asymmetry.	Cause an object to oscillate or vibrate.	**31. Porous materials**
5. Merging	Increase its frequency (even up to the ultrasonic).	Make an object porous or add porous elements (inserts, coatings, etc.).
Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations.	Use an object's resonant frequency.	If an object is already porous, use the pores to introduce a useful substance or function.
Make operations contiguous or parallel; bring them together in time.	Use piezoelectric vibrators instead of mechanical ones.	**32. Color changes**
6. Universality	Use combined ultrasonic and electromagnetic field oscillations.	Change the color of an object or its external environment.
Make a part or object perform multiple functions; eliminate the need for other parts.	**19. Periodic action**	Change the transparency of an object or its external environment.
7. Nested doll	Instead of continuous action, use periodic or pulsating actions.	**33. Homogeneity**
Place one object inside another; place each object, in turn, inside the other.	If an action is already periodic, change the periodic magnitude or frequency.	Make objects interacting with a given object of the same material (or material with identical properties).
Make one part pass through a cavity in the other.	Use pauses between impulses to perform a different action.	

Table A.7-Table A.9 are tabulated explanations of the 40 principles in Table A.6

Table A.8: 40 Principles with Brief Descriptions – Part B

8. Anti-weight	**20. Continuity of useful action**	**34. Discarding and recovering**
To compensate for the weight of an object, merge it with other objects that provide lift.	Carry on work continuously; make all prts of an object work at full load, all the time.	Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.
To compensate for the weight of an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).	Eliminate all idle or intermittent actions or work.	Conversely, restore consumable parts of an object directly in operation.
9. Preliminary anti-action	**21. Skipping**	**35. Parameter changes**
If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.	Conduct a process , or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.	Change an object's physical state (e.g. to a gas, liquid, or solid.)
Create beforehand stresses in an object that will oppose known undesirable working stresses later on.	**22. *Blessing in disguise* or *Turn Lemons into Lemonade***	Change the concentration or consistency.
10. Preliminary action	Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.	Change the degree of flexibility.
Perform, before it is needed, the required change of an object (either fully or partially).	Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.	Change the temperature.
Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.	Amplify a harmful factor to such a degree that it is no longer harmful.	**36. Phase transitions**
11. Beforehand cushioning	**23. Feedback**	Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).
Prepare emergency means beforehand to compensate for the relatively low reliability of an object.	Introduce feedback (referring back, cross-checking) to improve a process or action.	**37. Thermal expansion**
12. Equipotentiality	If feedback is already used, change its magnitude or influence.	Use thermal expansion (or contraction) of materials.
In a potential field, limit position changes (e.g. change operating conditions to eliminate the need to raise or lower objects in a gravity field).	**24. 'Intermediary'**	If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.
13. The other way round	Use an intermediary carrier article or intermediary process.	**38. Strong oxidants**
Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).	Merge one object temporarily with another (which can be easily removed).	Replace common air with oxygen-enriched air.
Make movable parts (or the external environment) fixed, and fixed parts movable.	**25. Self-service**	Replace enriched air with pure oxygen.
Turn the object (or process) 'upside down'.	Make an object serve itself by performing auxiliary helpful functions	Expose air or oxygen to ionizing radiation.
14. Spheroidality - Curvature	Use waste resources, energy, or substances.	Use ionized oxygen.
Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.	**26. Copying**	Replace ozonized (or ionized) oxygen with ozone.
Use rollers, balls, spirals, domes.	Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.	**39. Inert atmosphere**
Go from linear to rotary motion, use centrifugal forces.	Replace an object, or process with optical copies.	Replace a normal environment with an inert one.
40. Composite materials	If visible optical copies are already used, move to infrared or ultraviolet copies.	Add neutral parts, or inert additives to an object.
Change from uniform to composite (multiple) materials.		

Table A.9: 40 Principles with Multiple Examples

Principle	Explanation (& Simple Example)	Chemical Engineering Examples	Chemistry Examples	Business Examples	Other Examples
Compensate or Prepare For					
Asymmetry	Change from symmetrical to asymmetrical (flatten edge of parts so only can be installed one way)	Asymmetrical mixing vessels or vanes in symmetrical vessels improve mixing; lobe pumps	Chiral centers; stereoisomers; surfactants	Market segmentation--use different marketing approach for each class of clients	Spout added to circular opening on viscous liquid pouring bottles; cam
Counterweight	Compensate for an object's weight by joining with another object that has a lifting force	Use tanks above ground to provide suction head for pumps; vacuum jet	Add impurity to reduce melting point; add a counter-ion	Companies increase flagging sales by making connections with rising products; bundle services with product offfers	Boat with hydrofoils; helium dirigible
Prior Counteraction	Understand what will go wrong in the future to compensate for it	Buffer a solution to prevent harm from extremes of pH; add an inhibitor to prevent undesired polymerization	Drying of solvents for use in water-sensitive reactions; use of protecting groups in organic synthesis	Announce new products or contracts when announcing a profit shortfall; prior to lay-off, prepare compensation, outplacement, etc.	Genetically modified food benefits some properties
Prior Action	Take action beforehand to ease an event	Pre-pasted wall paper; pre-loading of tanks for batch operations	Add UV stabilizers to prevent sun damage; addition of seed crystals to control crystallization	Project pre-planning; publish an agenda before meetings	Pre-cooked meat; de-seeded fruit
Cushion in Advance	Prepare emergency means beforehand to compensate for the low reliability of an object (car airbag)	Pre-load cooling elements; pH buffers	Bursting discs on pumps; explosion prevention system	Run anti-virus software often; back up computer data	Saucer to catch spill from cup; crumple zone in car
Change Appearance, Structure, Composition, Condition					
Optimal Resource	Make each part of an object fulfill a different and useful function. Change structure from uniform to non-uniform	Vary internal design of distillation column to reflect varying flows and fluid characteristics; piping system transports and mixes	Surfactants--hydrophobic and hydrophilic; directing groups--change reactivity of different sites	Organizational division by function rather than product; working hours phased to accommodate people working on international, shifted time-zone projects	Pencil and eraser as one; hammer with nail puller
Equipotentiality	Change condition of work so object does not need to be raised or lowered	Locks in a channel between 2 bodies of water; tank car design features that limit movement upon impact or shock	Catalysts and enzymes; activating groups	Make "horizontal" career changes to broaden skills	Spring-loaded parts delivery system in a factory
Spheroidality	Replace linear with a curve or a sphere (roll of tape)	Curvilinear surfaces to increase resistance to pressure; centrifuge vs. gravity settler	Non-linear gradient for solvent mix in high-performance liquid chromatography	"meals on wheel's"; quality circles	Pringles--aesthetically pleasing potato chips
Dynamicity	Make characteristics of an object adjust for optimal performance at each stage of operation (movable flaps on airplane wings to expand surface area)	Adjustable settings on distillation columns, reactors, temperature control; a variable-speed pump	pH and redox buffers; remove aromaticity to make molecule more flexible	Customer response teams; flexible organization structure	Flexible drinking straws
Transition into a New Dimension	Go upwards, sideways, around corners, rotate object, change viewpoint	Five-axis cutting tool can be positioned where needed; orientation of process equipment to allow access for better mixing and rotation	Cross-linking polymers; branched rather than linear hydrocarbons	360 degree appraisals; multi-dimensional organization hierarchy charts	Electronic chips on both sides of a printed circuit board; dump truck at an angle
Replacement of Mechanical System	Replace a mechanical system with a field, e.g., magnetic, electrical, thermal. (magnetically levitated train)	Replace physical fence to monitor intrusion with optical and acoustic mechanism; to mix two powders, electo-statically charge one positive and one negative	Microwave reactions; sonochemistry	Electronic voting; setting up meeting requests and appointments via Outlook	Use bad smelling compound in natural gas rather than an instrument to alert users of a leak
Pneumatic or Hydraulic Construction	Replace solid parts of an object with a gas or liquid (hovercraft)	Pneumatic based process control systems; pneumatic conveying, dense and dilute	Use hydraulics for power when using flammable solvents; filter press	Flexible organization structure vs. fixed hierarchical structures; liquidation of assets	Comfortable shoe sole inserts filled with gel
Flexible Membranes or Thin Films	Use flexible shells or thin films instead of three dimensional structures	Gas separation membranes; plate and frame exchangers	Paints and inks; surface treatments	Single point of contact account management; business-technology manager	Use thin film structures as winter covers on tennis courts
Porous Material	Make an object porous (drain holes in flower pot)	Drill holes in a structure to reduce weight; store hydrogen in the pores of a palladium sponge	Filtration, zeolites, osmosis	Intranet; matrix management	Gortex, pores are small enough to let vapor through but not liquid; speaker covers
Changing the Color	Change the color of an object Liquid Crystal thermometer	Use color-sensitive labeling on temperature-sensitive foods; use color change to indicate a sign of reaction completion	Titration indicators; carbonless copying	Highlighter pens; use colors to communicate state of alert	Transparent bandage enabling a wound to be inspected without the dressing being removed
Transformation of Properties	Change the properties of an object to accommodate a useful benefit	Transport gas as liquid to reduce volume; liquid soap is concentrated and more viscous than bar soap	Precipitation; sublimation	Webcast vs. live presentation; team vs. hierarchy	Freeze the liquid centers of filled candies, then dip in melted chocolate, instead of handling messy liquid
Phase Transition	Change phases (melt metal to cast in a mold to form a shape)	Use of phase changes in materials to absorb heat or control its rate of release; use expansion and contraction properties of freezing	Alpha to beta copper phthalocyanine; allotropes of sulphur	Requirements of different stages … conception, birth, development … of a project	Heat pumps use the heat of vaporization and heat of condensation of a closed thermodynamic cycle to do useful work
Thermal Expansion	Use expansion or contraction of material by heat (mercury/alcohol thermometer)	Fit a tight joint together by cooling inner part and heating the outer part; bi-metallic instrumentation construction	Explosives; boiling	A fired-up individual will do the work of three who aren't; empowerment	Through-bars help straighten buckling walls in old buildings
Accelerated Oxidation	Make a transition from one level of oxidation to the next higher level	Accelerate waste oxidation reactions with enriched air, ozone; reduce NOx formation in combustion with enriched air	Bleaches; oxidizing agents; passivate a surface	Guest speakers at seminars; use case studies in training	To obtain more heat from a torch, oxygen is fed to the torch instead of atmospheric air
Inert Environment	Replace a normal environment with an inert one. Carry out process in a vacuum. (light bulb)	Use of argon when nitrogen may react with certain products at high temperature; add inert fillers to products to increase bulk or to improve functionality	Nitrogen blanket; vacuum	Time-out during negotiations; corporate retreats; task forces outside of normal offices	Cotton is treated with inert gas during transport so it won't catch fire in a warehouse
Composite Materials	Change from uniform to composite materials (steel-reinforced concrete)	Use of multi-layer polymers for barrier protection; use of composites for superior product performance in chemical tanks and golf clubs	Surfactants; alloys	Do training with a combination of lecture, simulations, on-line learning, videos; mix of thinking skills in a project team	Military aircraft wings are made of composites of plastics and carbon fibers for high strength and low weight
Do the Opposite, Different, or Take to Extreme					
Do it in Reverse	Do it the other way around, invert the action used to solve the problem	Reverse osmosis; vacuum vs. pressure swing adsorption	Back titrations; reverse chromatography to measure surface properties	Benchmark against worst instead of the best; expansion instead of contraction during recession	To loosen stuck parts, cool the inner part instead of heating the outer part
Partial or Excessive Action	--Achieve most of an effect with a lot less action (80/20 rule) --When a full effect is difficult, drive to completion by using excessive action (plant multiple seeds)	Reach 100% conversion or yield through the use of excess of reactants; over spray when painting, then remove excess	Add excess of reactant to push an equilibrium in the desired direction; take reaction to 90% instead of 100% to save batch time	Going into a new market, advertise by means of all media types; communicate more often and with more information than you think necessary	Pre-perforated packages are easy to open; Don't "top off" when filling the gas tank of your car
Periodic Action	Instead of continuous action, use periodic or pulsating actions (anti-lock brakes pulse to avoid locking)	Batch vs. continuous reaction processes; reciprocal pumps and compressors vs. centrifugal devices	Shaking vs. stirring	Get work done between meetings; change team leadership periodically	Facilitate removal of ketchup from bottle by tapping or shaking; alternating current
Continuity of Useful Action	Carry out actions without a break	Flywheel stores energy when a vehicle stops so the motor can keep running; run the bottleneck operations in a factory continuously	Continuous vs. batch production; react and distill final product in same apparatus	Institute continuous improvement; conduct training during pauses in work	Make heating/cooking times for desserts consistent with eating/digesting times for main course
Rushing Through	Do things at a high speed to reduce time for problems to occur	Cut plastic faster than heat can propagate in the material; minimize reaction times under hazardous conditions	Kinetically-controlled reactions	Fail fast, learn fast; rapid prototyping	Flash freezing to retain freshness
Convert Harm into Benefit	Use harmful factors to achieve a positive effect (vaccines)	Recycle waste material from one process as raw material for another; combine acidic waste from one facility with basic waste from another to neutralize	Recover and use by-products of a reaction; use waste heat to pre-heat reactants	Develop a market for a byproduct; eliminate fear of change by introducing fear of competition	Tenderizing meats; slash and burn farming; Surgery
Copying	Instead of using expensive and fragile objects, use a simple and cheap copy (crash test dummy)	Use moldings to shape plastic parts; measure an object by measuring the photograph	Molecular modeling; templating	Listen to audiotape instead of attending a seminar; have customers and suppliers benchmark you	The height of tall objects can be determined by measuring their shadows
Dispose	Replace expensive objects with multiple cheap ones (paper cups)	Use building models to train operators; run pilot processes	Disposable pipettes; use excess of less reactive but cheaper raw material	Flight simulator reduces pilot training costs; hire contractors for peak loads	Disposable diapers
Make the Same, Use Together, Combine					
Merging	Bring closer together similar objects or operations in space	Automated tank and blending systems; vanes in a ventilation system	Nitrocellulose--fuel and oxidant in the same molecule; one pot reactions	Merge companies with related products; personal computers in a network	Multi-vitamin tablets
Universality	Use same object for multiple purposes (airplane seat flotation device)	Reactive distillation column; an eduction system that mixes and pumps	Monomer used as solvent and reactant in UV inks; urea used as solvent and source of nitrogen in copper phthalocyanine synthesis	Team leader acts as recorder and timekeeper; mulit-skilling of work-force	Thermo-chromic beer bottle label that changes color when beer is cold enough
Nesting	Putting one thing inside another (extendable car antenna)	Encapsulated, time release formulations; nested control loops in control systems	Encapsulation; inclusion compounds	Store-in-store; incubators for new businesses	Pez sweet dispensers; Plug for ac to dc converter, hole inside of pin
Feedback	Return a system output back into the system as an input	Intermediate measurements are used to decide when to modify process; proportional, integral, an derivative control	Thin layer chromatography to monitor reaction progress; pH controlled pump	Enlist customers in the design process; electronic bulletin boards	Signal from gyrocompass is used to control simple aircraft autopilots
Self-service	Make an object serve or organize itself by performing auxiliary helpful functions	Use heat from a process to generate electricity; use heat off condenser to pre-heat feed into the column	Photochromic glass	Self-help groups; quality circles	Halogen lamps regenerate the filament during use--evaporated material is redeposited
Homogeneity	If two objects interact with each other, they should consist of the same material (metal bearings)	Use mutual solubility to enhance homogeneous catalysis; make a diamond cutting tool out of diamonds	Phase transfer reactions; comb copolymers; aluminum oxide passivation	Internal customers; co-located project teams	Make the container out of the same material as the contents, to reduce chemical reactions
Separate From, Remove, Disturb					
Segmentation	Separate into smaller parts or divide into independent parts (Lego)	Baffles in tanks and reactors; independent unit operations	Mass spectrometry; synergist/hyperdispersant	Divide an organization into different product centers; use a work breakdown structure for a large project	Sectional furniture; TV dinners
Extraction	Remove or separate interfering parts (clean room); Wisdom teeth removal	Locate a noisy compressor outside the building where compressed air is used; use fiber optics to separate hot light source from where light is needed	Chromatography; fractional distillation	Break down barriers between departments; transfer problem people	Low fat products; NutraSweet (sweet w/o calories)
Mechanical Vibration	Shaking, vibrating, sound waves, ultrasound	Distribute powder with vibrations; ultrasonic flow measuring systems	IR spectroscopy; sonochemistry	Communicate frequently in multiple modes; consultant	Electric knife with vibrating blades; "shake before opening"
Mediator	Use an intermediary object to transfer or carry out an action (car tire chains for traction)	Heat transfer solution; extraction	Phase transfer catalyst; dispersant on pigment	Use of impartial body during difficult negotiation; specialist for trouble-shooting	Pot holder to carry hot dishes
Rejecting and Regenerating Parts	When a part is used and no longer needed, throw it away, restore it, or recycle it (aluminum cans)	Use a dissolving capsule for medicine; auto-catalytic reactions	Ammonia recovery; silica gel for drying	Rotational jobs; internal consultants	Bullet casings are ejected after the gun fires

Table A.10: Messer Function Based Phenomena Catalog Augmented with TRIZ Phenomenon

Output / Input	Mechanical Energy		Pneumatical-/Hydraulical Energy		Electrostatic Energy		Magnetostatic Energy		Sound Energy		Light Energy		Thermal Energy		Chemical/Biological/Nuclear Energy (Nuclear-/reaction-/oxidation-energy)	
Mechanical Energy (Potential-/kinetic-/strain-energy)	- Inertia (translational/rotational) - Elastic/inelastic deformation (tension/compression/bending/shear/torsion/buckling/fracture/cutting/inversion/extrusion/drawing/flow) - Impact (translational/rotational) - Friction (static/dynamic) - Refraction (waves/particles) - Lever-effect (translational/rotational) - Poisson's-effect (positive/negative) - Stress-induced Martensitic transformation - Force field (gravity/surface-tension/contact-force/atomic-force) - Wedge-effect - Boyle-Mariotte-law - Magnus-effect - Lotus-effect - Resonance - Co-/Adhesion - Capillary-effect - Weissenberg-effect - Load spreading (fixed/flexible constraints or unconstrained) - Blocking and bracing - Topology	6. - Mechanical oscillations - Centrifugal forces 7. - Wave movement - Capillary force - Centrifugal forces - Weissenberg effect 11. - Reactive Force 12. - Centrifugal forces - Effect of a magnetic field via ferromagnetic substance 14. - Cavitation - Resonance 15. - Elastic deformation - Gyroscope 16. - Deformations - Oscillations - Waves, including shock waves 19. - Deformations 21. - Friction - Mechanical oscillations 23. - Deformation 24. - Interference waves - Standing waves - Mechanical oscillations 27. - Tunnel effect	- Bernoulli-principle - Viscosity - Toricelli's law - Gravitation - Boyle-Mariotte-law - Impact - Buoyancy - (In)compressibility	7. - Bernoulli's effect	- Electrostriction - Induction - Electrokinetic-effects - Electrodynamic-effects - Friction - Capacitance-effect - Josephson-effect - Deformation electrical resistance - Impact-ionization - Stewart-Tolman-effect - Lenard-effect	16. - Electromagnetic induction 19. - Electrostriction (Piezoelectrical effect) 25. - Electrostriction (Piezoelectrical effect) 27. - Josephson effect	- Magnetostriction - Induction - Aligning magnetical dipoles - Elastic/inelastic deformation - Barnett-effect	16. - Electromagnetic induction 19. - Magnetostriction	- Impact - Stick-slip-effect - Doppler-effect	5. - Doppler effect 14. - Ultrasonics 21. - Acoustical oscillations 24. - Acoustical oscillations	- Mechanochromics - Dichroic-effect - Mechanolumin-(fluor-, phosphor-)escence - Doppler-effect	5. - Doppler effect	- Pressure state change - Friction - Hysteresis - Turbulence - Inelastic deformation - Joule-Thomson-effect - Doppler-effect - Conduction - Convection - Radiation	2. - Joule-Thomson effect 3. - Vortical currents 5. - Doppler effect	- Residual stress - Phase transformations	15. - Phase Transition
Pneumatical-/Hydraulical Energy (Potential-/kinetic-/pneumatic/hydraulic-energy)	- Lift - Buoyancy - Turbulence - Magnus-effect - Flow resistance - Backpressure - Reaction principle - Compressibility	6. - Pressure transfer in liquid or gas 12. - Generating high pressure	- Bernoulli-principle - Continuity-law - Conduction - Absorption - Dalton's-law - Lotus-effect - Von Kármán vortex street	7. - Bernoulli's effect	- Electrostriction		- Magnetostriction	19. - Magnetostriction	- Impact		- Friction - Mechanochromics		- Pressure state change - Friction - Inelastic deformation - Joule-Thomson-effect	2. - Joule-Thomson effect	- Residual stress - Phase transformations	15. - Phase Transition
Electrostatic Energy (Capacitive-energy)	- Electrostriction (piezoelectric materials, electroactive polymers) - Capacitance effect - Coulomb's-law - Johnson-Rhabeck-effect - Biot-Savart-law - Electrokinetic-effects - Friction - Induction	6. - Applying elecrical field to influence charged object. 7. - Capillary force 8. - Applying electrical fields 11. - Applying electrical fields - Fixing in liquids which harden in magnetic and electrical fields 12. - Electrohydraulic effect 13. - Johnson-Rhabeck effect 14. - Electrical discharges - Electrohydraulic effect 16. - Electromagnetic induction 17. - Applying electrical fields (no-contact influence instead of physical contact) 19. - Electrostriction (Piezoelectrical effect)	- Electrostriction - Electrorheology - Electrophoresis - Cataphoresis - Electro-osmosis	9. - Electrophoresis 25. - Electro-osmosis	- Interference - (Super-/Semi-) Conduction - Ohm's-law - Faraday's-law - Impedance - Capacitance-effect - Skin-effect - Quantum tunneling	16. - Superconductivity 25. - Electrical discharges - Electronic emissions 28. - Screening/Faraday Cage	- Eddy current - Biot-Savart-law - Faraday's-law - Hall-effect - Meissner-effect	3. - Eddy currents 28. - Screening/Faraday Cage 29. - Faraday effect	- Electrostriction		- Photostriction - Kerr-effect - Pockels-effect - Stark-effect - Electrolumin-(fluor-, phosphor-)escence - Electrochromism - Liquid-crystal/sus-pended-particle effect - Incandescence - Laser-effect	27. - Luminescence - Gunn effect 29. - Electrical optical phenomena - Gunn effect - Kerr effect	- Joule-heating - Eddy current - Electric arc - Peltier-effect - Hysteresis	2. - Peltier, Seebeck, and Thomson effects - Thermoelectrical Phenomena 3. - Electromagnetic induction - Eddy Currents - Dielectrical Heating - Electronic Heating - Electrical Charges - Peltier and Thomson effects	- Electrochemistry - X-Ray-effect - Electrodialysis - Electrolysis	8. - Electrolysis
Magnetostatic Energy (Inductive-energy)	- Magnetostriction - Ferro-/electro-magnetism - Christoffos-effect - Induction (Lorentz-effect) - Elihu-Thomson effect - Einstein-de-Haas-effect	6. - Applying magnetic field to influence an object or magnet linked to object. - Applying magnetic field to influence a conductor with DC current going through 8. - Applying magnetic fields 11. - Applying magnetic fields 16. - Electromagnetic induction 17. - Applying magnetic fields (no-contact influence instead of physical contact) 19. - Magnetostriction 22. - Magneto-elastic effect 24. - Magnetic waves	- Magnetostriction - Magnetorheology	19. - Magnetostriction	- Faraday's-law - Hall-effect - Induction (Lorentz force) - Magnetoresistivity	16. - Electromagnetic induction 22. - Hall effect 25. - Hall effect - Gyromagnetic phenomena 28. - Screening/Faraday Cage 29. - Faraday effect	- Interference - (Super-/Semi-) Conduction - Reflection - Total reflection - Refraction - Absorption - Induction - Faraday's-law - Ferromagnetism - Saturation - Remanence	12. - Effect of a magnetic field via ferromagnetic substance 16. - Electromagnetic induction	- Magnetostriction - Barkhausen-effect	1. - Barkhausen effect 19. - Magnetostriction 22. - Barkhausen effect 25. - Barkhausen effect	- Faraday-effect - Zeemann-effect - Cotton-Mouton-effect - Magnetolumin-(fluor-, phosphor-)escence	23. - Magnetic-optical effects 29. - Magnetic-optical effects - Faraday effect	- Eddy current - Hysteresis - Demagnetization - Thermal Hall-effect (Righi effect)	2. - Magnetic calorie effect	- Ferromagnetism - Electromagnetism	
Sound Energy (Kinetic-energy)	- Sound excitation	14. - Resonance - Ultrasonics 21. - Acoustical oscillations 24. - Acoustical oscillations 30. - Ultrasonics	- Sound pressure		- Electrostriction		- Magnetostriction		- Reflection - Refraction - Interference - Dispersion - Birefringence - Polarization		- Acousto-optic effect		- Eddy current - Hysteresis - Demagnetization - Thermal Hall-effect (Righi effect)		- Elastic deformation	30. - Ultrasonics
Light Energy (Quantum-energy)	- Photostriction - Electromagnetical radiation pressure	6. - Pressure of light	- Electromagnetical radiation pressure	8. - Pressure of light	- Photostriction		- Photostriction		- Acousto-optic effect		- Reflection - Refraction - Birefringence - Interference - (Super-/Semi-) Conduction - Photonic crystal effect - Fluor-/phosphor-escence - Phosphorescence - Fermat's principles - Polarization - Photolumin-(fluor-, phosphor-)escence (Photochromics)	16. - Radiation - Lasers - Fiber optics - Light reflection 21. - Ultraviolet radiation 29. - Refraction and reflection of light	- Thermolumin-(fluor-, phosphor-)escence - Radiation	14. - Use of lasers	- Photoeffect - Photoresistor-effect - Photochemical-effect	
Thermal Energy (Heat-capacity/-enthalpy)	- Temperature change of state - Thermal expansion - Steam pressure - Osmotic pressure - Gas laws - Heat-induced martensitic transformations	1. - Thermal expansion and its influence on natural frequency of oscillations 6. - Thermal expansion 7. - Osmosis 12. - Thermal expansion 19. - Thermal expansion	- Temperature change of state - Thermal expansion - Steam pressure - Osmotic pressure - Gas laws - Thermophoresis (Soret-effect)	1. - Thermal expansion and its influence on natural frequency of oscillations 6. - Thermal expansion 7. - Osmosis 12. - Thermal expansion 19. - Thermal expansion	- Thermoelectric-effect - Thermionic emission - Pyroelectricity - Thermal-noise-effect - Conductivity - Semiconductivity - Superconductivity - Curie-Weiss-law	1. - Thermoelectrical Phenomena 16. - Superconductivity 23. - Thermoelectrical effects	- Curie-Weiss-law	23. - Thermomagnetic effects	- Thermo-optic effect		- Pyroelectricity - Thermolumin-(fluor-, phosphor-)escence - Thermocromics		- Conduction - Convection - Radiation - Insulation - Condensation - Evaporation - Freezing	3. - Evaporation 16. - Thermal conductivity - Convection	- Heat capacity - Phase transformations - Heat induced martensitic transformations - Thermoelectric effect - Stefan-Boltzmann-law - Wien's displacement-law - Destillation	2. - Phase Transition 4. - Phase Transition
Chemical/ Biological/ Nuclear Energy (Nuclear-/reaction-/oxidation-energy)	- Exothermic reactivity - Osmosis - Molecular-velocity - (De)Sorption - Nuclear fission - Nuclear fusion - Isometric/isotonic contraction - Cell growth	12. - Osmosis	- Exothermic reactivity - Osmosis - Adhesion - Cohesion - Nuclear fission - Nuclear fusion - Chromatography - Effusion - Cell growth	12. - Osmosis	- Electrochemistry - Molecular dipole - Ionization - Fermentation - Bioelectromagnetism - Semiconducting (doping)		- Magnetic-dipole-formation - Bioelectromagnetism		- Exothermic reactivity - Nuclear fission - Nuclear fusion		- Cotton-effect - Combustion - Chemochromics - Chemolumin-(fluor-, phosphor-)escence - Exothermic reactivity - Nuclear fission - Nuclear fusion - Di-/Association	16. - Induced radiation 27. - Cherenkov effect	- Combustion - Conduction - Exothermic reactivity - Nuclear fission - Nuclear fusion	3. - Absorption of radiation by the substance 12. - Use of explosives 14. - Induced radiation	- Photosynthesis - Endo-/exo-thermic reactivity - Nuclear fission - Nuclear fusion - Radiation - Absorption - Oxidation/Reduction - Ionic transport - Bohr-effect - Di-/Association/(Dis-)Solution - Adsorption - Electrodialysis - Autolysis - Catalysis - Phase separation - Meiosis - (Bio-)Sensing (antibody, DNA, receptor, enzyme, abzyme, (living) tissue, cell, organelle, isotopes, microbes) - Self-replication/-repair/-assembly/-diagnostic/-destruction/-replication	14. - Induced radiation 27. - Induced radiation

Table A.10 - Table A.16 Are the tables of the Messer catalog, augmented with TRIZ, referenced in sections: 3.3.2.3, 4.2.2, 5.3.2.3.

Table A.11: Design catalog solution principles associated with (in)elastic deformation with TRIZ augmentations and links

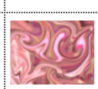
Pheno-menon	Scale	Characteristics				Associated TRIZ 40 Principle(s)		Standard Solution of TP Relation (w/ related Altshuller's Numbers)
		Solution Principle		Properties	Applications	Strong	Weak	
		"Monolithic" materials	From a macroscale, monolithic materials are referred to as matter, i.e., the substance of which physical objects are composed.					
		- Metals		Compared to all other classes of material, metals are stiff, strong and tough, but they are heavy. They have relatively high melting points. Only one metal - gold - is chemically stable as a metal. Metals are ductile, allowing them to be shaped by rolling, forging, drawings and extrusion. They are easy to machine with precision, and they can be joined in many different ways. Iron and nickel are transitional metals involving both metallic and covalent bonds, and tend to be less ductile than other metals. However, metals conduct electricity well, reflect light and are completely opaque. Primary production of metals is energy intensive. Many require at least twice as much energy per unit weight than commodity polymers. But, metals can generally be recycled and the energy required to do so is much less than that requried for primary production. Some are toxic, others are so inert that they can be implanted in the human body.	- Aluminum-, copper-, magnesium-, nickel-, steel-, titanium-, zinc-alloys - Carbon-, stainless-,...steels - Amorphous metals,...	3. Local quality 27. Cheap short-living objects 30. Flexible shells and thin films	4. Asymmetry 6. Universality 14. Spheroidality - Curvature 37. Thermal expansion	
		- Polymers		Polymers feature an immense range of form, color, surface finish, translucency, transparency, toughness and flexibility. Ease of molding allows shapes that in other materials could only be built up by expensive assembly methods. Their excellent workability allows the molding of complex forms, allowing cheap manufacture of integrated components that previously were made by assembling many parts. Many polymers are cheap both to buy and shape. Most resist water, acids and alkalis well, though organic solvents attack some. All are light and many are flexible. Their properties change rapidly with temperature. Even at room temperature many creep and when cooled they may become brittle. Polymers generally are sensitive to UV radiation and to strongly oxidizing environments. They have exceptionally good electrical resistance and dielectric strength as well as low thermal conductivity. - Thermoplastics are quite soft and ductile, can be easily melted and reform into a solid when cooled. This allows them to be molded to complex shapes. As the molecular weight increases, the resin becomes stiffer, tougher, and more resistant to chemicals, but, more difficult to mold. Most accept coloring agents and fillers, an many can be blended to give a wide range of physical, visual and tactile effects. Their sensitivity to sunlight is decreased by adding UV filters and their flammability is decreased by adding flame retardants. - Thermosetting plastics are quite strong, stiff, durable and hard with high temperature resistance and little or no creep. When heated, they do not melt but degrade. Hence, once shaped, thermosetting plastic cannot be reshaped. However, they have greater dimensional stability than thermoplastics, but, can sometimes also be soft and flexible. They cannot be recycled. - Properties of elastomers lie between those of thermoplastics and thermosets. They remember their shape when stretched (some 5 or more times their original length) and return to it when released. They allow conformability and damping. However, they have a low stiffness and can't be remolded or reshaped, or recycled once shaped. - Semicrystalline polymers (folded chain polymers) can be quite dense, chemically resistant and highly heat resistant, allowing many properties to be imparted to them that are not normally associated with polymers (e.g., conductivity).	- Thermoplastic polymers: ABS, Cellulose, Ionomers, Nylon/PA, PC, PEEK, PE, PMMA, POM, PP, PS, PTFE, tpPVC, tpPU, PET/PETE/PBT - Thermosetting polymers: Epoxy, Phenolic, Polyester, tsPU, tsPVC - Elastomers: Acrylic elastomers, NR, Neoprene, EPDM, EVA, Viton, Isoprene, natural rubber, NBR/BUNA-N, Polybutadiene, Polysulphide, Silicone, SBS, TPE/TPO - Conducting polymers, organic light-emitting diodes	3. Local quality 27. Cheap short-living objects. 30. Flexible shells and thin films. 31. Porous materials.	4. Asymmetry 10. Preliminary action. 14. Spheroidality - Curvature. 35. Parameter change.	
		- Ceramics and glasses		Ceramics and glasses are the most durable materials, particularly at high temperatures. They are not good electric conductors, exceptionally hard and brittle. Ceramics and glasses tend to fail along special cleavage planes and possess high resistance to high temperatures and heating. Often, they are used as refractory materials. Their high melting points give them a low expansion coefficient. They have a high thermal conductivity and low impact resistance.	- Alumina, Boron carbide, Silicon carbide, Tungsten carbide, Borosilicate glass, Silica glass, Soda lime glass, tranparent ceramics, sintered corundum, calcium fluorid crystals, piezo-ceramics, electroceramics, semiconductors, ...	3. Local quality	6. Universality 27. Cheap short-living objects	
		- Composite materials		Composites are high-performance materials that are made by combining two or more primary materials, comprising a huge class of materials. Constituent materials have significantly different physical or chemical properties. On the macroscopic level, they remain separate and distinct within the finished structure. In general, there are two constituent phases: matrix and reinforcement/enhancement. At least one portion of each phase is required. The matrix surrounds and supports the reinforcement/enhancement by maintaining relative positions. The reinforcements/enhancement impart their special physical properties to enhance the matrix properties. A synergism produces material properties unavailable from the individual constituent phases.	- Multilayer composites, multiphase composites, multifunctional composites, ...	3. Local quality 6. Universality 40. Composite materials	27. Cheap short-living objects	
		- Fluids		A fluid differs from a solid in that it cannot support a shear stress. In a fluid, shear deformation will continue as long as any shear stress is applied. The constitutive equation for a fluid relates the rate of deformation to the applied stress. A fluid is a subset of the phases of matter and includes liquids, gases, plasmas and, to some extent, plastic solids. Fluids can be characterized as Newtonian fluids, where stress is directly propoortional to the rate of deformation, and Non-Newtonian fluids, where stress is proportional to the rate of deformation, its higher powers and derivatives.	- Newtonian fluids - Non-Newtonian fluids: Kelvin material, anelastic material, rheopectic material, thixotropic material, generalized Newtonian fluids, super-paramgentic liquids, electro, magneto-rheological fluids, ...	3. Local quality 29. Pneumatics & Hydraulics		4.2 - 2.4.3M

Table A.12: Design catalog solution principles associated with (in)elastic deformation with TRIZ augmentations and links (Continued)

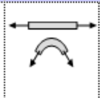
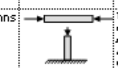
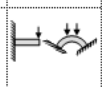
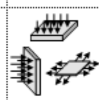
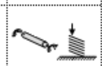
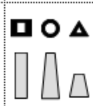
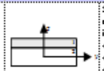
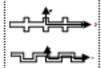
Macroscale	**Fundamental structural elements**	Basic engineering elements on the mocroscale primarily supporting loads are referred to as fundamental structural elements.					
	- Tie, cable, wire or continuous fiber		These structures are capable of carrying tensile loads only. The maximum energy that can be absorbed per unit weight before tensile instability supervenes depends upon the ultimate tensile strength and strain. If tension devices are for example used as simple type of energy absorber, they suffer from the stroke, i.e., maximum displacement, or maximum strength limitation imposed by the ultimate strain or strength of specific material system.	- Single-, coaxial-, multicore-,... cables	1. Segmentation 3. Local quality	24. Intermediary	
	- Struts or columns		These structures are capable of carrying compressive loads only. With respect to buckling and plastic collapse the specific ultimate tensile strength is an excellent indicator of the ability of a material to absorb energy. If struts or columns are for example used as energy absorber, the absorbed energy per unit mass in static tests is minimial because of the limited zone of plastic deformation during buckling.	- Hinged-, fixed-, free-,... columns	1. Segmentation 3. Local quality	17. Another dimension	
	- Beams or archs		Beam and archs (curved beams) are structural elements that carry load primarily in bending (flexure). In general, they are characterized by their profile (the shape of their cross-section), their length, and their material. Beams and archs may for example be used for energy dissiption or blocking and bracing, i.e., locating supports in contact with stronger parts of a structure, so that imparct forces are directed to those parts.	- Cantilever-, simply-supported-, ... beams	1. Segmentation 3. Local quality	14. Spheroidality - Curvature	
	- Plates/panels, shells, membranes or foils		Plates are initially flat structural elements, having thicknesses much smaller than the other dimensions. Whereas shells only bear in-plane loads, plates bear bending moments as well. Membranes are curved shells. Panels are non-horizontal plates. For example, their load spreading effect (i.e., spreading the forces at impact over a large area so that pressure is reduced) has been used in energy dissipation devices.	- Fixed-, simply-supported-,... plates and panels - Multifunctional foils: load bearing, aesthetic, ...	30. Flexible shells and thin films.	14. Spheroidality - Curvature	
	- Shafts or torsion springs		Shafts or torsion springs are structural elements primarlily loaded in torsion. Besides torsion, compression and bending, torsion of bars or tubes, featuring relatively large deceleration strokes, has also been used in energy dissipation devices.	- Torsion-, compression-...spring	15. Dynamics 35. Parameter Changes	11. Beforehand Cushioning 18. Mechanical Vibration	4.2 - 2.2.4
	Structural shape	The external macroscopic outline of structural elements - in contrast to the matter of which it is composed - is referred to structural shape. Governing design variables are dimensions and topologies of structures.					
	- Plain-/open-sections		Many structural elements with specifically shaped plain or open sections are standardized. Also, a number of sepcialist and proprietary sections are readily available. However, shape selection or design is based on the moments of inertia: $I = \int_A x_i^2 \, dA$ or other multifunctional considerations (e.g., heat or fluid flow, etc.).	- Rectangular-, circular-, prismatic-sections - I-, Z-, L-, single/double T, U-, C-,...sections - Extruded sections of various shapes	3. Local quality	4. Asymmetry 14. Spheroidality - Curvature	
	- Tubes and frustra		Structural elements may also be available in a variety of tubes and frustra. For example, from the point of view of energy absorption capacity it was found that circular tubes and frustra under axial compression provide one of the best devices and hence are the most frequently used components in energy dissipating systems. Circular tubes and frustra provide a high stroke length per unit mass and a reasonably constant operating force, which is in some applications a prime characteristic. Structures based on tubes and frustra generaly have relative densities of 0.2 - 0.3. Local quality. However, the collapse load and energy absorbing capacity of single tubular components can be increased by using tensile bracing members. $\varepsilon_D \approx 1 - 2\frac{t}{R_t} = 1 - \rho_{rel}$ - Densification strain open-top tubes: $\frac{\sigma_{pl}}{\sigma_{ys}} \approx 1.26\ \rho_{rel}^{1.5}$ - Relative strength open-top tubes: $\varepsilon_D \approx \frac{2}{3}$ - Densification strain closed-top frustra: $\frac{\sigma}{\sigma_{ys}} \approx 0.35(\rho_{rel}\rho_s)^{-1}$ - Relative strength closed-top frustra:	- Rectangular, circular, prismatic, ... tubes and frustra - Open- and closed-top tubes and frustra	3. Local quality	4. Asymmetry 14. Spheroidality - Curvature	
	- Bodies		Structural elements may also be shaped in three dimensions in a variety of ways. For example, the mechanisms of spherical shell inversion, i.e., material passing into the central dimple region through a circular knuckle whose radius increases with deformation, is somewhat similar to tube inversion in that it is an efficient method of energy absorption.	- Sphere, cube, cylinder, etc.	3. Local quality 14. Spheroidality - Curvature 17. Another dimension	4. Asymmetry	
	Composite structures	Assemblies or combinations of monolithic materials and structures to enhance structural or functional performance on macroscales while maintaining the properties of each component are referred to as composite structures.					
	- Sheet-structures		Sheet-structures are referred to as composite structrues that consist of an additional layer(s) or outer sheating in a material. Examples include multifunctional clad metals or coated materials featuring coatings that can kill germs, be fire-resistant, self-cleaning, anti-fog, determine appearance, etc. Governing design variables are number, dimensions, configuration, topology and material of constituting layers.	- Clad structures: clad metals, coated or painted materials, bimetals, etc.	1. Segmentation 17. Another dimension 40. Composite materials	7. Nested doll 11. Beforehand Cushioning	1.2 - 1.1.7 1.3 - 1.1.8 2.3 - 1.2.4 4.2 - 2.2.2
	- Sandwich-structures		Structural member made up of two stiff, strong skins separated by a lightweight core are known as sandwich panels. The separation of the skins by the core increases the moment of inertia of the panel with little increase in weight. Therefore, sandwich panels may significantly increase structural stiffness for resisting bending. Also, introducing stabilizing core structures resistance against buckling loads is increased. The mechanical behavior of a sandwich thus depends on the properties of the face and core materials and on its geometry. In general, it is a costly process of assembling a sandwich shell by joining precurved face sheets and core.	- (Un)symmetrical three-, multi-, ...layer sandwich panels	1. Segmentation 7. Nested doll 17. Another dimension 40. Composite materials		1.2 - 1.1.7 2.1 - 1.2.1 1.3 - 1.1.8
	- Stiffened-structures		On macroscales, structures can be enhanced/reinforced through the addition of stiffeners of various shape or curvatures (inelastic deformation) of the structure itself. Stiffened structures yield a higher moment of inertia and hence increased stiffness. Governing design variables are dimensions and topologies of constituents. For example, hat-stiffened plates are generally regarded to be one of the most efficient light weight constructions for compression panels loaded in direction, waffle-stiffened plates for compression panels loaded in two direction. In general, it is a costly process of joining (precurved) face sheets and stringers or machining.	- Stiffeners of various shapes - Curved structures of various shapes	1. Segmentation 5. Merging 40. Composite materials	7. Nested doll	3.2 - 1.1.2 7.4 - 5.1.2

Table A.13: Design catalog solution principles associated with (in)elastic deformation with TRIZ augmentations and links (Continued)

...sion, bending, shear, torsion, buckling, fracture, cutting, inversion, extrusion, drawing, flow)

Mesoscale

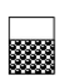
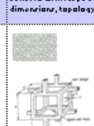
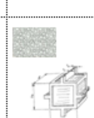
Honeycomb-core sandwiches	Honeycomb-core sandwiches take their name from their visual resemblance to a bee's honeycomb. With controllable core dimensions and topologies on mesoscales, they feature relatively high stiffness and yield strength at low density. Large compressive strains are achievable at nominally constant stress (before the material compacts), yielding a potentially high energy absorption capacity. Honeycomb-core sandwiches have acceptable structural performance at relatively low costs with useful combinations of thermophysical and mechanical properties. Usually, they provide benefits with respect to multiple use.					4.3 - 2.2.6 7.1 - 5.1.1.1 7.4 - 5.1.2
- In-plane honeycombs		Core cell axes of in-plane honeycomb cores are oriented parallel to the face-sheets. They provide potentials for decreased conductivity and fluid flow within cells. Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D \approx 1-1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approximated as: $\frac{E}{E_s} \approx 1\,\rho_{rel}^3$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.5\,\rho_{rel}$	- Prismatic-, square-, chiracal-, etc. core in-plane honeycombs	3. Local quality 40. Composite materials	31. Porous materials	4.3 - 2.2.6 7.1 - 5.1.1.1 7.4 - 5.1.2
- Out-of-plane honeycombs		Core cell axes of out-of-plane honeycomb cores are oriented perpendicular to face-sheets. They provide potentials for decreased conductivity. Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D \approx 1-1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approximated as: $\frac{E}{E_s} \approx 1\,\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 1\,\rho_{rel}$	- Hexagonal-, sqaure-, etc. core put-of-plane honeycombs	3. Local quality 40. Composite materials	31. Porous materials	4.3 - 2.2.6 7.1 - 5.1.1.1 7.4 - 5.1.2
Fiber-composites	The combination of polymers or other matrix materials with fibers has given a range of light materials with stiffness and strength comparable to that of metals. Commonly, resin materials are epoxies, polyesters and vinyls. Fibers are much stronger and stiffer than their equivalent in bulk form because the drawing process by they are made orients the polymer chains along the fiber axis or reduces the density of defects.					3.2 - 1.1.2
- Continuous fiber composites		Continuous fiber composites are composites with highest stiffness and strength. They are made of continuous fibers usually embedded in a thermosetting resin. The fibers carry the mechanical loads while the matrix material transmits loads to the fibers and provides ductility and toughness as well as protecting the fibers from damage caused by handling or the environment. It is the matrix material that limits the service temperature and processing conditions. On mesoscales, the properties can be strongly influenced by the choice of fiber and matrix and the way in which these are combined: fiber-resin ratio, fiber length, fiber orientation, laminate thickness and the presence of fiber/resin coupling agents to improve bonding. The strength of a composite is increased by raising the fiber-resin ratio, and orienting the fibers parallel to the loading direction. Increased laminate thickness leads to reduced composite strength and modulus as there is an increased likelihood of entrapped voids. Environmental conditions affect the performance of composites: fatigue loading, moisture and heat all reduce allowable strength. Polyesters are the most most widely used matrices as they offer reasonable properties at relatively low cost. The superior properties of epoxies and the temperature performance of polyimides can justify	- Glass fibers [high strength at low cost], polymer fibers (organic (e.g., Kevlar) or anorganic (e.g., Nylon, Polyester)) [reasonable properties at relatively low cost], carbon fibers [very high strength, stiffness and low density] - Strands, filaments, fibers, yarns (twisted strands), rovings (bundled strands) - Nonwoven mattings, weaves, braids, knits, other	3. Local quality 35. Parameter change 40. Composite materials	6. Universality	3.2 - 1.1.2
- Discontinuous fiber composites		Polymers reinforced with chopped polymer, wood, glass or carbon fibers are referred to as discontinuous fiber composites. The longer the fiber, the more efficient is the reinforcement at carrying the applied loads, but shorter fibers are easier to process and hence cheaper. Hence, fiber length and material are the governing design variables. However, fibrous core composites feature shape flexibility and relatively high bending stiffness at low density.	- Glass fibers, polymer fibers (organic (e.g., Kevlar) or anorganic (e.g., Nylon, Polyester)), carbon fibers	3. Local quality 35. Parameter change 40. Composite materials	6. Universality	3.2 - 1.1.2 4.3 - 2.2.6
Dispersion-composites	A multi-component material produced when metal, ceramic or polymer materials provide a macrostructural matrix for the distribution of strengthening agents, such as flakes, throughout the material, increasing its structural or functional performance. Each component however maintains its properties.					3.2 - 1.1.2 4.3 - 2.2.6 7.4 - 5.1.2
- Particle-composites		Particle-composites are materials made by reinforcing/enhancing polymers or other matrix materials with particulates (fillers) of for example silica sand, talk. The combination of polymers with fillers has given a range of light materials with stiffness and strength comparable to that of metals as well as enhanced processability. Governing design variables are dimensions, topology and material of fillers as well as matrix material properties. Blending allows other adjustments of properties, e.g., plasticizing additives give polymers leathery behavior or flame retardant additives reduce flammability of polymers. Particle-matrix composites (such as aluminum with silicon carbide) extend the property range of materials, usuallly to make them stiffer, lighter, more tolerant of heat or add other functionality. But, their cost limits their applications.	- Carbide, polymer concerte,...	3. Local quality 31. Porous materials 35. Parameter change 40. Composite materials	6. Universality	3.2 - 1.1.2 4.3 - 2.2.6 7.4 - 5.1.2
- Granular-materials/ powders		A granular material is a conglomeration of discrete solid, characterized by a loss of energy whenever its particles interact mostly through friction. The constituents that compose granular material must be large enough such that they are not subject to thermal motion fluctuations. Governing design variables are filler dimensions, topology and material. For example, filling structures with crushable granular material (sand) is a way of mobilizing membrane stresses at large deformations and increase friction. Axial crushing of filled tubes or honeycombs is focus of current research to increase energy dissipation.	- Granular fill materials, fill powders, ...	3. Local quality 35. Parameter change 40. Composite materials	6. Universality 15. Dynamics	3.2 - 1.1.2 4.3 - 2.2.6 7.4 - 5.1.2
- Solid-/fluid-mixtures/ additives		Solid-/fluid-mixtures are dispersion composites made by adding or mixing and often processing multiple materials with or without additives. Governing design variables are dimensions and materials. Prominent examples are microencapsulation - individually encapsulated small particles or substances to enable suspension in another compound - and sintering - fabrication of metals or ceramics based on powdery educts (starting materials) at high temperatures and pressures - as well as nanoscale additives.	- Metal and/or ceramic composites, ... - Reactive metal powder mixtures, ... - Aerogels, ...	3. Local quality 35. Parameter change 40. Composite materials		3.2 - 1.1.2 4.3 - 2.2.6 7.1 - 5.1.1.5 7.4 - 5.1.2
Foams	In general, polyhedral cells which pack in three dimensions to fill space are referred to as three-dimensional cellular materials foams. Techniques today exist for foaming almost any material. Foams reduce material usage and increase bending stiffness without increasing weight through a relatively high stiffness and yield strength achievable at low density. Large compressive strains can be achieved at nominally constant stress (before the material compacts), yielding a relatively high energy absorption capacity through bending dominated plastic yielding. Foams feature benefits with respect to multiple use and shape flexibility. Governing design variables are the relative density, cell dimensions, topology and material.					7.1 - 5.1.1.1
- Open-cell foams		If the solid of which the foam is made is contained in the cell edges only so that the cells connect through open faces, the foam is said to be open-celled. Open-cell foams provide potentials for decreased conductivity (especially for polymer and glass) and fluid flow within cells. Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D = 1-14\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approxiamted as: $\frac{E}{E_s} \approx 1\,\rho_{rel}^2$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.4\,\rho_{rel}^{1.5}$	- Filatration, thermal insulation, cushioning, packaging, padding, ... devices	3. Local quality 31. Porous materials		7.1 - 5.1.1.1
- Closed-cell foams		If the faces of open-cell foams are solid too, so that each cell is sealed off from its neighbors, the foam is said to be closed-celled. In closed-cell foams, the fluid within cells is compressed and provides potentials for decreased conductivity (especially for polymer and glass). Relative densities range from 0.001 to 0.3. Their densification strain can be approximated as: $\varepsilon_D = 1-14\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be approxiamted as: $\frac{E}{E_s} \approx 0.33\,\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.3\,\rho_{rel}$	- Flotation, thermal insulation, cushioning, packaging, padding, ... devices	3. Local quality 31. Porous materials		7.1 - 5.1.1.1

Table A.14: Design catalog solution principles associated with (in)elastic deformation with TRIZ augmentations and links (Continued)

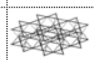
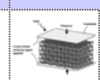
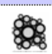
Elastic/inelastic deformation (tension, compress	Microscale	**Microtruss-structures**	Stretching dominated, periodically arranged microtruss-structures, where struts support axial loads, tensile in some, compressive in others when loaded, offer greater stiffness and strength per unit weight than those in which the dominant mode of deformation is by bending. With microtruss-structures, relatively high stiffness and yield strength becomes achievable through stretching dominated plastic yielding at low relative density. They feature a relatively high energy absorption capacity, but, in compression the stretching-dominated materials have a softening post-yield response due to the buckling of the struts. However, they provide benefits with respect to multiple use and fluid flow within cells.					7.1 - 5.1.1.1
		- Pyramidal structures		Relative densities for pyramidal microtruss-structures range from 0.01 - 0.1. Their densification strain can be approximated as: $\varepsilon_D = 1 - 1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be appraxiamted as: $\frac{E}{E_s} \approx 0.25\,\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.5\,\rho_{rel}$	- Shock-/noise-absorption devices, etc.	3. Local quality 31. Porous materials		7.1 - 5.1.1.1
		- Tetragonal structures		Relative densities of tetragonal microtruss-structures range from 0.01 - 0.1. Their densification strain can be approximated as: $\varepsilon_D = 1 - 1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be appraxiamted as: $\frac{E}{E_s} \approx 0.44\,\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.66\,\rho_{rel}$	- Shock-/noise-absorption devices, etc.	3. Local quality 31. Porous materials		7.1 - 5.1.1.1
		- Kagome structures		- Kagome structures may mimic random cellular structures as encountered in armadillo shell structures and young swap froths. Their exact behaviour however is currently analyzed.	- Shock-/noise-absorption devices, etc.	3. Local quality 31. Porous materials		7.1 - 5.1.1.1
		Microtruss-laminates	Periodic microtruss-laminates are synthesized through textile-based approaches based on wire weaves joined using transient liquid phases. They have the compliance and necessary open space for cell collapse, i.e., large compressive strains achievable at nominally constant stress before the material compacts, thereby absorbing large amounts of energy when compressed. Besides this relatively high energy capacity, they feature relatively high stiffness and yield strength achievable at low density as well as benefits with respect to multiple use.					4.3 - 2.2.6 7.1 - 5.1.1.1 7.4 - 5.1.2
		- Textile-based weave (3 dimensional knitting)		Relative densities of tetragonal microtruss-structures range from 0.01 - 0.3. Their densification strain can be approximated as: $\varepsilon_D = 1 - 1.4\left(\frac{\rho}{\rho_s}\right)$ Their relative stiffness can be appraxiamted as: $\frac{E}{E_s} \approx 0.5\,\rho_{rel}$ Their relative strength can be approximated as: $\frac{\sigma_y}{\sigma_{ys}} \approx 0.5\,\rho_{rel}$	- Shock-/noise-absorption devices, etc.	3. Local quality 7. Nested doll 40. Composite materials	31. Porous materials	4.3 - 2.2.6 7.1 - 5.1.1.1 7.4 - 5.1.2
		Machine-augmented-composites	Machine-augmented composites are formed by embedding mechanisms in a matrix material. Theoretically, these mechanisms may include: - Wheel-gears (friction-/form-locking) - Cam-mechansims, worm/helical gears, gate gears - Belt-/chain-drives (friction-/form-locking) - 4-bar-turning/sliding-pair linkages, multilink mechanisms Potentially, machine-augmented composites might also be formed by embedding micro-electro-mechanical systems					7.1 - 5.1.1.1 7.4 - 5.1.2
		- Microtruss-mechanisms		- Composite formed by embedding simple microtruss-mechanisms, with or instead of fiber or particulate reinforcements, in a matrix material to obtain a multifunctional material with new properties. The mechanisms may take on many different forms and serve to modify power, force, or motion in different ways, hence creating as many different mechanical properties as there are possibilities for the cross-sectional shapes of machines.	- Shock-/noise-absorption devices, etc.	3. Local quality 7. Nested doll 40. Composite materials	6. Universality	7.1 - 5.1.1.1 7.4 - 5.1.2
		Microstructure-compo-sites	Microstructure-composites are isotropic cellular materials that attain theoretical upper bounds for the bulk and shear moduli of a voided solid to maximize the stiffness to weight ratio.					7.4 - 5.1.2
		- Coated spheres assemblages		Coated sphere architectures are differential schemes for constructing composite structures with the extremal Hashin-Shtrikman bulk and shear moduli.		3. Local quality 40. Composite materials	14. Spheroidality - Curvature	7.1 - 5.1.1.1 7.4 - 5.1.2
		- Rank-laminates		Rank laminates attain both the bulk and shear H-S bounds with a finite number of layering directions. Rank laminates are obtained by a sequential process where at each stage the previous laminate is laminated again with a single phase (always the same) in a new direction.		3. Local quality 17. Another dimension 40. Composite materials 7. Nested doll		7.4 - 5.1.2
		- Vigdergauz microstructures		Vigdergauz microstructures are isotropic two-dimensional square symmetric composites feature optimal shape of single inclusions and hence attain theoretical upper bounds for the bulk or shear moduli.		3. Local quality 40. Composite materials		7.1 - 5.1.1.1 7.4 - 5.1.2
		- Sigmund microstructures		Sigmund microstructures are statistically isotropic (or at least square symmetric) two-phase microstructure, consisting of disconnected convect polygonal regions with pure phase 1 or 2 material connected by laminated regions of the phases in equal proportions, for which exact solutions for the hydrostatic loading case exist. This composite has bulk modulus equal to either the upper or the lower Hashin-Shtrikman bound if the lamination direction is perpendicular to the stiffer or lower phase respectively. According to Sigmund, an isotropic honeycomb-like hexagonal microstructure belonging to this class of composite has maximum bulk modulus and lower shear modulus than other known composites.		3. Local quality 40. Composite materials		7.1 - 5.1.1.1 7.4 - 5.1.2
		Nano-structures	Nanoscale-structured materials of extraordinary multifunctional (mechanical, electrical, optical and thermal) properties are referred to as nano-structures.					3.2 - 1.1.2
		- Microtubes		Microtubes are very small diameter tubes (in the nanometer and micron range) that have very high aspect ratios and can be made from practically any material in any combination of cross-sectional and axial shape desired. Potential applications are lightweight structural reinforcement or multifunctional composite materials.	- Microtubing, semiconductor microtubes or resonators, micro-machines/-devices, etc.	3. Local quality 35. Parameter change 40. Composite materials		3.2 - 1.1.2 7.1 - 5.1.1.1
		- Nanotubes		Since carbon-carbon covalent bonds are among the strongest bonds in nature, nanotubes are commonly realized and known as carbon-nanotubes, a structure based on a perfect arrangement of these bonds oriented along the axis of the nanotubes producing a very strong material with an extremely high strength-to-weight ratio. More specifically, a carbon nanotube is a hexagonal network of carbon atoms rolled up into a seamless, hollow cylinder, with each end capped with half of a fullerene molecule. In general, it is only a carbon nanotubes isotropic topology that distinguishes it from other carbon structures and gives it unique properties. Besides extraordinary high tensile strength, low density and high Young's modulus, the most striking effect is the combination of high flexibility and strength with high stiffness. Thus, nanotubes are very stiff for small loads, but turn soft for larger loads, accommodating large deformations without breaking. Hence, carbon nanotubes have an extraordinary potential in energy dissipation applications. At the same time, they have a unique electronic and optical character.	- Single-/multi-walled carbon nanotubes, etc.	3. Local quality 35. Parameter change 40. Composite materials		3.2 - 1.1.2 7.1 - 5.1.1.1
		- Nanoparticles		The use of nanoscale filers exploits the advatages that nanometer-size particulates offer comapared with macro- or microscopic filllers, such as huge surface area per mass, ultra-low filler levels required for connectivity through the sample, extremely small interparticle separations, very high aspect ratios. Also, the formation of genuine nanocomposites introduces new physical properties and novel behaiors that are absent in unfilled matrices, effectevly changing their nature.	- Polymer-based nanocomposites, molecular composites, etc.	3. Local quality 35. Parameter change 40. Composite materials		3.2 - 1.1.2 7.1 - 5.1.1.5

Table A.15: Design catalog solution principles associated with (in)elastic deformation with TRIZ augmentations and links (Continued)

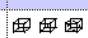
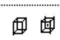
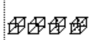
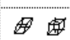
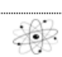
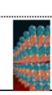
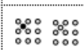
Nanoscale	**Phase transformations**	Solid-fluid-gas or solid state phase change - that is a molecular rearrangement, which occurs in shape memory alloys or polymers: pseudo-elasticity and shape memory effect, more specifically stress and heat induced martensitic transformations - are referred to as phase transformations on picoscales affecting material properties on macroscales.					10.1 - 5.3.4
	- Stress-induced martensitic transformations		Stress-induced matrensitic transformations refer to the ability of a material to undergo enormous elastic or reversible deformation (pseudo-elasticity). This pseudo-elasticity features the plateau stress-deformation characteristic crucial for enhanced energy dissipation.	- Shape-memory alloys - Shape-memory polymers	36. Phase transitions		10.1 - 5.3.4
	Molecular arrangement	Controlling the precise molecular arrangement to be either crystalline, polycrystalline, semicrystalline or amorphous on nanoscales determines material properties on macroscales.					
	- Crystalline		An orderly and repetitive arrangement of atoms and molecules held together with different types of chemical bonding forces is referred as a crystalline molecular arrangement. These patterns form regular lattice structures of which there are many different types with corresponding material structures. A crystalline structure is made up of large number of identical unit cells that are stacked together in a repeated array or lattice.	- Metals and minerals	33. Homogeneity		
	- Polycrystalline		A random structure with little if any order as exhibited by a large number of small cyrstals or grains not arranged in an orderly fashion is referred to as a polycrystalline arrangement. For a number of reasons the growth of a crystalline pattern is interrupted and a grain is formed. Particular grains meet one another at irregular grain boudnaries and are normally randomly oriented to one another. Grain size can vary due to multiple reasons (including heat treatment and cold working). Alterations in the grain structure can produce changes in material properties. Governing design variables are grain size, grain boundaries, lattice orientation and phase topology.	- Ceramics and glasses, metals	4. Asymmetry		
	- Semicrystalline		Periodic arrangement of chains that are crystalline in nature are referred to as a semicrystalline molecular arrangement. These chains are not cross-linked and have multi-layered structures. Governing design variables are chain length and topology of the multi-layered structure.	- Folded chain polymers	17. Another dimension		
	- Amorphous		A random structure with little if any order as exhibited by interwoven and cross-linked chains is referred to as an amorphous molecular arrangement. Main design variables are chain length, chain interconnectedness, and degree of interweavement.	- Polymers	4. Asymmetry		
	Line defects	Line variations from the perfect crystal lattice on the nanoscale typically cause changes in the macroscopic properties of materials, particularly metals.					7.1 - 5.1.1.1
	- Edge dislocations		The border of an extra plane of atoms, where the dislocation line identifies the edge of the extra plane, is referred to as an edge dislocation. Edge dislocations include edges of surfaces where there is a relative displacement of lattice planes or rows of missing atoms.		1. Segmentation		7.1 - 5.1.1.1
	- Screw dislocations		Crystals displaced parallel to a cut and finally reconnected into the configuration are referred to as screw dislocations. The dislocation line is the edge of the cut and hence also the border of the displaced region.				7.1 - 5.1.1.1
Picoscale	**Crystal systems**	A crystal structure is a unique arrangement of atoms in a crystal. A crystal structure is composed of crystal unit cells, sets of atoms arranged in a particular way. The characteristics and geometry of crystal unit cells are determined by its basic atomic structure. Basic morphological considerations indicate that there are 14 basic lattice structures (Bravais lattices) that can be made from the seven basic unit cells. Crystal systems can be classified according to the length and angles involved.					
	- Cubic		The cubic crystal system has the same symmetry as a cube. Three cubic Bravais lattices exist - the simple cubic, face centered cubic and body centerd cubic.	- Chromium, molybdenum, tungsten - Aluminum, silver, gold, copper - Pyrite, garnet	1. Segmentation 17. Another dimension 35. Parameter change		
	- Tetragonal		Tetragonal crystal lattices result from stretching a cubic lattice along one of its lattice vectors, so that the cube becomes a rectangular prism with a square base and height different from the base length. There are two tetragonal Bravais lattices - the simple tetragonal and the face centered tetragonal.	- Zircon, anatase	1. Segmentation 4. Asymmetry 17. Another dimension 35. Parameter change		
	- Orthorhombic		Orthorhombic lattices result from stretching a cubic lattice along two of its lattice vectors by two different factors, resulting in a rectangular prism with a rectangular base and height different from both rectangular base length. The three lattice vectors remain mutually orthogonal. Four orthorhombic Bravais lattices exist: simple orthorhombic, base-centered orthorhombic, body-centered orthorhombic, and face-centered orthorhombic.	- Olivine, sulfur	1. Segmentation 4. Asymmetry 17. Another dimension 35. Parameter change		
	- Hexagonal		The hexagonal crystal system has the same symmetry as a right prism with a hexagonal base and six atoms per unit cell.	- Magnesium, titanium, zinc - Beryll, Nepheline	1. Segmentation 4. Asymmetry 17. Another dimension		
	- Rhombohedral		In the rhombohedral system, the crystal is described by vectors of equal length, of which all three are not mutually orthogonal.	- Quartz, calcite	1. Segmentation 4. Asymmetry 17. Another dimension		
	- Monoclinic		In a monoclinic crystal system, the crystal is described by vectors of unequal length forming a rectangular prism with a parallelogram as base. Two monoclinic Bravais lattices exist - the simple monoclinic and the face centered monoclinic lattices.	- Gypsum, clinopyroxene	1. Segmentation 4. Asymmetry 17. Another dimension 35. Parameter change		
	- Triclinic		In the triclinic system, the crystal is described by vectors of unequal length where all three vectors are not mutually orthogonal.	- Feldspar	1. Segmentation 4. Asymmetry 17. Another dimension		
	Molecular structures	Control of molecular constituents and structures on the atomic scale affects properties on macroscopic scales in order to achieve given performance requirements.					
	- Solid solutions (alloying)		Solid solutions are formed through for example combining various elements or adding alloying elements to a base material to obtain a (base) material with unique and specific characteristics. However, the combination of (alloying) elements in solid solutions may result in constituents which, far from producing a favorable cumulative effect with regard to a certain property, may counteract each other. For example, the mere presence of alloying elments in steel is nothing but a basic condition for the desired characteristic which can be obtained only by propert processing and heat treatment.	- Alloying elements: C, Al, Sb, As, Be, B, Ca, Cr, Co, Cu, H, Pb, Mn, Mo, Ni, N, O, P, Si, S, Sn, V, W	3. Local quality 35. Parameter change		7.1 - 5.1.1.8
	- Atomic elements		Progress in science suggests the feasibility of achieving thorough control of the molecular structure of matter via controlled molecular assembly, i.e., using individual atoms to build molecules precisely as building blocks for bottom-up molecular construction.	- Elements in periodic table: H, Li, Na, K, Rb, Cs, Fr, Be, Mg, Ca, Sr, Ba, Ra, Sc, Y, Ti, etc.	1. Segmentation 35. Parameter change		7.2 - 5.5.1
	- Subatomic particles		Subatomic particles have less structure than atoms. These include atomic constituents such as electrons, protons, and neutrons, where protons and neutrons are composite particles made up of quarks, as well as particles produced by radiative and scattering processes, such as photons, neutrinos, and muons, as well as a wide range of other particles.	- Electrons, protons, neutrons, photons, neutrinos, muons, etc.	1. Segmentation		

Table A.16: Design catalog solution principles associated with (in)elastic deformation with TRIZ augmentations and links (Continued)

		Atomic Bonding	The type of bonding ultimately determines many of the intrinsic properties and major behavioral differences between materials. Bonding forces produce different types of aggregation patterns between atoms to form various molecular and crystalline solid structures. Intermetallic compounds with various types of bonding exist.					3.2 - 1.1.2
		- Ionic		Ionic bonding involves electrostatic forces where one atom transfers electrons to another atom to form charged ions. Multiple ions typically form into compounds composed of crystalline or orderly lattice-like arrangements that are held together by large interatomic forces. Ionic compounds are solid at room temperatures, and their strong bonding force makes the material hard and brittle. In the solid state, all electrons are bonded and not free to move, hence ionic solids are not electrically conductive. Solid materials based on ionic bonding have high melting points and are generally transparent. Many are soluble in water. In the melted or dissolved state, electrical conduction is possible.	Ceramics and glasses	5. Merging 35. Parameter change		3.2 - 1.1.2
		- Covalent		Covalent bonding involves local sharing of electrons and frequently occurs between neighboring non-metallic elements thereby producing localized directions. In some cases, small covalent arragements of atoms or molecules can be formed in which individual molecules are relatively strong, but forces between these molecules are weak. Consequently these arrangements have low melting points and can weaken with increasing heating. They are also poor conductors of electricity. In other cases (such as carbon or diamond), it is possible for many atoms to form a large and complex covalent structure that is extremely strong. These structures are very hard, have very high melting points, will not dissolve in liquids and, because electrons are closely bound and not free to move easily, are typically poor electrical conductors.	Ceramics and glasses, molecules in polymer chains	5. Merging 35. Parameter change		3.2 - 1.1.2
		- Metallic		Metallic bonding involves non-localized sharing of electrons. Outer shell electrons contribute to a common electron cloud, resulting in good electric and heat conducting as well as often ductile deformation characteristics.	Metals	5. Merging 35. Parameter change		3.2 - 1.1.2
		- Secondary		Secondary bonding involves permanent or fluctuating dipole bonds. Bonding forces are relatively weak by comparison to ionic, covalent and metallic bonds. They can break easily under stress and they allow molecules to slide with respect to one another.	Polymer chains	5. Merging 35. Parameter change		3.2 -1.1.2
		Atomic Point defects	Variations from the perfect lattice on pico scales that typically cause changes in the properties of materials, particularly metals, at macro scales.					7.1 - 5.1.1.1 4.3 - 2.2.6
		- Vacancy impurities		Vacancy impurities involve the absence of an atom at a normally occupied lattice site.		2. Taking Out 35. Parameter change		4.3 - 2.2.6 7.1 - 5.1.1.1
		- Substitutional impurities		Substitutional impurities involve atoms of a different element than the bulk material that occupies a normal lattice site.		5. Merging 35. Parameter change		3.2 - 1.1.2 4.3 - 2.2.6 7.1 - 5.1.1.5
		- Interstitial impurities/self		Interstitial impurities/selfs are atoms occupying a position between normal lattice sites. They can be either self (same type of bulk material) or impurity (another type as the bulk material) interstitials atoms.		5. Merging 35. Parameter change		3.2 - 1.1.2 4.3 - 2.2.6 7.1 - 5.1.1.5

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