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Contributions to inventive design methods of systems based on lattice structures

(Contributions aux méthodes de conception inventive de systèmes à base de structures lattice)

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Mohamed ABDELLATIF

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Acronyms and Abbreviations

PSM	Problem-Solving Method
A.I.S	Analysis of Initial Situation
GTP	Generalized Table of Parameters
FEM	Finite Element Modeling
CAD	Computer-Aided Design
TRIZ	A Russian acronym, translated into English as "Theory of Inventive Problem Solving"
DoE	Design of Experiments
MOO	Multi-Objective Optimization
CDB	Contextual Database
PhP	Physical Parameter
PrP	Performance Parameter
AP	Action Parameter
EP	Evaluation Parameter
GPC	Generalized Physical Contradiction
GTC	Generalized Technical Contradiction
GSC	Generalized System of Contradiction
PC	Physical Contradiction
TC	Technical Contradiction
SoC	System of Contradiction
Source 1	Refers to a scientific database e.g., articles, books, patents
Source 2	Refers to the experts' opinions
Source 3	Refers to the analysis of computer-aided design software CAD and finite element modeling software FEM, as a source of knowledge
SC	Solution Concept

Greek symbols

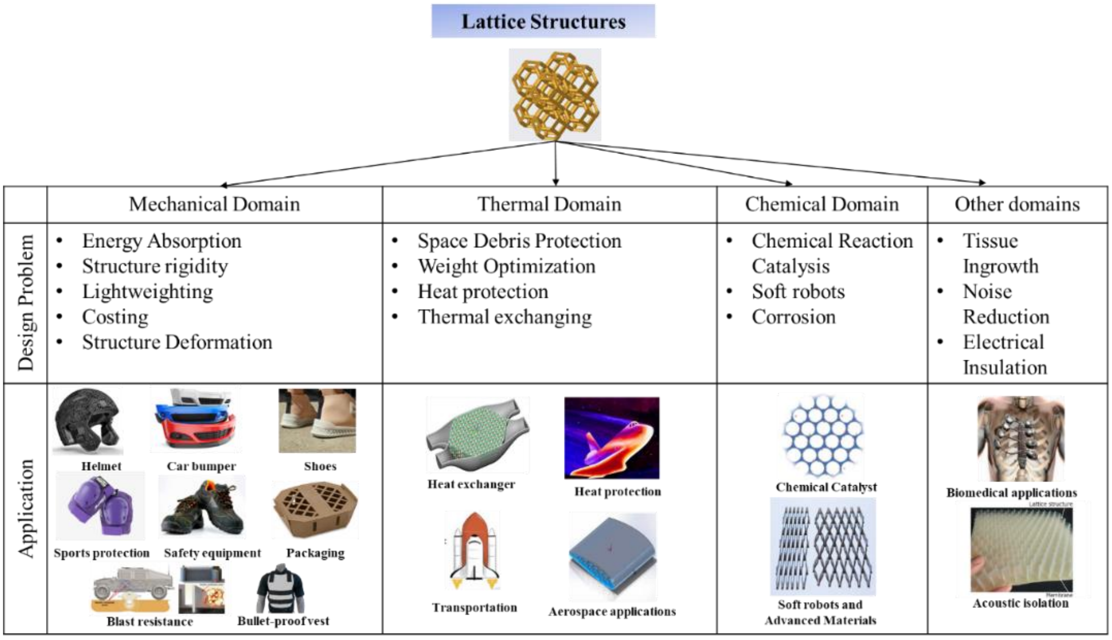
σ	Stress (in MPa)
ε	Strain (no unit)
F	Applied Force (in N)
E	Young’s modulus (in MPa)
W_v	Absorbed energy per unit volume (in J/mm^3)
ρ_{relative}	Relative density of the lattice structure (no unit)
ρ_{Lattice}	Density of the lattice structure (kg/mm^3)
ρ_{base}	Density of the base material from which the lattice is made (kg/mm^3)
K_{IC}	Fracture toughness of lattice structure (MPa mm$^{1/2}$)
σ_{fs}	Facture strength of the lattice structure (in MPa)
ℓ	Cell size of lattice structure (in mm)
t	Strut thickness (in mm)
ΔL	Change in length (no unit)
L_0	Initial length (in mm)
$\varepsilon_{\mathrm{true}}$	True strain value (no unit)
$\varepsilon_{\mathrm{engineeering}}$	Engineering strain value (no unit)

Chapter 1 General Introduction

The works presented in this thesis are conducted in the ICube laboratory (Le laboratoire des sciences de l'ingénieur, de l'informatique et de l'imagerie), under the direct supervision of the team CSIP (Conception, Système d'Information et Processus inventifs). This research team is a part of the laboratory ICube, UMR7357. The team CSIP works on the formalization of the invention activity e.g., TRIZ-based methods, in Product/System design in the light of engineering and information sciences. This project is funded by the French doctoral school ED269 Mathématiques, Sciences de l'Information et de l'Ingénieur (MSII).

The industrial world has undergone significant evolution over the decades, characterized by rapid technological advancements, increased competition, and growing consumer expectations. This evolution has highlighted the need for efficient product design methods to address the increasingly complex challenges faced by industrial companies. Therefore, it is essential to have effective methods for analyzing, understanding, and systematically solving these problems to ensure the creation of products that meet industrial needs and requirements. These methods save time by quickly identifying issues, finding appropriate solutions, and avoiding costly design errors.

In this thesis, we explore the use of inventive design methods to address a family of design problems related to systems based on lattice structures. To introduce the practical problem of this investigation, let's take an example. Suppose we want to produce a sports shoe sole, a bicycle helmet, and an acoustic insulator based on a lattice structure. The expected properties of the lattice structure are not the same for each of these objects. The sole is expected to absorb energy and provide thermal cooling; the helmet is expected to absorb energy and provide rigidity; and the insulator is expected to absorb or reflect sound waves (see more examples in Figure 1). What these three examples have in common is the desire to find ways to realize these properties using lattice systems, but the problems involved in finding these solutions can be very different. The solution process can exploit resources common to all three problems. One of our questions is how to capitalize on knowledge and make it available to designers in the most operational way possible.



	Mechanical Domain	Thermal Domain	Chemical Domain	Other domains
Design Problem	• Energy Absorption • Structure rigidity • Lightweighting • Costing • Structure Deformation	• Space Debris Protection • Weight Optimization • Heat protection • Thermal exchanging	• Chemical Reaction Catalysis • Soft robots • Corrosion	• Tissue Ingrowth • Noise Reduction • Electrical Insulation
Application	Helmet Car bumper Shoes Sports protection Safety equipment Packaging Blast resistance Bullet-proof vest	Heat exchanger Heat protection Transportation Aerospace applications	Chemical Catalyst Soft robots and Advanced Materials	Biomedical applications Acoustic isolation

Figure 1: Different problems from different domains linked to one system of lattice structure

It is apparent that problem solving is important. The Problem-Solving Methods (PSM) can be classified into two categories: routine and inventive. The routine problem-solving methods primarily focus on analyzing root causes of a problem and applying known, standard solutions, whereas inventive problem-solving methods encourage invention by using principles and models to generate new and original ideas. It is important to note that these categories are not mutually exclusive and can be combined as needed. Sometimes, a routine approach may be used to solve part of a problem, while an inventive approach can be applied to address another more complex part or stimulate creativity. In this thesis, design is approached from the perspective of inventive problem-solving methods and possible improvements to these methods.

The challenge is therefore to propose solutions for interconnected complex problems that may be in different domains. Another challenge is to propose generic solutions that can be adapted according to the case study being examined.

Inventive PSM aims to stimulate creativity by using specific principles, models, and techniques to solve design problems. A well-known family of methods widely used in the scientific and industrial community originates from TRIZ (Theory of Inventive Problem Solving). It is a set of systematically organized methods to find creative and inventive solutions to design problems. TRIZ encourages creative thinking, in-depth analysis of contradictions (conflicts), and the use of existing solution principles as a source of inspiration to resolve problems. In the context of improving and systematizing inventive design, several developments have been made at the ICube laboratory in recent years. The most advanced approaches [1]–[3] integrates the following steps: Analysis of Initial Situation, System Modeling, Optimization, Contradiction Extraction, and finally, Problem Resolution.

Initial Situation Analysis (AIS): This first step involves analyzing the initial situation in detail and gaining a clear understanding of the design problem or challenge. This may include identifying objectives, constraints, requirements, and critical aspects related to the problem.

System Modeling: Once the initial situation is analyzed, the next step is to model the system in a structured manner by specifying its parameters and their relationships for the application of optimization or inventive design methods. This may involve creating diagrams, charts, or visual representations to understand the components, interactions, and dependencies of the system or process in question.

Optimization: After modeling the problem, the next step is to check if a standard solution can be found. A solution is considered standard if it falls within the domain defined by the set of parameters modeling the system, without calling into question the relationships between these parameters or adding a new parameter or relationship. Optimization approaches explore the solution space defined by these relationships. If no satisfactory standard solution is found, or if better solutions are sought, an inventive approach to problem solving is required, first identifying the contradictions that need to be resolved to achieve the design objectives.

Contradiction Extraction: In the optimization process, contradictions of objectives may arise, meaning situations were improving one aspect results in the deterioration of another aspect. Contradiction extraction involves identifying these conflicting objectives and their causes, which can also be expressed as conflicting values on design parameters of the system. These contradictions constitute the inventive problem to be solved.

Problem Resolution: Once the contradictions are identified, various methods and tools can be used to resolve the problem, such as applying inventive problem-solving principles and models, using separation principles, or exploring existing solutions in other domains that have addressed similar generalized contradictions.

All these steps are integrated into the design process shown in Figure 2 where the black rectangles provide the main phases of the method and the blue boxes the expected design activities, means for activities, and outputs of each phase.

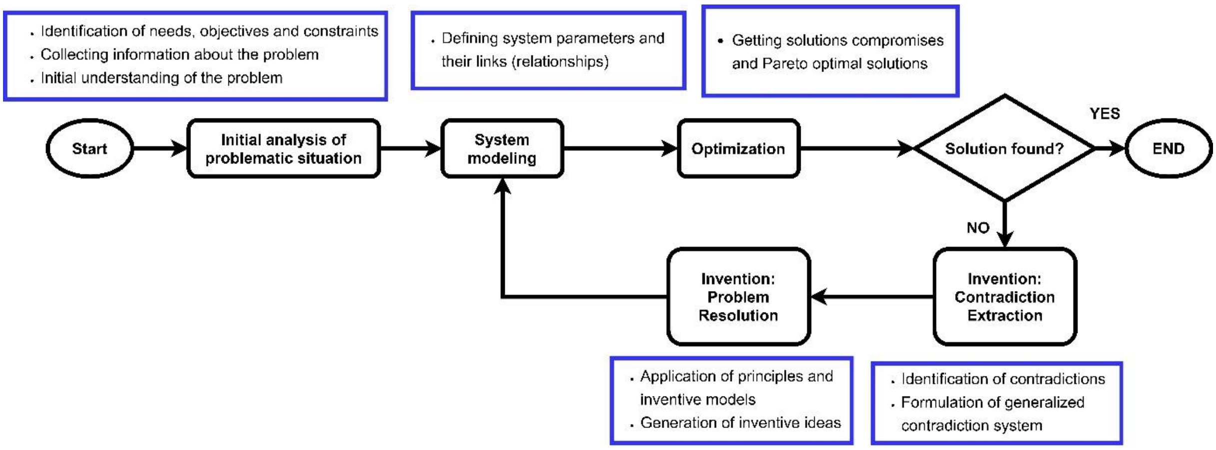


Figure 2: The iterative design process includes a part of the main steps, activities, means of activities, and outputs of the studied method.

1.1 Initial Problem(s)

Each step of the (meta) method described in Figure 2 can be accomplished using specific tools and methods that allow or facilitate their implementation. The available tools are diverse; the choice of tools and the notion of "implementation facilitation" depend on the user's prerequisites and to some extent on the problem being addressed. In this thesis, we explore the implementation of the above-mentioned approach on problems related to the design of products or materials based on lattice structures, extensively utilizing simulation, optimization, and contradiction identification tools from available data. Initially, the approach was conducted using the tools known and accessible to the contributors of this research project. At each step, limitations were identified, and efforts were made to improve the instrumental process.

In this context, one of the phases considered to be underdeveloped is the initial analysis of the situation. It is perhaps the least formalized phase of the problem-solving process and relies on gathering information from experts. This information collection may reveal inconsistencies among expert opinions and may face challenges related to the experts' availability. Hence, the objective of this thesis is to address the following question:

"What approach to adopt for solving complex problems, based on the analysis of the initial situation according to the objectives to be achieved and the extraction, resolution of priority contradictions, without relying too heavily on experts and utilizing available data?"

1.2 Research methodology

After highlighting the initial research problem(s), a research methodology followed to carry out this research work which is composed of five steps: (1) The first step includes a state-of-the-art on the existing approaches and methods in the design problem-solving area in order to understand how these initial problem(s) were handled by other research works, and what are the limitations of these contributions. (2) Based on results of the first step, the second step consists in developing research questions to be answered either completely or partially by doing the research process. (3) The third step includes proposing approaches and methods to overcome the research gap found during the third step. this step is supposed to be accomplished by exploiting the available resources such as scientific databases, experts' feedback, experimental, qualitative, and numerical approaches. (4) The fourth step is an illustration of the strength and limitations of the proposed methods in the third step. The illustration is done by applying the proposed method(s) to complex problems of lattice structure in the mechanical field as a case study. Case studies can provide feedback on using this proposed method(s), which is useful for developing future research work. (5) The fifth step is a result from applying the proposed method successfully, which is resulting in proposing a new product of lattice structure. This product is tested and fabricated to examine its feasibility and applicability.

Since Lattice structure is playing a vital role in this PhD as a resource to illustrate the proposed method(s), it is important to present clearly different aspects and facts about lattice structure problems, definitions, used materials, and related research work. These aspects will be discussed during the next section.

1.3 Design of lattice structure as a resource

Many recent applications, including industrial needs, invoke innovation to create new means and tools which satisfy these needs and render necessary properties. This requires creating and innovating new structures of materials. Therefore, lattice structures were a kind of state-of-the-art in innovative cellular structures. These structures are defined as a specific shape of cell which is continuously repeated and interconnected in either two or three dimensions (in two and three dimensions). The core idea of these lattices came from partitioning the space into cells in order to minimalize the surface area [4], [5], as illustrated in Figure 3.

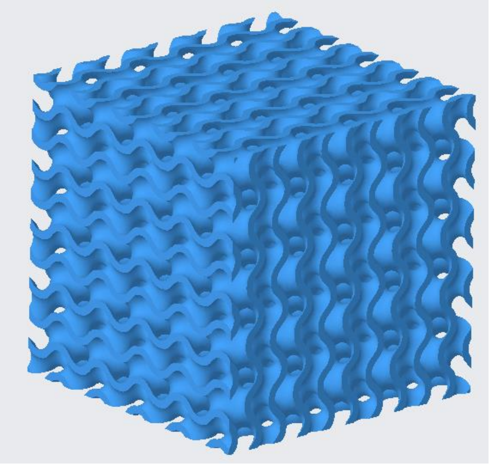


Figure 3: Lattice structure (cell type is Gyroid)

Promising future perspectives for this kind of structure with the advent of additive manufacturing technology and relevant printing, curing techniques. The advanced techniques of 3D printing helped, and still, to achieve several goals like reduction of materials utilized in manufacturing process. That happens through the automation of every single step during the printing process, so that it renders a fully computerized process. Secondly, additive manufacturing helps to reduce that time taken to give the product to the final shape ([5], [6]). In other words, it helps to reduce the total time wasted between several manufacturing procedures and steps. But additive manufacturing still has this drawback of quasi-slow production rate. However, this side, which is time, is to be enhanced and developed with time and with several manufacturing means. Lattice skeleton structures came to fill a good niche in manufacturing. Those structures satisfy mainly core properties, such as energy, time saving, durability. However, it went further to be used for promising properties like acoustic and vibrational damping, energy absorption ([7], [8]), high strength-to-weight ratios and thermal management capabilities as well ([9], [5]). As well, these properties were tested on some real applications like vehicular crashing and collision ([10]), airfoil ([11]), and Blast resistance ([12]).

One important reason of the interest of a new structure of materials, comes from the fact that these structures can render new mechanical, electric or magnetic properties, solely or as a composite with other materials [13]. As mentioned before, lattice structures render the entire skeleton with very interesting properties. Energy absorption is one of the important properties, which is used to fabricate shock absorbers and attenuate vibrations [14]. The work of [15] has tested the capability of hollow trusses which are used to fabricate the lattice skeleton. It results in higher load bearing capacity in compare with this solid truss. [14] also showed a distinguished ability of two new kinds of functionally reconfigurable two/three dimensional mechanical metamaterials which containing opposite or parallel snapping curved (U- shaped) segments, thanks to snapping behaviors which is to develop such structures to be appropriate for engineering conditions (e.g., shock absorber and damper). Although lattice structures can seem lighter and much more porous than bulk solid material, but it renders some distinguishing properties such as the ability to maintain a relative high strength comparing to the solid object [16], [14], [17]. On the other hand, some other structures give back some good properties to be used for thermal functionalities [18][19]. Lattice structures also serve for multifunctionality like acoustic damping while resisting against crashworthiness [20]. One of the widely studied design problems is mechanical energy absorption. This design problem will be presented in the next sections.

Lattice structures occupy an interesting niche in manufacturing. These structures can be used further for promising properties such as acoustic and vibrational damping, energy absorption [7]; [21], high strength-to-weight ratios, and thermal management capabilities [11], [6]. Moreover, these properties have been tested on some real applications like vehicular crashing and collision [22], [10], airfoils [11], and Blast resistance [12]. The wide range of applications for lattice structures is determined by their characteristics. Lattice structures are frequently used in many fields and applications [23]:

- The structural design of aircraft, rockets, etc.
- The automotive industry, due to their light weight and high strength. Moreover, their great capacity to absorb mechanical energy (crashworthiness), such as the energy absorbers in car bumpers.

- The biomechanical field, as they can be molded into the shape of human tissues and bones to replace diseased organs, thanks to their high strength and biocompatibility.
- The medical industry, thanks to their adaptable mechanical and structural qualities, can meet unique requirements, such as medical implants.
- Aerospace applications, such as the manufacture of thermal control systems, which have demonstrated a 50% reduction in weight and a 60% increase in thermal capacity compared with traditionally manufactured structures.
- Military applications, such as the use of zero or negative Poisson’s ratio structures in protective and blast-resistant armor.
- Chemical applications, such as catalytic support, thanks to highly porous structures offering a large surface area.
- Thermal fields, such as the heat exchangers
- Packaging, thanks to their high capacity to absorb shock energy.

Several other applications can be added daily to integrate the fabricated lattice structures in industrial applications in different scientific fields (e.g., mechanical, chemical, thermal, electromagnetic), as illustrated in Figure 4.

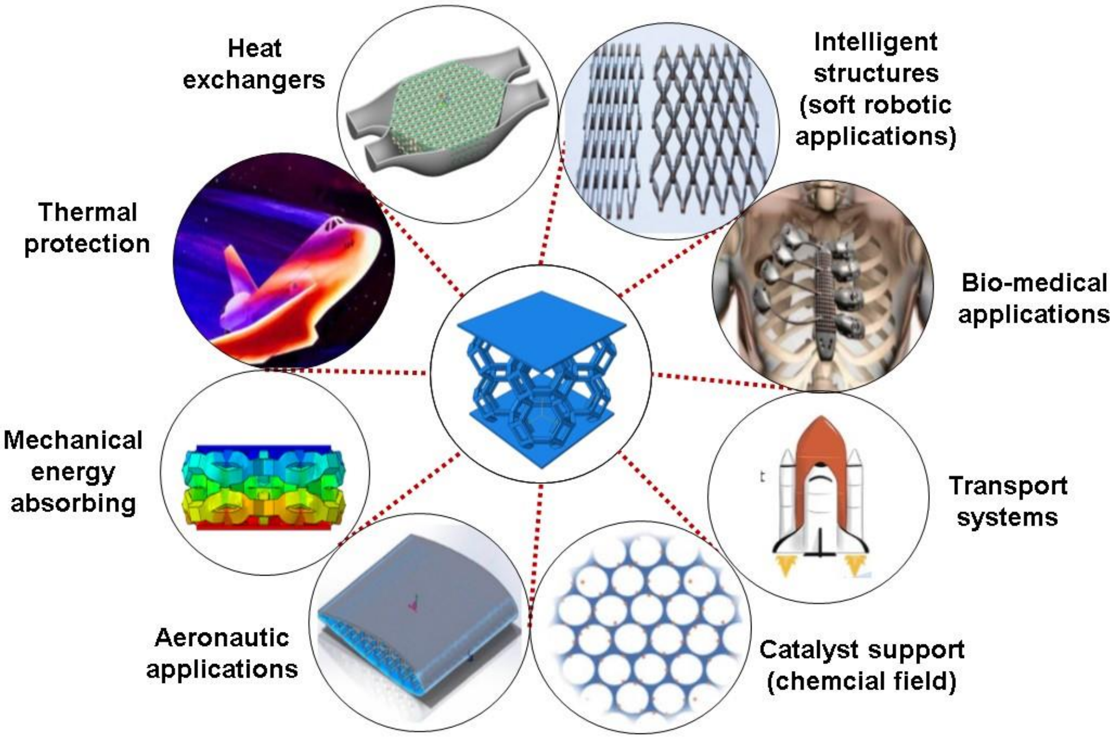


Figure 4: A side of the applications of lattice structure

In this chapter, we focus on design problems in the mechanical field, especially the problems related to mechanical energy absorbers such as helmets, car bumpers, and protection pads. The case study, handled in this PhD, will be about the fabrication of lattice-based mechanical energy absorbers.

The proposed structure should be fabricated by using additive manufacturing technology. In the next sections, we focus more on design problems by using lattice structures and especially within the available resources at our research laboratory.

1.3.1 Problem of energy absorption

Energy absorption is defined as the surface below the load-displacement curve as shown in Figure 5. The best energy absorbers have a long, plateau stress–strain (or load-deflection) curve, indicating that the absorber (or the lattice structure in this study) yields plastically at a quasi-constant stress called the plateau stress. Energy absorbers for packaging and protection are chosen so that the plateau stress is just below that which will cause harm and damage to the protected object; the best choice is then the one which has the longest plateau, and therefore absorbs the most quantity of energy [24].

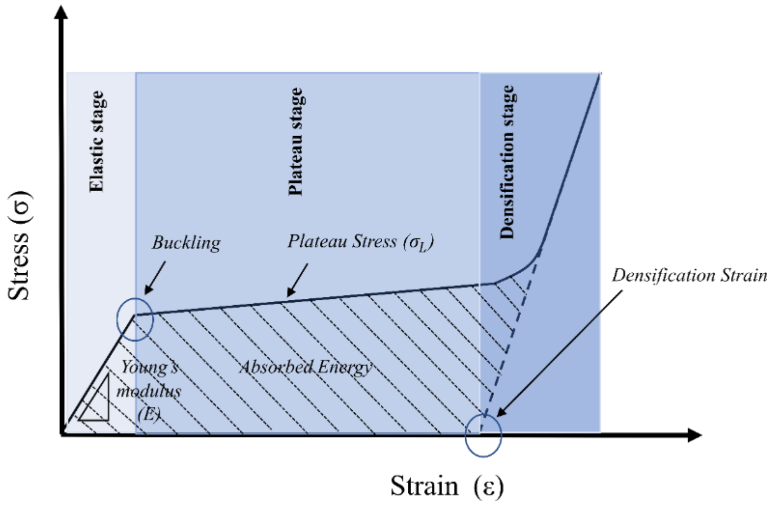


Figure 5: A typical compression stress-strain curve of a cellular structure

The capacity of a cellular structure (e.g., lattice structure) to absorb the mechanical energy per unit volume W_v can be calculated by a mathematical equation, which is representing an integral equation of the area under stress-strain curve up to densification point. The absorbed energy per unit volume is expressed with the equation (1):

$$W_v = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \tag{1}$$

To resolve the problem of energy absorption, different lattice structures were fabricated and tested, indeed. This motivates us by showing the process of fabrication itself by using the additive manufacturing technology, the used material, and the structure topology. These topics will be presented within the upcoming sections.

1.3.2 Additive manufacturing process

In this section, we show the broad strokes of how this process works and the sequential procedures. First, Additive manufacturing or as shorten as AM, is stemmed from the desire of building specific structures with architectures designed to meet specific applications. These structures are built in the form of layer-by-layer. The printing process extends beyond the robotic machine, it starts with creating the model which would be printed. This structure is made by using CAD (computer-aided design) software such as PTC Creo®, SolidWorks® or Rhino®. This mentioned software facilitates the design of structures through bench of design tools. Moreover, it can provide STL (stereolithography) files. This file is one of the most used formats for 3D printing. Then slicing software like Slic3r, 3DPrinterOS, MakerBot Print, or a customized software provided by a manufacturer, can interpret this STL and convert this geometry into G-code to be read by the printing machine[6], as shown in Figure 6. Finally, the printing machine can read this G-code and trace the trajectory to fabricate a touchable product.

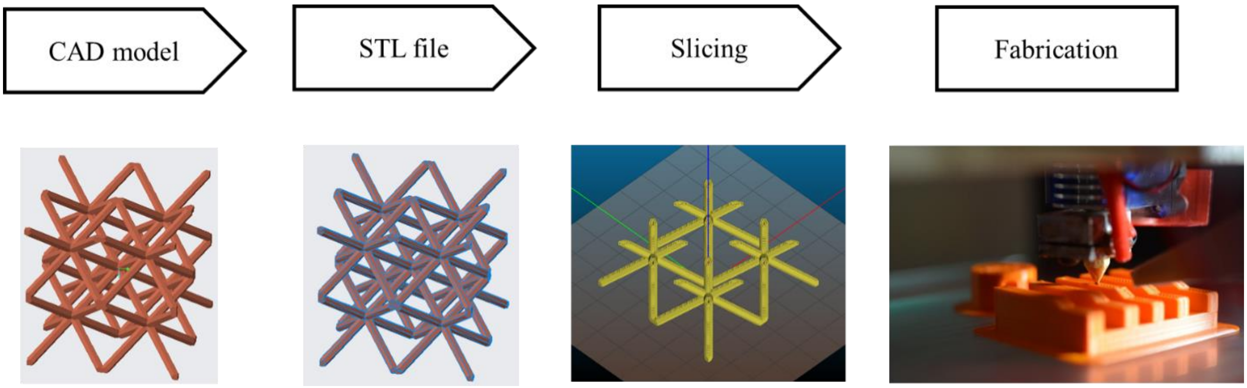


Figure 6: The additive manufacturing process

The interest of using additive manufacturing technology to fabricate the product models in this thesis is for many reasons. we mention some of these reasons [25]; additive manufacturing is to save the amount of energy utilized during manufacturing the product. Since it depends on working in the framework of such printing machine beside another vessel/machine for curing (if necessary). in addition, 3D printing attempts to satisfy the fabrication trade-offs and contradictory objectives e.g., quality and quantity. Other advantages such as the amazing design possibilities, labor, cost, and time reduction. Moreover, it reduces the risk of danger associated with some manual prototyping processes. A good advantage, as well, is that 3D printing can allow for more customized designs and allow for more new inventive designs and shapes. Finally, this fabrication process can be considered as eco-friendly. As with any manufacturing technologies, some materials are customized for this process, this will be the topic of the next section.

1.3.3 Materials for AM

With the extensive research and advent of additive manufacturing process, it extended the capability to print much complex geometries with various choice of material. Very careful attention was given to the choice of printed material. Recently, one can neither choose one single type of polymers to be suitable for all applications, nor choose one AM technique for all purposes. Nowadays, we see a wide range of specific techniques of AM, besides, a large various materials, such as polymer [6], ceramics [26], metals [27] and, even, glass [28]. Over this section we are not going to go deeper for AM techniques but for the used materials. In the frame of this thesis, we are going to exploit the available resources at CSIP (Conception, Système d'Information et Processus inventifs) research team to fabricate the models in this research work. For this reason, we will focus on polymeric materials as a base material from which we will fabricate the proposed applications and products in this thesis.

1.3.3.1 Polymers for AM

Polymers are widely used materials for 3D printing process, used to fabricate a large set of daily-used stuff such as toys, bottles, packages, appliances, and many of else useful tools. That justifies the continuous development of the polymer materials used for AM. We list afterwards some of the common commercial polymers harnessed for printing process like PLA (Polylactic acid), ABS (acrylonitrile butadiene styrene), PC (Polycarbonate), ULTEM (polyetherimide), TPU (thermo-plastic polyurethane), PEEK (polyether ester ketone), in addition to Nylon and its grand subsets which are very often used for printing process. Finally, it is worth mentioning that we will use polymeric materials in the context of illustrative case studies in this thesis.

1.3.4 Types of lattice structure

In this part, the essential elements concerning the cell geometries of lattice structures will be presented. Lattice structures consist of a fundamental unit cell featuring a defined geometry that is regularly replicated throughout space. Lattices can be classified in various manners; as 2D or 3D, random or periodic, open or closed, and homogeneous or heterogeneous [29]. As well, [23] classified unit cells of lattice structures to three categories, unit cell design based on geometric wireframe, unit cell design based on mathematical algorithm, and unit cell design based on topology optimization. Nevertheless, the most distinctive classifications include four categories [30]:

- Strut-based cellular structures, as shown in Figure 7
- Skeletal-TPMS based cellular structures, as illustrated in Figure 8

- Sheet-TPMS based cellular structures, as illustrated in Figure 9
- Shell-based cellular structures, as shown in Figure 10

In the case of strut-based lattices, the unit cell is comprised of an array of interconnected crossbars (s), linked at nodes (n). On the other hand, utilizing mathematical algorithms to define the unit cell is a precise approach for describing lattice structures [23]. Among these mathematical methods, the utilization of Triply Periodic Minimal Surfaces (TPMS) stands out as it effectively translates theoretical mathematical models into tangible lattice structures. TPMS-based designs can be achieved through two main techniques: by augmenting the minimal surface to generate sheet-based cellular structures, or by solidifying the volumes enclosed by the minimal surfaces to establish skeletal-based cellular structures [30]. The last type is the structures where the fundamental units consist of plates instead of struts. These lattice configurations are characterized as TPMS-like, although their surfaces might not possess zero mean curvature. They are commonly referred to as "shell lattices" [31].

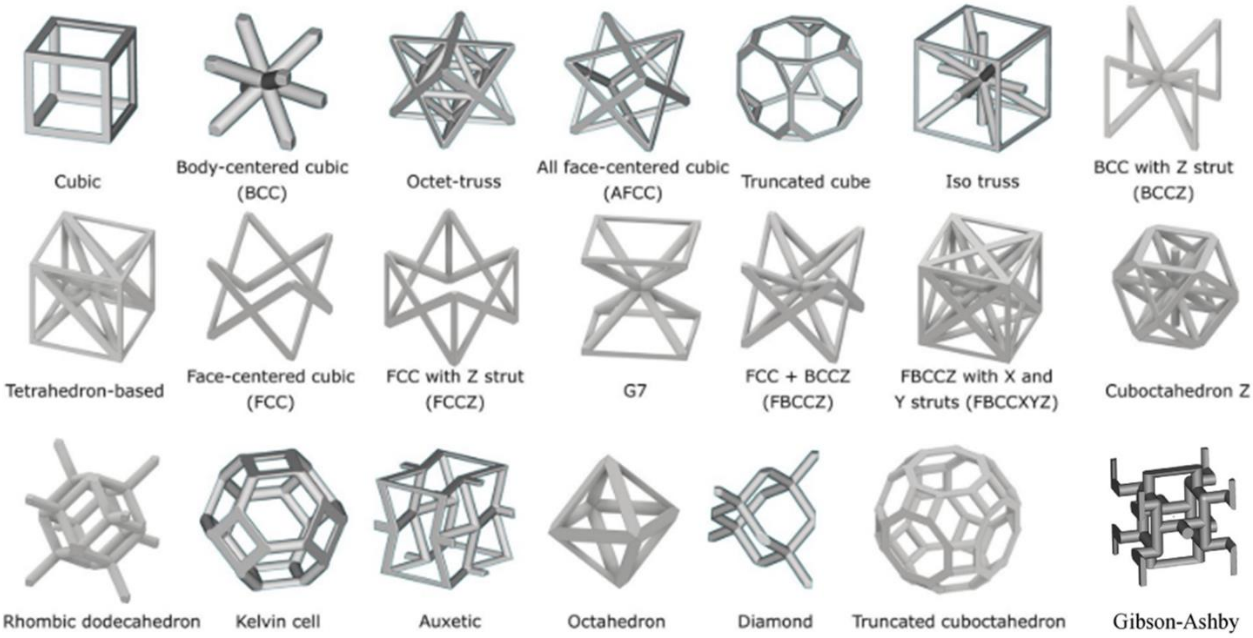


Figure 7: Different cellular forms of the strut-based cellular lattice structures (edited from [106] and [108])

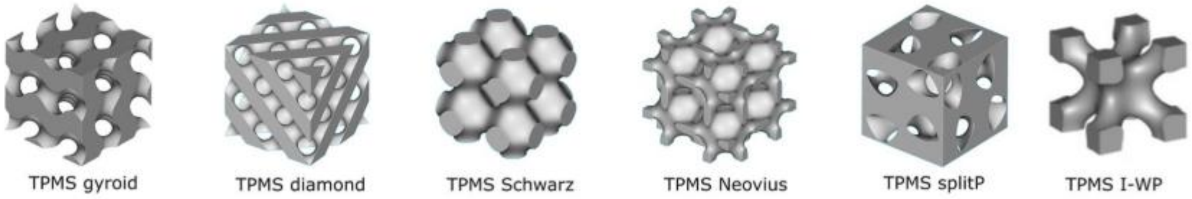


Figure 8: Different cellular forms of the skeletal-TPMS based cellular structures (edited from [32])

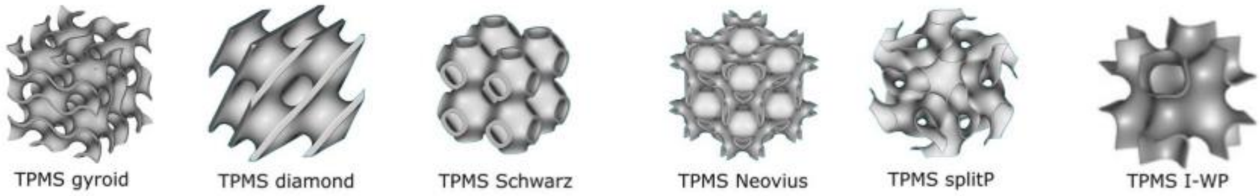


Figure 9: Different cellular forms of the sheet-TPMS based cellular structures (edited from [32])

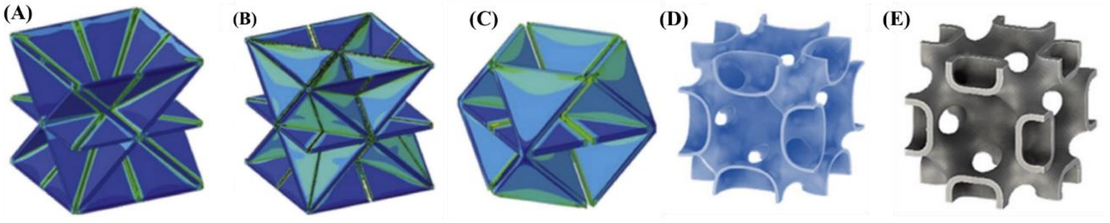


Figure 10: Lattice unit cells with shell-based structures are formed by positioning plates on the closest-packed planes of cubic crystals, effectively combining simple cubic (SC), BCC and FCC: (A) SC-BCC, (B) SC-BCC-FCC, (C) SC- FCC, (D) TPMS-like, and (E) Iso-shell (edited from [33] and [31])

1.3.5 Optimization and inventive design of lattice structure

Even though the wide research articles published on lattice structure, few of intention was given to exploit TRIZ methods to invent new lattice-based concepts. In [34] the article contributes a novel approach using machine learning to discover optimal lattice unit cells with significantly higher buckling load, leading to the design of high-performance sandwich structures in the field of lattice structures. On the other side, [35] presents an AI-based design approach using a 3D convolutional neural network and genetic algorithm to control anisotropic properties in microscale lattice meta-structures, enhancing the design of mechanical properties in macrostructures through mesoscale subregion decomposition and automatic adjustment of lattice structure combinations. In [17] proposed a new crash box design for optimizing its energy absorption performance through a multi-objective optimization approach, resulting in enhanced crashworthiness. The study [36] explores multi-objective crashworthiness optimization for novel lattice-filled thin-walled tubes, demonstrating that BCC hybrid lattice designs outperform BCC-Z counterparts in reducing peak crash force and increasing energy absorption. However, the limitation of these studies is the exploration of solutions within the known space of the problem. In other words, their contribution stopped at the frontier of optimization problems, and they showed no significant contribution in the inventive design. For this reason, we would like to explore more research work which contributed to solving lattice-structure-based problems by using inventive methods. In the works [37], [38], the authors used lattice-based structures to illustrate a computational design exploration approach that combines Genetic Algorithm (GA) and Theory of Inventive Problem Solving (TRIZ). This approach is supposed to aid engineers in defining design problems and generating solutions. In the paper [39] the authors integrated machine learning algorithms, into TRIZ-based methods to enhance the initial analysis phase of inventive design by automating information retrieval from scientific papers, and [40] to accelerate inventive solutions' development. Both contributions were illustrated by a new lattice structure solution in materials. Lastly, [41] integrated optimization-based and TRIZ-based methods to propose a new inventive lattice structure to enhance its crashworthiness.

1.3.6 Conclusion and synthesis

In this section, concentration was given to the mechanical design problems solved by using lattice structure. In the meanwhile, the chapter projected to different other applications. The chapter presented previous research works exploited optimization and inventive process to solve design problems by using lattice structures. Even though the cited contributions are interesting, the clear limitation between many of them is that they found solution concepts based on, only, a classical-TRIZ formulated problem e.g., two evaluation parameters involved. Another limitation is that some of these approaches solved the technical contradictions without solving the physical contradiction which is the core problem of the system. For this reason, in our study, we will concentrate on extracting and solving the complex core problems by using TRIZ-based methods.

This research work aims to explore the possibility of systematizing the inventive design process within an expanded general context, meaning to propose a method that offers the ability to solve multiple independent or related problems within the same general context. The challenge of this approach lies in the vast amount of information to be studied and modeled. Therefore, we proposed the two approaches mentioned in the section 1.1. To illustrate this method, the study of the "mechanical behavior of Lattice structures" is used as a case study. The choice of this study is justified by two reasons. The first is related to the methodological interest of the case. Indeed, in the case of the mechanical behavior of lattice structures, we have the possibility to leverage the solution in several categories of problems, such as energy absorption, structural rigidity, impact resistance, etc. The different categories listed earlier are linked to various performance parameters, all related to several system parameters such as the structure geometry, the used base material, the manufacturing process, etc. This diversity of parameters will enable the application of this method to specific applications in the mechanical field. While our application is restricted to the mechanical behavior of lattice structures, this method can potentially be extended to other fields such as thermal or acoustic, etc. The second reason for choosing the case of lattice structure is based on the significant industrial demand for this type of structure, to solve challenges where conventional structures such as bulk material or even composites are not sufficient.

1.4 Thesis structure

The remain part of the dissertation is structured in six chapters after the chapter of general introduction:

Chapter 2 "State of the Art on Existing Problem-Solving and Design Methods": This chapter reviews traditional and inventive product design and problem-solving methods found in scientific literature. It emphasizes the characteristics of each approach, their advantages, and limitations. This literature review helps position the thesis's contribution in the domain of inventive design. The chapter also underscores the research problem introduced in Chapter 1, which revolves around the development of tools and methodologies aimed at enhancing existing inventive design practices. Key objectives include evaluating existing design problem-solving methods, assessing their efficacy in modeling design system parameters, and scrutinizing how these methods account for the intricate relationships and influences between design parameters.

Chapter 3 "Generalized Table of Parameters (GTP)": This chapter details the proposed method for creating the Generalized Table of Parameters (GTP). It explains how the parameter table is obtained by gathering various relevant information about the design problem. The different stages of GTP creation, including information collection from experts and the inclusion of domain-specific bibliography, are described in detail. The proposed Generalized Table of Parameters (GTP) aggregates essential system-related data, including physical, qualitative, quantitative, and performance variables. This aids in understanding interrelationships among parameters, enhancing system modeling. The Contextual Database (CDB) links GTP cells to supporting information, streamlining contradiction extraction for inventive solutions. Automation via VBA scripting simplifies this process, offering a comprehensive resource for efficient problem-solving. This approach promotes knowledge sharing and collaboration, adaptable across various domains, although the focus here is on the mechanical domain.

Chapter 4 "Exploitation of the GTP (identifying the contradictions)": Building on the foundation outputs of Chapter 3, this chapter focuses on the use of the GTP in the inventive problem-solving process. It explains how the GTP facilitates the analysis of the initial situation and system modeling by providing quick and structured access to diverse knowledge. It explores the System of Contradictions (SoC) model within the TRIZ framework. The chapter introduces a method to extract and prioritize not only Classic TRIZ contradictions but also generalized systems of contradictions using the GTP and the extensive database. A concrete example is presented to illustrate how the GTP is applied in the context of lattice structures to extract a prioritized system conflict.

Chapter 5 "Invention through Design of Experiments (DoE)": This chapter introduces a Design of Experiments (DoE) method to tackle design problems when traditional sources and expert opinions are insufficient. The chapter outlines a systematic methodology, exemplified by addressing mechanical behavior in lattice structures. It demonstrates how experimentation, physical or numerical, helps understand parameter-performance relationships, unearth potential contradictions, and optimize solutions. The incorporation of a threshold streamlines the model adjustment process and encourages thoughtful constraint evaluation. The chapter employs software tools and packages such as PTC CREO®, ABAQUS®, Minitab®, and Pymoo® for experimentation, analysis, and optimization. By integrating TRIZ-based inventive methods, some solution concepts would be proposed and tested by using the numerical approach. This approach seeks to achieve design objectives and enhance problem-solving efficiency.

Chapter 6 “Conclusion and Perspectives”: In this concluding chapter, the culmination of a journey to revolutionize industrial product and material design is evident. Faced with a rapidly evolving technological, competitive, and consumer-driven landscape, this research has systematically developed a methodology addressing various aspects of inventive problem-solving. It begins by revisiting the research questions raised in earlier chapters and summarizing the contributions and limitations. The research also opens doors to promising avenues for future exploration and innovation, including qualitative parameter handling techniques, process automation through artificial intelligence and machine learning, and enhanced solution concept evaluation methods.

Chapter 2 State of the Art: Problem-Solving and Design Methods

When designing a new system, either a product or a process, a problem is being solved. Bonnardel in [42] stated that problem solving is a very common activity during designing or developing products. She recognized the role of problem-solving activity in the frame of design since she described the design activities as the same as specific problem-solving situations. Therefore, over the last few decades, many design-problem-solving approaches, methods, and theories were proposed to contribute to solving many design problems. Starting from the design loop process illustrated in Figure 2, the searched methods would be investigated to understand to what extent they addressed the initial question, asked in section 1.1. This chapter serves in showing the state of the art on the developments released in the frame of design problem-solving methods. The presented methods are discussed in the light of the initial question:

What approach to adopt for solving complex problems, based on the analysis of the initial situation according to the objectives to be achieved and the extraction, resolution of priority contradictions, without relying too heavily on experts and utilizing available data?

2.1 Design methods

The methods of design problem solving could be classified into two main categories. First, the routine problem-solving methods, which focus on analyzing the root causes of a problem and applying known and standard solutions. Second, inventive problem-solving methods which encourage invention by utilizing principles and models to change the existing model and generate new and original ideas. Scaravetti in [43] and Hiller in [44] differentiated between the different types of the design process and classified them into routine and inventive design, as well. In [45], [46] authors presented a comparison between both categories, routine and inventive, as illustrated in Table 1.

Table 1: Comparison between routine design and inventive design

Routine design	Inventive design
Handle what is known	Explore the unknown
Optimize available data for optimal results	Go beyond the optimized data of optimal solutions
Can give a compromise of solutions	Aims to solutions with no compromise

Searching the solution by using routine methods is an effective approach in many situations and for many of problems, but it is not an effective approach when it comes to an inventive problem which requires adding new variables and new relationships between these variables. Since routine methods search for potential solutions within the stated problem space, there is a probability of finding a final global solution. Some examples on the routine methods are Value analysis [47], functional analysis [48], six sigma [49], Plan–Do–Check–Act (PDCA) cycle [50], morphological matrices [51], Brainstorming [52], DFMA (Design for manufacture and assembly) [53], C-Sketch [54], Design catalogue [55], Quality Function Deployment [56]. On the other hand, inventive design theories and methods propose changing the stated problem space and therefore defining a new space of problem. Some inventive methods are based on TRIZ theory [57] (Theory of Inventive Problem Solving) and others non based on TRIZ. Some examples of the non-TRIZ-based methods used for inventive process are: C-K theory [58], Axiomatic design [59], Function–Behaviour–Structure (FBS) Framework [60], Brainstorming [52]. In this PhD, the focus would be more on the TRIZ-based methods and their development. For this reason, the next section will be dedicated to explaining TRIZ theory and its relevant element used within the design process. The reasons beyond choosing the theory TRIZ as a baseline on which this research work is developed, are three main reasons:

- TRIZ is described as a systematic approach to inventive design. It suggests a four-stage process for problem-solving: finding factual problems, formulating generic problems, generating generic solutions, and converging to specific solutions. Like that, TRIZ helps in decreasing the psychological inertia of users which means that TRIZ as a theory of related approaches could be used by individuals with no need, partially, to specify a high level of expertise.
- The team CSIP, in which this research work is conducted, works on the formalization of the invention activity e.g., TRIZ-based methods, in Product/System design in the light of engineering and information sciences. Hence, this team is specialist in TRIZ-based approaches.
- This research work is dedicated to develop the iterative design method [1]–[3], developed based on TRIZ theory. Therefore, this research work takes TRIZ theory as a referral baseline of this developed method.

2.2 TRIZ (theory, used tools, linked design methods)

TRIZ is one of the inventive design theories that proposes a set of systematic approaches. In this section we present the theory of TRIZ and its relevant methods and approaches. Then, we present the TRIZ-based methods of inventive design.

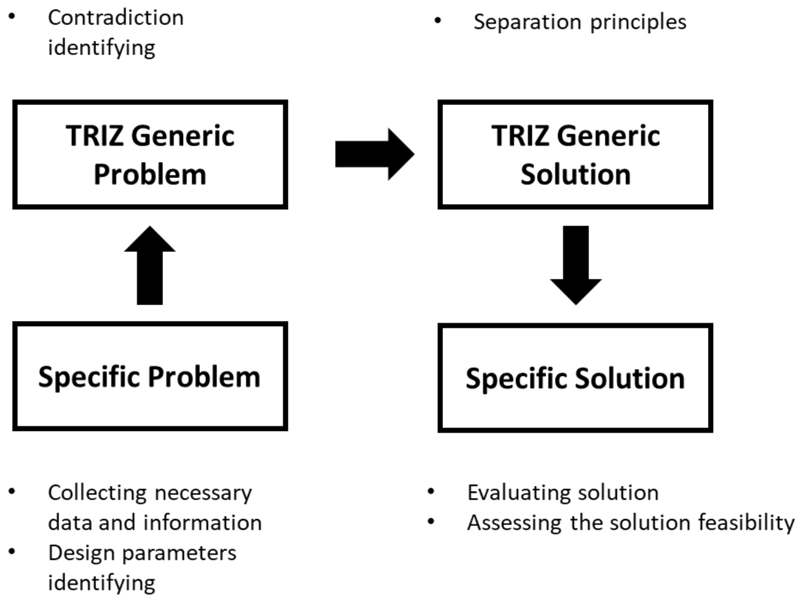


Figure 11: TRIZ approach to solve problems

TRIZ*: Theory of Inventive Problem Solving* (TRIZ -Russian acronym for: teoriya resheniya izobretatelskikh zadatch, which is translated in English: ‘‘Theory of solving inventive problems’’) [57], TRIZ is a systematic approach of inventive design which was originated by Altshuller in 1946, in this year Altshuller started working on TRIZ [61]. By 1985, Altshuller published the essential ideas with conceptual character of classical TRIZ (supplemented by complementary instrumental aspects). After 1985, the era of post-TRIZ started which included an expansion of the theory in terms of its partial formalization, combination with other methods and approaches.

Axioms of the theory are three [62]:

1. Laws of the evolution of technical systems: the evolution of a technical system is guided by a set of tendencies that are common to any system.
2. Contradiction of evolution: to evolve, a technical system must overcome the barrier of contradictions in accordance with its environment.
3. Specific conditions: the way a new technical system solves the contradiction depends on the available resources.

A set of methods organized as a system for solving inventive problems, in accordance with the preceding axioms, constitute a second interpretation of the term "TRIZ".

2.2.1 The approach of TRIZ to solve problems

One can elicit the fundamental of TRIZ theory which is: to eliminate the contradictions of a system by using the available resources to increase its functionality of this system and the ideality of the technological system. TRIZ suggests four-stages process to solve a problem: first, finding factual problems; second, formulating as-TRIZ generic problems; third, generating as-TRIZ generic solutions; and, finally, converge to specific solutions. As illustrated in Figure 11.

2.2.2 Design parameters

The General Theory of Advanced Thinking (Russian acronym: OTSM-TRIZ) is one of the developed theories based on TRIZ theory [63]. OTSM-TRIZ used a model called Element-Name of element-Value of element (ENV). This model is said to describe the system which is composed of (a) element (b) name or parameter (c) value. To model the design problem, it is needed to define these elements, so let us invoke the definition of each element of the model (ENV):

Elements: are the components constituents of the system and it could be expressed with a name, noun, or a group of names, e.g., table carry a cup, then table is an element

Parameters: these are qualifying elements by a given specificity. To indicate the parameters, one can use adverbs, names, or complements to object. When various specialists represent them, the form of their expression varies, and this is one drawback of taking only experts' feedback in consideration [64]. Parameters can be divided into two groups:

Values: This is the adjective applied to a certain parameter. e.g., the table must be thick, 'thick' is the value that describes the thickness.

As shown in Figure 11, the approach that TRIZ follows for framing the specific problem includes the data collection and parameter identification. The following phase, which is the generation of the design problem, could be formed by identifying the system 'conflict' which is reflexing the core problem of the system. This 'conflict' is called 'contradiction' in TRIZ is the subject of the next sub-section.

2.2.3 Contradictions in TRIZ

One can conclude and elicit that the basic of TRIZ theory is to remove a system's conflicts (which are called contradictions) by utilizing available resources to improve the system's functionality and ideality [65]. In the TRIZ, three types of contradictions are defined [66]: Administrative contradiction, technical contradictions and physical contradictions. These contradictions are representing the problem of a treated system in different stages of understanding the available and possible means to act on the treated system in order to solve its problem [57]. They are defined as:

- The administrative contradiction: it refers to a situation where there is a conflict between the demands or requirements and the knowledge to fulfil those demands.
- The technical contradiction: it refers to two opposite requirements. Once improving one requirement, the other deteriorates.
- The physical contradiction: it refers to two opposing states yet necessary for the same parameter.

However, OTSM-TRIZ kept only the two types of contradiction: technical and physical contradictions. A physical contradiction appears when the same subsystem of a technical system is demanded to have mutually exclusive requirements, such as property, characteristic, parameter, etc. To simplify the explanation of the physical contradiction, let's think about an example with electron emitters used in flat panel displays. These emitters need to make a strong electrical current. A needle-like shape would be great for this, but it can also cause the emitter to burn out. This creates a problem: the edges of the emitter should be thick to avoid burning out, but they also need to be sharp to emit a good current. These two types, physical and technical, are linked together in one problem model so-called system of contradictions, and we call this system "classical TRIZ system of contradiction SoC" (see Figure 12a). As shown in the Figure 12, the system of contradictions in TRIZ theory is based on contradictive evaluation parameters and on contradictory values of one design parameter when seeking to a given desired result. For this reason, studies implemented in the frame of TRIZ theory must search for contradictive parameters or values when a given desired result is due. Nevertheless, this model of contradiction shows the system of contradictions involving two evaluation parameters and one action parameter. In real life problems more evaluation parameters and action can be involved in the system of contradictions. In [3] the limitation of the classical-TRIZ and OTSM-TRIZ system of contradiction was revealed, and the concept of Generalized System of Contradictions (GSC) (see Figure 12b) was proposed to overcome this limitation in [66] and [67]. The GSC is expanded to consider not only a pair of EPs but two sets of EPs, for forming the generalized technical contradictions (GTC). Unlikely classic-TRIZ model of contradiction, the GSC considers two states of several action parameters APs instead of two states of one AP, for forming the generalized physical contradiction (GPC). In [67], the Generalized System of Contradictions is linked to Design of Experiments model (DoE), and an algorithm is developed in [68] for identifying and extracting generalized technical contradictions (GTC) from experiments. Another algorithm is proposed in [69] to identify and extract the Generalized Physical Contradictions (GPC) from experiments. Hence, automating the entire process of the extraction of the Generalized System of Contradictions (GSC). However, one of the downsides of this extraction is the huge number of extracted GTC and GPC. Thus, the same second obstacle of classical-TRIZ system of contradictions which is the selection of the contraction model to be treated by TRIZ. For this reason, a method was developed for choosing relevant GTC based on the optimization solutions located on Pareto front [70]. This method is detailed in the next sections to show its limitations in the light of this study.

At the end of this section, and for this thesis, we emphasize the extraction of the GSC to model the core problem of the design system.

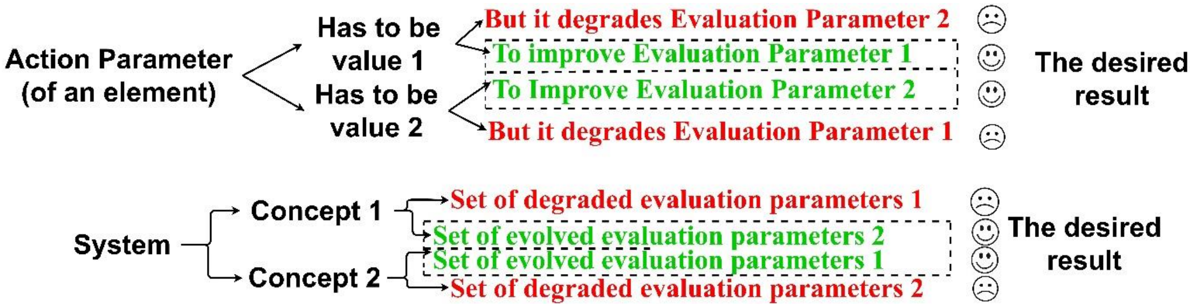


Figure 12: (a) Classical TRIZ system of contradictions, (b) Generalized System of Contradictions (GSC)

Back to the referral approach of TRIZ to solve problems, in the section 2.2.1, and after extracting the problematic contradiction, solving this contradiction could open the door to propose solutions concepts. Hence, we focus on the use of the separation principles of TRIZ [71] which aims at solving a physical contradiction and therefore solving the core problem of the designed system. These principles are presented within the next section.

2.2.4 Separation principles in TRIZ

TRIZ addresses both spatial and temporal aspects of contradictions, to analyze the system in space and time, as a part of the analysis of system. These contradictions occur within the operational zone and during the operational period, pinpointing the precise location and timing of the contradiction. After analyzing the system, and according to recent research work in TRIZ [2] [72], four key-principles to solve a physical contradiction are used. They are separation principle in space, separation principle in time, separation principle upon condition, and separation principle between parts and whole.

Separation principles were applied widely in many research papers to solve the physical contradictions and enhance the problem-solving process. In [2] authors applied the separation principles to improve the performance of a cutting tool used for machining composite materials. In the study [73], author introduces a model based on the separation principles to shed light on why certain risks are challenging to anticipate and to propose potential avenues for discovering hidden risks. In the study [74] authors introduce two new Compression Resin Transfer Molding (CRTM) mold designs based on the application of TRIZ separation principles to solve the physical contradictions. Moreover, in the paper [72] authors emphasize that TRIZ can effectively resolve conflicts that arise due to differing demands in the aeronautic and automotive sectors by exploiting the separation principles. Lastly, in [75] authors the principles to solve the physical contradictions in the conceptual design phase. Rajic's methodology capitalizes on the principle of parameter multiplication within the LT units system to address physical contradictions [76].

However, some promising research works acknowledged certain limitations in their studies, such as [2] which mentions the difficulty of solving complex generalized physical contradictions. Moreover, [74] and [72] which addresses only classical-TRIZ contradictions and lack testing the feasibility of proposed approaches. Even the contributions that leveraged the multiplications of parameter units to solve physical contradictions [76], may cause a vagueness in the resulting length-time-based unit. Based on these research works, we concluded that while the separation principles effectively address physical contradictions i.e., classical TRIZ physical contradiction, they may not provide a satisfactory solution when dealing with complex physical contradictions e.g., generalized physical contradiction. This problem is supposed to be handled within this thesis, as well.

2.2.5 TRIZ-based methods

TRIZ theory is a base of myriad of developed work. Many of *theories* were proposed which are TRIZ-based ones, such as, The General Theory of Advanced Thinking (Russian acronym: OTSM) [77], The Theory of Development of a Strong Creative Personality (TRTL) [78] and The Theory of the Evolution of Technological Systems (TRTS) [66]. *Frameworks*, such as, Inventive Design Method (IDM) [79]–[81], Way of Oriented Innovation Strategy (WOIS) (translated in Germany: Widerspruch-sorientierte Innovations strategie), Unified Structured Inventive Thinking (USIT) [82], Advanced Systematic Inventive Thinking (ASIT) [83]. *Approaches*, such as, Network of Problems, as a part of ORSM [84]–[86]. *Models*, such as, model bridging optimization methods and inventive problem-solving tools [66]. *Approaches*, such as, a global approach to find the optimal solution out of Design of Experiments (DoE) and to increase this optimum by the complementary use of TRIZ-based methods [87]. Even many of computer-based algorithm were developed based on TRIZ theory, such as, Algorithm for identifying generalized technical contradictions in experiments [68], and an exact algorithm to extract the generalized physical contradiction [69]. Moehrle in [88] presented a structure of TRIZ tools according to the field of application which is important to analyze and solve the problem. Chou in [89] and Ilevbare et al., in [90], presented an overview on the tools used in the frame of TRIZ, such as, 40 inventive principles, Effects database, Separation principles, Contradiction matrix, Patterns of evolution of technical systems, IFR and ideality, Function analysis, ARIZ (the Algorithm for Inventive Problem Solving), S-curve analysis, multi-screen, Analysis of system resources, and Substance field (Su-field) analysis.

The integration of TRIZ with other tools yields advantages [91]. Numerous published works substantiate this claim, proving the amalgamation of TRIZ with various tools and methodologies to attain diverse objectives. Several studies have attempted to fuse TRIZ tools with techniques for addressing non-technical issues such as logistics [92] and Maritime Transportation [93]. Research illustrates instances of enhanced processes resulting from the synergy between TRIZ and other tools.

In [94] a systematic approach to integrating TRIZ/QFD into one system of optimization of Engineering requirements. Other contributions tried to integrate both approaches, TRIZ and QFD, such as [95] and [96]. Nevertheless, these suggestions faced certain restrictions. Initially, the scope of defining a problem is constrained by a set of limited requirements gathered from customers. Moreover, the treatment of design problems and collected data depends, heavily on the level of experience of working team. This risks the increase of subjectivity in regards of problem formulation and potential solutions. Furthermore, the requirements and design elements guided by them are overly tailored to a specific design issue linked to a particular product and a specific group of customers. Consequently, the design approach cannot be applied broadly to various design problems or a larger group of problems.

Many developers presented numerous approaches to reveal key problems in border with TRIZ theory. One of the most popular processes used to reveal the key problem is Root Cause Analysis (RCA). RCA is a process to find causal relationships of the problem to identify the causes of this problem [97]. A set of research contributions were dedicated to get benefits of integrating TRIZ with RCA approaches, such as the Functional Why-Why approach [98] which reformulates the problem in the initial situation into the so-called Why-Why contradictions. Another approach is developed based on CECA method [99]. Lastly, the developed approach is Root Conflict Analysis (RCA+) [100]. On the other hand, in the framework of the Inventive Design Methodology (IDM) [79]–[81], [86]. The TRIZ-based methods, such as network of problems (NoP) [85] was integrated with non TRIZ-based methods such as Pugh's matrix [101].

In [102] the Generalized System of Contradictions (GSC) was proposed and linked to Design of Experiments model. In [68] an algorithm was presented for identifying and extracting generalized technical contradictions (GTC), a part of the generalized system of contradictions (GSC), from experiments. The algorithm used to extract the other part of the GSC which is the generalized physical contradictions (GPC), was presented in [103]. However, the main limitation of these approaches was the huge number of extracted contradictions, so that the human expert is not able to deal with them. On the other hand, in the papers [2], [87] authors presented a general approach to build a continuum between optimization and inventive methods, mainly based on the consideration of the Pareto-frontier as a link between both approaches. This approach was based on the exploitation of experimental model i.e., Design of Experiments DoE. In [41] authors concatenated optimization methods with inventive ones to propose new lattice structure which give a response to industrial needs i.e., energy absorption. This approach is DoE-based as same as the previous one. Lastly, authors of [64] proposed a TRIZ-based approach to prioritize the system conflict "*Contradictions*" to be solved out of expert's interviews.

Among all these methods, and others not mentioned yet, this study exploits some TRIZ-based methods along with the iterative approach presented in [1]–[3] and illustrated in Figure 2. This iterative design process (design loops) will be presented in the next section.

2.3 Inventive design loop phases

The iterative inventive design problem-solving method that is intended to be enhanced in this work is shown in Figure 13. It is composed of an iterative process steps which are based on four main phases: Analysis of initial situation, System modeling, Optimization, and Invention (model change) [3], [104]. In this section, two main lines will be followed, the first line presents the original methods used in different phases of this design process. The second line is presenting the developed design methods for each phase of the entire process and how did they address the initial research question:

What approach to adopt for solving complex problems, based on the analysis of the initial situation according to the objectives to be achieved and the extraction, resolution of priority contradictions, without relying too heavily on experts and utilizing available data?

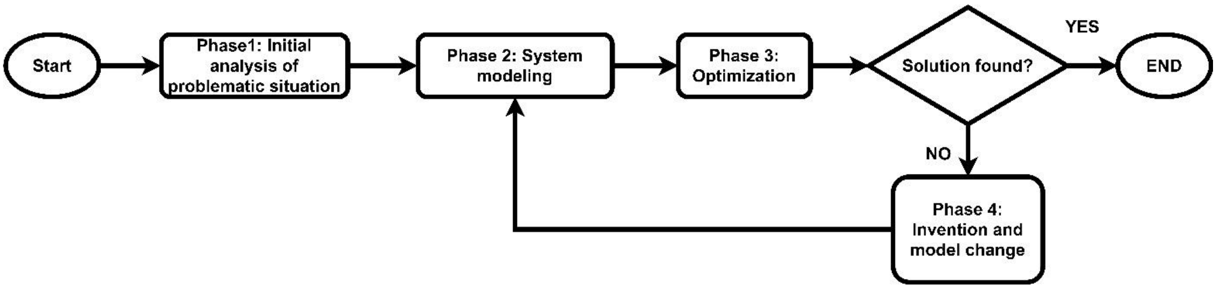


Figure 13: The iterative inventive design process (design loop)

2.3.1 Analysis of initial situation

Analysis of initial situation (A.I.S.) is the first phase in the inventive design problem-solving methods. During this phase, the objective is to understand the administrative contradiction and hence understand the system itself. To achieve this goal, pertinent information is collected, derived from sources like literature reviews, expert insights, experiments, patents, internal company records, and other relevant data concerning the topic. Following this, designers employ a diverse array of techniques and methods to identify the problem to be solved. Inventive Design Methodology (IDM) [79]–[81], [86] as a systematic approach exploited a set of methods to analyze the initial situation, such Network of Problem (NoP) [86] and nine-screens analysis [89] [90]. In the same direction, [64] developed an approach to enable the choice of the design problem, based on qualitative information, through problem experts' interviews within the initial situation.

A main limitation of many expert-based design methods is that the robustness of the manipulated data undergoes the level of experience of the working team. Therefore, this risks the variation of the output results such as, the design parameters, based on the experience level of experts. These limitations hinder from expanding the problem space and discovering further parameters contributing to comprehending the design problem. Moreover, this can be a limiting factor in terms of accuracy and completeness.

In [105] the authors presented the Inverse Problem Graph (IPG) which is an approach of starting from a lower-level problem, concentrating on the most significant issue, aligns with Lean principles. In [39] the authors introduced a new method for the initial analysis phase of inventive design by integrating the artificial-intelligence-based methods with the Inverse Problem Graph (IPG). On the level of graphical representation, the network representation of design parameters such as used in [64] and representation of design problems such as used in (Khomenko and Guio, 2007a) and [100]. This representation showed a very good level of representation for problems, subproblems, and relevant parameters within the phase of AIS. However, these representations are not very effective in the case of representing a large number of parameters. The reason is that with the increase of the number of parameters, reading such networks becomes more difficult. For example, a network composed of 200 parameters with their interactions.

2.3.2 System modeling

System modeling is one of the important phases in the inventive design method. Modeling the problem can be implemented by using different approaches [106]: Experimental approach; Numerical approach; Analytical approach; and Qualitative approach.

Experimental approach: this approach involves conducting physical experiments and gathering data to understand and model the system's behavior.

Numerical approach: it relies on computational simulations and mathematical algorithms to represent and analyze the system.

Analytical approach: this method employs mathematical equations and theoretical models to describe the system's behavior and properties.

Qualitative approach: it focuses on non-quantitative aspects, such as system descriptions, diagrams, and experts' feedback, to provide an abstract representation of the system.

Many system modeling methods were proposed, and others were exploited. In the work [64], authors developed the Network of Parameters (NoP) to analyze the qualitative data in order to model the design problem, which is considered a qualitative model. This paper presented an approach by integrating the

OTSM-TRIZ Network of Problems [86], which is developed at CSIP team as a qualitative model, to construct a Network of Parameters for identifying priority problems. IDM framework which is an extension of TRIZ was developed at INSA Strasbourg [79]–[81], is based on modeling the design problem by using the qualitative approach to analyze expert's feedback, as well. In IDM framework, the problem is modeled by using the NoP. On the other hand, the paper [107] exploited the experimental approach to model the problem by utilizing simulation data to link Action Parameters (APs) and Evaluation Parameters (EPs). This model helped identify generalized technical and physical contradictions. In [108] the article used the experimental approach to model the problem. In [1] authors used the experimental approach to model the problem for solving supply chain problems in the domain of supply chain. In [92] the paper modeled the problem by using the experimental and qualitative approaches. This approach was based on analyzing the past experiences of using TRIZ for green logistics problems to uncover potential and unexplored areas in this field. The paper [41] integrated the numerical approach as a way to model the design problem, with TRIZ-based methods, to propose a new inventive lattice structure to enhance its crashworthiness. The papers [2], [87] exploited the experimental approach by performing the Design of Experiments DoE to model the design problem. The proposed method aimed to optimize machining productivity while ensuring product quality through Pareto frontiers and solution concepts. The study [109] focuses on the challenges of analytical and experimental model generation and provides an analysis of the state of the art in automated model generation, offering insights into modeling strategies within the context of Industry 4.0. On the other hand, [110] employs data-driven modeling, both experimental and qualitative, to simulate and analyze complex remanufacturing systems, aiding decision-making and performance evaluation.

2.3.3 Optimization

In the context of the iterative inventive design process (design loop), this section provides a focused exploration of existing methodologies, specifically optimization methods. Rather than an exhaustive survey of optimization techniques, our objective is to illuminate the role of optimization within the inventive design loop. Optimization is the systematic refinement of system parameters to achieve better designs. Inputs to this process encompass system models generated through various approaches such as regression modeling, while outputs yield optimized design solutions and/or partial solutions. Previous implementations of this loop have tackled diverse optimization problems, employing tools such as Design of Experiments (DoE). Some research work which exploits optimization methods and related developed ones for both single-objective and multi-objective problems, will be discussed.

2.3.3.1 mono-objective optimization problem

The mono-objective optimization is the process of searching for one optimal solution for each output performance parameter e.g., evaluation parameter. For this type of optimization, we search to optimize one evaluation parameter independently of the others. In [111] authors contributed in devising intelligent cutting condition selection tools, enhancing surface quality, tool lifespan, and production efficiency, partially, through mono-objective optimization approaches. In [41] a new lattice structure was presented and its behavior is optimized, partially, by using mono-objective optimization methods. The main limitation of this type of optimization is its inability to consider trade-offs and conflicting objectives, often leading to suboptimal solutions that do not account for the diverse goals inherent in complex systems.

2.3.3.2 multi-objective optimization problem

The optimization process that considers more than one objective is called multi-objective optimization. Plenty of real-life problems contain more than one objective to be satisfied [112], [113]. In [111] authors contributed in devising intelligent cutting condition selection tools, enhancing surface quality, tool lifespan, and production efficiency through multi-objective optimization approaches. Other research works showed that the integration and proposal of optimization methods attracted a lot of attention. The paper [109] emphasized the need for instant modeling and simulation, which is crucial for optimization in large-scale production systems. This research work showed a potential integration of data-driven systems within the design loop. In the work of [107], solutions to the multi-objective search or optimization problem based on the DoE performed on the simulator and/or optimization algorithms, are searched. In [108] the article introduces a method to link optimization and invention process through introducing the benefits of prioritizing the Generalized System of Contradictions (GSC). The paper [41] integrated optimization-based and TRIZ-based methods to propose a new inventive lattice structure to enhance its crashworthiness. The papers [2], [87] proposed an approach that combines Design of Experiments DoE and TRIZ-based methods to optimize machining productivity while ensuring product quality through Pareto frontiers and solution concepts. However, many of these research works did not explicitly, show how to integrate the multi-objective optimization within the design loop. On the other hand, in [1] the authors presented a novel methodology integrating ARIZ with optimization and simulation for solving supply chain problems in the domain of supply chain. In [92] links optimization and the invention process by proposing the use of TRIZ methods to explore new conceptual solutions for multi-objective problems in Green Supply Chain Management (GSCM), contributing to optimizing GSCM processes and achieving better performance through the synergy of TRIZ and optimization approaches. The last contributions showed the strength of performing iterative design process, but they did not show how to enlarge the design process to encompass a larger number of design problems without repeating the same process and consume a lot of time and efforts.

2.3.4 Invention (model changing)

The research team CSIP is specialized in inventive process, and for sure, there are a lot of contributions in this direction. In this section we will cite a part of these contributions. Inventive Design Methodology (IDM) [79]–[81], [86] was developed as a systematic inventive method to solve complex problems. Network of Problem (NoP) [86] was developed as a tool to model the design problem inventively based on TRIZ theory notions. In the same direction, [64] developed an inventive approach to enable the choice of the design problem. In [105] the authors presented the Inverse Problem Graph (IPG) which is a TRIZ-based approach of starting from a lower-level problem, concentrating on the most significant issue, aligns with Lean principles. On the other side, CSIP contributed with the automation of some TRIZ-based methods, or some steps, through integrating new algorithms. For example, [114] enhanced AntMiner-based rule classifiers by setting the minority class as the default, resulting in fewer rules, reduced runtime, and improved classification performance for databases with varying complexities. The work of [115] improved machine learning-based methods for recognizing Generalized Physical Contradictions (GPC). [69] presented an algorithm that bridges routine and inventive design by extracting generalized physical contradictions (GPCs) from experiments. [68] proposed an algorithm for identifying and extracting generalized technical contradictions (GTCs), by utilizing data from statistical design of experiments. In [39] the authors contributed to speed up the inventive design process by integrating Artificial Intelligence methods like neural network doc2vec and machine learning into the IDM framework. [116] enhanced inventive design and TRIZ theory by using NLP to categorize patents, facilitating problem-solving and improving efficiency in handling unstructured data. [117] improved the extraction of inventive information from patents by focusing on the hierarchical structure of patent claims, addressing the issue of noise in the output results generated by NLP methods. The work of [107] introduced a method that utilizes simulation data to identify generalized technical and physical contradictions, extending TRIZ-based methodologies for multi-objective problems. In [108] the article introduces a method to formalize and automate TRIZ-based patterns through a Generalized System of Contradictions (GSC), addressing simulation-based problem resolution and the role of contextual contradictions in TRIZ principles. In [1] the authors presented a novel methodology integrating ARIZ with optimization and simulation for solving supply chain problems in the domain of supply chain. In [92] the paper explored the application of TRIZ in addressing innovation challenges within green logistics, analyzing past experiences of using TRIZ for green logistics problems to uncover potentials and unexplored areas in this field. The paper [41] integrated optimization-based and TRIZ-based methods to propose a new inventive lattice structure to enhance its crashworthiness. The papers [2], [87] proposed an approach that combines Design of Experiments DoE and TRIZ-based methods to optimize machining productivity while ensuring product quality through Pareto frontiers and solution concepts. [93] introduced a novel approach for problem-solving in the maritime industry, combining TRIZ with semi-structured interviews to identify and resolve contradictions among different objectives. Lastly, CSIP members contributed in the phase of design evaluation. For example, [46] recognized the need for a systematic method to evaluate the behavioral performance of solution concepts in inventive design, aiming to bridge the gap between conceptual descriptions and formal evaluation for effective solution concept selection. On the other side, [118] proposed an Function-Structure-Behavior (FSB) modeling approach for evaluating TRIZ-based solution concepts in innovative design.

The common limitation between these contributions is that they did not show how to systematize the design process to solve a larger family of design problems without repeating the same process for each single problem. The fact of solving many design problems within an enlarged general context to include many application fields within the same process, this fact is not explicitly treated from previous research works.

Among the presented methods developed at CSIP team, we selected two of the existing design problem-solving methods to be presented in detail. The first method is an approach used to hierarchize and prioritize the problems out of qualitative data. The second method is an approach to extract and solve GSC, only lying on pareto front, out of experimental data. The first method will be applied in chapter 4 to reveal its limitations, however, the second one will be applied in chapter 5. The shortage in the efficiency of outcome results of both methods will be treated by proposing developed methods in both chapters.

Developed method 1: Global approach to prioritize contradictions

In the frame of problem-solving methodologies, the pursuit of effective methods to identify the priority problems to be solved has been a fundamental challenge, particularly in fields involving complex systems. Among the array of methodologies, TRIZ (Theory of Inventive Problem Solving) has stood out as a prominent approach to resolving technical problems. Despite the effectiveness of TRIZ approach to solve problems, it encountered a notable shortcoming - the identification of the priority problem that demands resolution.

To fill this gap, the research community proposed alternative methods to reinforce the Analysis of Initial Situation (AIS) phase, such as OTSM-TRIZ Network of Problems [86], ARIZ-85A [119]. However, these approaches were often tethered to their own constraints. They presented no tool to hierarchize the problems. The work in [64] presented an approach that aims to the identification of priority problems within the context of complex systems and technical challenges. By leveraging the power of qualitative data, it offers a systematic way to discern the most pressing issues in problem-solving scenarios. This approach is composed of three phases:

Phase 1: this phase begins by defining the final goal of the solution and identifying known solutions and bypass approaches. These initial steps lay the groundwork for building a Network of Problems (NoP), which serves as a graphical representation of the problem space.

Phase 2: this phase involves analyzing the relationships between Action Parameters (A.P.) and Evaluation Parameters (E.P.), all while considering their influence on the problem. The method shows the interconnection between parameters through building a table of parameters. This table is then transformed into a Network of Parameters, a visual representation that exposes the dynamics of the system's parameters and their influences.

Phase 3: in the final phase, the Network of Parameters is scrutinized to identify the priority Generalized System of Contradictions (GSC) that merits resolution.

Developed method 2: Pareto analysis (Design-of-Experiments-based approach)

In contrary with single objective optimization problem, the solution to a multi-objective optimization problem is of a concept than a definition (Arora, 2004). In the multi-objective problem, there is no single global solution, but a set of points (solutions) that fit a predetermined definition for an *optimum*. The predominant concept in defining an optimal point (solution) is that of *Pareto optimality (or pareto frontier or pareto front)* [121]. Optimal solutions are defined as non-dominated solutions by any other solutions, and these optimal solutions are representing different trade-offs between the objectives (see Figure 14). The selection of one solution among others -solutions of pareto optimal set- (in case such is needed to be selected) is left to the decision maker (DM). They choose according to the required and the current needs and based on their own criteria and project goals.

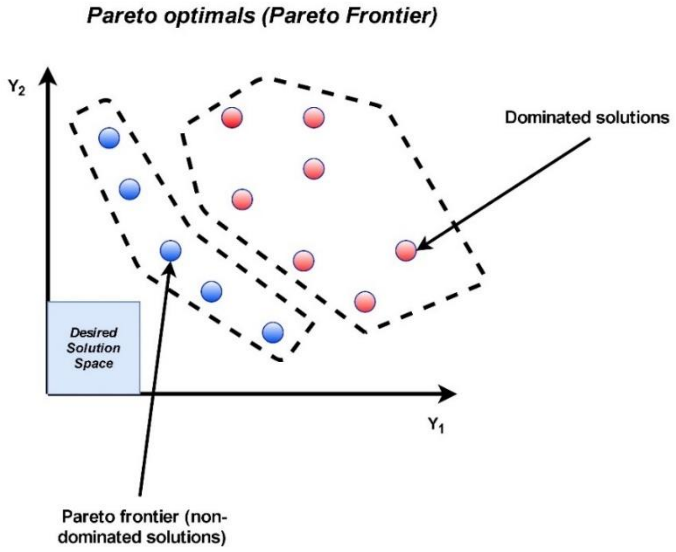


Figure 14: Identification of optimal solutions by Pareto optimal

Starting from this concept of optimum solutions, [107] exploited this concept to propose the extraction of robust GTC and hence relevant GSC, in an example of logistics which is a fleet cost reduction problem. The analysis of pareto optimums is of our interest, as well, so that the optimum solutions of the design problem could be selected out of a large set of solutions. In [108], authors proposed a method to go from simulation until inventive problem resolution. In [2], authors proposed a global approach for determining the optimal solution from a DoE and overcoming this optimum by the complementary use of TRIZ-based methods. This developed method is divided into three main phases, as follows:

1. Optimization: in this phase the DoE is performed, then, the approach aims at finding a final desired solution by confronting solutions to the formulated objectives. If this final solution is found, the approach stops, otherwise, it continues to the second phase.
2. Obtain GSC By Pareto analysis: this phase aims to obtain robust GSC located on pareto frontier.
3. Solve GSC: in this phase, the approach applies inventive methods to solve the extracted GSC.

The selection of generalized contradictions in this version of the developed approach is based of excluding any dominated solution (not located on pareto front). Thus, it is proposed to only consider, as robust GTC, the ones located on the Pareto front. This method will be applied in chapter 5, therefore, its limitations would be revealed in the frame of the inventive design problem-solving method.

2.4 Problem(s) and Research Question(s)

In the beginning of this section, a reminder of the initial problematic question is due:

What approach to adopt for solving complex problems, based on the analysis of the initial situation according to the objectives to be achieved and the extraction of priority contradictions, without relying too heavily on experts and utilizing available data?

In the light of this question, the state-of-the-art was carried out. In this section, we present a conclusion and synthesis of the cited state-of-the-art to treat problems linked to the iterative inventive design process (design loop). In the section 2.2.4, the research discussed contributed, partially, in addressing the initial research problem through the application of separation principles, particularly in the context of classical TRIZ physical contradictions. However, the cited work raised questions about the difficulty of solving complex generalized physical contradictions, and the limitation with resolving classical SoC only. Even though [76] leveraged the parameter units to solve physical contradictions, his approach may lead to vagueness in the resulting length-time-based unit.

In the section 2.2.5, while the cited approaches and integrations have proven beneficial within the inventive design problem-solving process, certain limitations are also noted. First, the scope of applying the inventive design problem-solving process may be constrained by limited requirements gathered from customers. They do not provide, explicitly, an approach for systematizing the design process to solve a broader range of design problems without the need to repeat the same process for each individual problem. Second, the level of experience of the working team can heavily influence the treatment of design problems, risking subjectivity in problem formulation and potential solutions, generally decision-making process. This was the common synthesis with the section 2.3.4. Last drawback is fitting with the synthesis of the section 2.3.1 which is concerning the initial situation analysis (A.I.S.) in inventive design problem-solving. Many of the cited work in this section states that they often rely on expert judgment, and even the robustness of the data depends on the experience of the working team. This can lead to variations in the results based on the expertise of the experts involved, limiting the expansion of the problem space and the discovery of additional parameters. These variations can affect the accuracy and completeness of the analysis. Additionally, graphical representations used in these methods, while effective for smaller numbers of parameters, become less effective when dealing with a large number of parameters, such as networks containing 200 parameters and their interactions. The readability of such representations becomes fuzzier with the increase of the complexity of design problem.

Within this PhD, the case study would be about a set of design problems. Therefore, this leads us to concentrate on multi-objective problems. The approaches and method cited in the section 2.3.3 are exploiting different optimization methods. Although these approaches show the strength of the inventive design process, some methods often lack explicit integration of multi-objective optimization within the iterative design loop. This drawback aligns with the one mentioned in the section 2.3.4. Moreover, the contributions cited in this section did not show how to systematize the design process to solve a larger family of design problems without repeating the same process for each single problem. The fact of solving many design problems within an enlarged general context to include many application fields within the same process, this fact is not explicitly treated from previous research works.

To overcome the limitations found in the previous research works cited in the state-of-the-art, partially, or completely, this PhD is presented. Two main approaches are proposed in this work to address the initial problem. The first approach is the construction (in advance) of a Generalized Table of Parameters (GTP) linked to a contextual database expressing relationships between pairs of system parameters. Once created, it allows experts and non-experts to formulate and prioritize contradictions for a range of problems. Moreover, this approach allows them to achieve solution concepts for the extracted contradictions. The second approach is to explore the extent to which formal methods, such as "Design of Experiments," can also lead to understanding the relationships between parameters and thereby extract contradictions for resolution and solve them. The second approach allows users to examine the feasibility of solution concepts for determining whether they are final or partial solutions of the extracted conflict(s).

Despite the existing approaches and methods in the iterative inventive design problem-solving, the state-of the art revealed that the iterative inventive design process (design loop) still suffers from some limitations and drawbacks through the different steps. This synthesized refining the initial problem question and formulating a set of research problems to be tackled within this thesis. The research problems of this thesis can be resumed in four main problems:

Q1: How can a systematic inventive design process be adapted to address problems in an expanded general context with various potential application fields?

Q2: Based on the built model, collected information and data, how to extract the most prioritized problem to be solved?

Q3: How can experiments be used to gain deeper insights into system behavior to develop the system towards ideality?

Q4: How can the model change process, particularly in resolving generalized contradictions, be simplified, and made more feasible within the inventive design problem-solving process?

Tackling those research problems, totally or partially, will be detailed within the next chapters. The future work or problems treated partially will be explained in the last chapter.

Chapter 3 Generalized Table of Parameters (GTP)

In this chapter, the proposed approach is based on the observation that some information for problem formulation is specific to the system or family of systems under study and represents only a small portion of the information contained in the domain's bibliography [122]. This information is largely common to the design problems concerning these systems and can, therefore, be extracted independently of the specific problem and in advance of its treatment (at least with the design process described in Figure 2). Thus, our first proposition is to accomplish a part of the work that the designer must undertake in advance by creating a Generalized Table of Parameters (GTP) for the system, encompassing various relevant information about the system and frequently expected performances. It represents the different parameters characterizing the system or the process, including physical, qualitative, or quantitative variables, as well as variables reflecting expected performances. Identifying and understanding these parameters and their relationships within the system enables a better understanding of standard and inventive design constraints and opportunities. Indeed, comprehending these interconnections can help identify dependencies and interactions among parameters that may influence the system and, consequently, better model the problem to be addressed. The table synthesizes and organizes vast literature review documents, expert perception, and reports of CAD/FEM trials, on the specific domain under study. In this thesis, the studied behaviors are in the mechanical domain, concerning rigidity, energy absorption, deformation, weight, and cost of lattice structures. The sources can include research articles, books, case studies, patents, numerical simulations (FEM models), CAD models and other resources providing in-depth information on concepts, methods, and standard solutions proposed in the field. It can also be enriched by the opinions and knowledge of domain experts, who can offer unique perspectives, valuable advice, and recommendations based on their experience.

Furthermore, each cell of the table cross-referencing system parameters is linked to a set of source information that explains, validates, or extends its content. This source is called in our study “Contextual Database (CDB)”. The generalized aspect of the table and its accompanying database is crucial, allowing easy enrichment with new information, studies, or research results. However, the update and maintenance aspects of the database are not addressed in this thesis. Extracting contradictions from the database by analyzing the links between parameters, their weights, and significance helps highlight conflicts within the system and, consequently, extract contradictions. This guides the search for inventive solutions and contributes to effective problem resolution in the industrial context.

Since the number of cells of such tables may increase enormously, it could be difficult to create customized files and link it to each cell manually. For overcoming this problem and to automate the generation of database files and establish hyperlinks with GTP cells, VBA script was developed. This script automates the process, making it more efficient, less prone to errors and less time-consuming. The full script of this VBA script is available in appendix A.

- Database for other applications

The generalized table of parameters, along with its references and appendices, can serve as an instant tool in a specific field for solving a set of problems. Its linked database offers comprehensive collected equations, graphs, applications, keywords, values, and geometries extracted from many articles. making it an efficient tool for researchers or users seeking to solve different problems in the same field without referring to a long list of references repeatedly. Moreover, if the researcher or user aims to solve the design problem, they can directly search for the system parameters in the table and use the database to obtain models such as equations, graphs, experiments, and expert feedback. The table of parameters provides a significant advantage by saving considerable effort and time that would otherwise be required for searching information. The use of a generalized table of parameters can also promote the sharing of knowledge and expertise across different domains and disciplines, enhancing collaboration and innovation in research and development. Moreover, the table can be extended, dynamically, to represent multiple domains for solving multi-physical and coupling design problems such as thermomechanical or electromechanical problems. However, in this thesis, we will exploit this representative table and its connected database to serve the case studies in the mechanical domain, only.

3.1 Generalized table of parameters

3.1.1 Introduction and definitions

We remind that the objective of this chapter is to propose a unified approach to build a generalized table of parameters. And since this generalized table will be used as a tool to facilitate understanding the inventive design problems, these problems will be linked to systems and this system will be defined within a general context. So, before any deeper discussions, definitions of “System”, “Design problem”, “General context” and “Parameter” should be presented, first.

System: the system can be a product or a process which is a well-organized group of components (or subsystems) that work closely together to provide a variety specific function(s).

Design problem: It represents an unsatisfactory situation and the barrier that forbids a system from achieving a satisfactory situation within a general context. For example, heavy structures for certain applications require light-weight structures.

General context: a frame formed by a set of conditions, boundaries, requirements, and constraints and within this frame the system is located, and the problem should be solved. For example, fish can stay alive in an aquarium but cannot fly, so this is a restriction.

Parameter: it is a characteristic of the system which represents a situation and by the change of its value, the function of the system is realized.

"*Generalized table of parameters*": is a tool used to represent and model data and information about general parameters linked to a specific system within a general context in a field/domain (e.g., mechanical field) to be integrated in the process of developing new products in this field by solving design problems modeled by general parameters and provided in the same table.

Statistical research and testing are often only made possible by clearly identifying and manipulating different parameters to extract useful information. However, in this study, the generalized table of parameters involves certain types of parameters, and each of these parameters should be illustrated in terms of its definition, as follow:

Quantitative parameter: it is a numerical measurement or value that can be objectively measured or calculated. Examples of quantitative parameters include dimensions, weight, speed, temperature, pressure. Quantitative parameters can be expressed using mathematical equations, graphs, or charts, and are typically used for precise analysis and optimization of a system or product.

Qualitative parameter: it is a descriptive attribute or characteristic that cannot be expressed in numerical terms. Examples of qualitative parameters include color, shape, material type, and overall aesthetics. Qualitative parameters are often subjective and depend on individual opinions or perceptions.

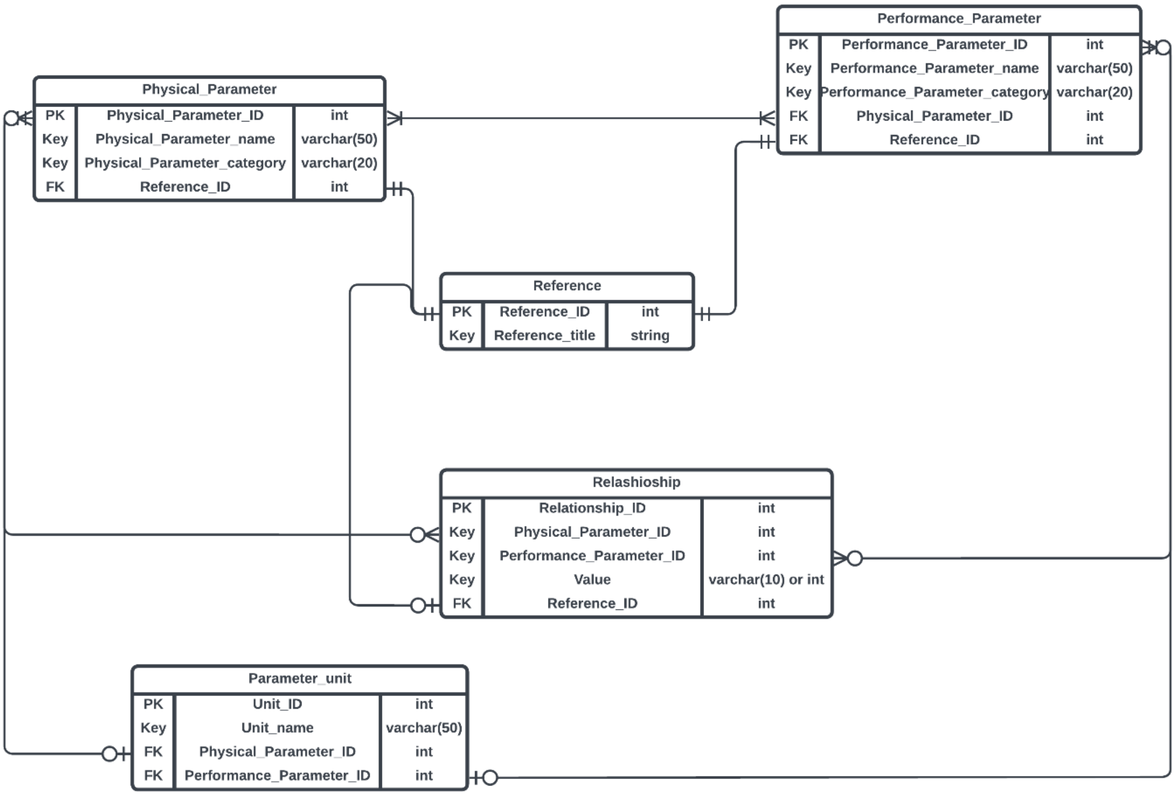
Physical parameter (PhP): it is a parameter by its adjustment the situation changes before the existence of the context of specific design. PhP could be independent from another PhP or not and it is a quantitative or qualitative parameter. For example, gradience is a physical parameter but it is linked to changing the thickness and/or the overall size. The Action parameter is a special case of the physical parameter.

Family of physical parameter: it represents a group of PhP which is including one or more of PhPs. in this study, this parameter is qualitative or quantitative. e.g., the global structure of lattice structure cells is a family, it is composed of many physical parameters such as, 'global dimensions', 'global form'.

Performance parameter (PrP): this type of parameter provides a reference value and measurements of the expected performance of a system before the existence of a design problem. In this study, this parameter is quantitative or qualitative. The evaluation parameter is a special case of performance parameter.

Family of performance parameter: in this study, this parameter is qualitative or quantitative. One or more of EP form a family of EP, e.g., 'energy' is a family and 'absorbed energy per unit volume' is a performance parameter in this family.

ER diagram is built to describe the relationship between different attributes and elements of the proposed database, in Figure 15.



Physical_Parameter

PK	Physical_Parameter_ID	int
Key	Physical_Parameter_name	varchar(50)
Key	Physical_Parameter_category	varchar(20)
FK	Reference_ID	int

Performance_Parameter

PK	Performance_Parameter_ID	int
Key	Performance_Parameter_name	varchar(50)
Key	Performance_Parameter_category	varchar(20)
FK	Physical_Parameter_ID	int
FK	Reference_ID	int

Reference

PK	Reference_ID	int
Key	Reference_title	string

Relashioship

PK	Relationship_ID	int
Key	Physical_Parameter_ID	int
Key	Performance_Parameter_ID	int
Key	Value	varchar(10) or int
FK	Reference_ID	int

Parameter_unit

PK	Unit_ID	int
Key	Unit_name	varchar(50)
FK	Physical_Parameter_ID	int
FK	Performance_Parameter_ID	int

Figure 15: Database ER diagram to show the different relationships between different entities in the CDB

3.1.2 Topology of the table

The topology of the GTP refers to the structure or layout of the table and how the different parameters are organized within it. The GTP is designed to be a comprehensive and unified model of the product system parameters, and as such, its topology is carefully planned to ensure that it can capture all relevant data/information, provide flexibility in inserting and/or extracting data/information, represent the data/information with a high performance. The Table 2 and Figure 16 show a capture from the GTP which shows the organization of information and data inside.

Indices: The GTP is provided with two indices (Alphabet on vertical axe and numbers on horizontal axe) to facilitate reaching out information inside. The cells inside the table are named by using these indices by following the format (“vertical index” + “- “+ “horizontal index”). For example, the four cells in the Table 2 are, A-1, A-2, B-1, and B-2.

Parameter type: In the proposed table, two types of parameters are provided, Physical Parameter PhP, and Performance Parameter PrP. PhPs start with PhP_1 and end by PhP_i where i is the number of physical parameters. Next to PhPs, PrPs are located and start with PrP_1 and end by PrP_j where j is the number of performance parameters. The left side part of this table where PhP is intersecting with themselves is symmetric. On the other hand, the part which is linking PhP with PrP is not strictly symmetric.

Table 2: An indicative table with an example to illustrate the topology of the Generalized Table of Parameters (GTP)

Index	→						1	14.94	15	15.1	15.2
↓	Parameter type	→					PhP	PhP	PrP	PrP	PrP
	↓	Source of parameter	→				1,2	2	1,2,3	1,2,3	1,2,3
		↓	Parameter unit	→			No unit	No unit	Joule/mm^3	N/mm^2	No unit
			↓	Parameter family	→		Structure	Cell	Energy	Energy	Energy
				↓	Parameter category	→	Quantitative	Qualitative	Quantitative	Quantitative	Quantitative
					↓	Parameter name	Relative density of lattice structure	Strut shape	Energy absorption per unit volume	Plateau stress	Densification Strain
A	PhP	1,2	No unit	Structure	Quantitative	Relative density of lattice structure		other	1	1	-1
B	PhP	1,3	Millimeter (mm)	Structure	Quantitative	Global dimensions	-1	0	other	other	other
C	PhP	1	No unit	Structure	Qualitative	Shape of structure	0	0	other	X	X

Value	Explanation
1	(increase) when a Parameter from row increases, then, a Parameter from column increases, as well
-1	(decrease) when a Parameter from row increases, then, Parameter from column decreases
0	(No influence) no influence of a Parameter from row on a Parameter from column
X	(No information) no information about the relation between two Parameters
other	It means one or more than one scenario:
	1.There is extra information in another file, related to the cell contains (other)
	2.The cell links qualitative parameter with another qualitative parameter or qualitative parameter with quantitative parameter

Source	Explanation
1	The parameter is extracted from S1 which is literature reviews only
2	The parameter is extracted from S2 which is experts' opinions only
3	The parameter is extracted from S3 which is from the analysis of CAD/FEM software only
1,2	The parameter is extracted from both S1 and S2 which are literature reviews and experts' opinions
1,3	The parameter is extracted from both S1 and S3 which are literature reviews and the analysis of CAD/FEM software

2,3	The parameter is extracted from both S2, and S3 which are experts' opinions, and the analysis of CAD/FEM software
1,2,3	The parameter is extracted from S1, S2, and S3 which are literature reviews, experts' opinions, the analysis of CAD/FEM software
▨	The intersection between the parameter in a row and itself in a column

Source of Parameter: the GTP is based on wrangling data from multiple sources, for this reason, it was necessary to show the source of each parameter in the table. Source = 1 refers to scientific database e.g., articles, books, source = 2 refers to the experts' opinions, whereas source = 3 refers to parameters extracted from the analysis of computer aided design software CAD and finite element modelling software FEM.

Unit of parameter: To increase the performance of the provided information, it was necessary to provide data about the standardized units used to measure each parameter (if exists). The provided units are undergoing the SI (Standard International) system of units.

Parameter Family: each one or more of parameters can be grouped into a family which can be used for a specific context e.g., cell, structure.

Parameter category: the parameter in the table is categorized based on the fact of being quantitative e.g., dimensions, or qualitative e.g., form.

Parameter name: each parameter should have an identical name which is simple and expressive such as, young's modulus of lattice structure.

Value: it represents the influence (effect) which is describing the direction of a relationship between two parameters. The influence has two scenarios, as follow: first, if the relation between the pair of parameters is directly proportional, then the influence value is +1. Second, and if the relation is inversely proportional, then the influence value is -1.

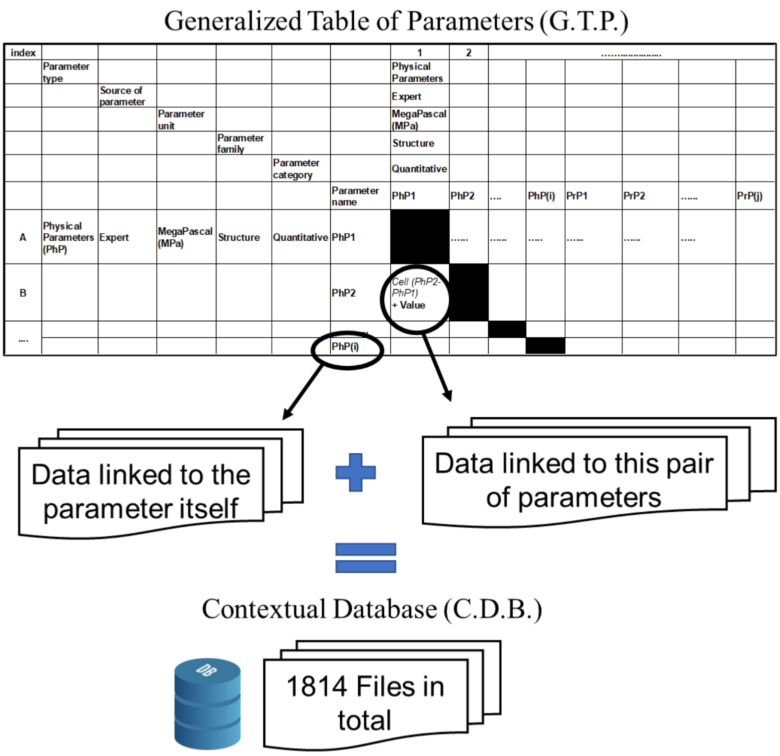


Figure 16: The link between the files of the CDB and the table GTP

3.1.3 General context of the table

Concerning the generalized table of parameters, the established table will undergo a general context to frame the types of problem for which this table can be used. This general context includes some concerns, in case of this system is a product, such as:

- The technology used for manufacturing (e.g., injection molding, additive manufacturing)
- The material used for manufacturing (e.g., polymer, metal)
- The composition of the expected developed product (e.g., composite, specific material)
- The expected applied deformation to this product (e.g., Quasi-static, dynamic)
- The concerned field (e.g., mechanical, thermal)
- The potential design problem(s) linked to the concerned domain e.g., thermal and electrical

The generalized table of parameters could be valid and usable for potential set of design problems, in case of this system is a product, for example, manufacturing defects, structure rigidity, or costing.

3.1.4 Rules to transform the collected data and fill the GTP

Before of all, reading the table GTP requires readers to start from row towards column. In other words, the reader has to start from parameters in the row, parameter A for example, to meet parameters in column, parameter B for example. By following this example, when parameter A changes, parameter B changes, consequently.

Inside the generalized table of parameters, see Table 2, the one cell is coupling two parameters, by providing certain information as mentioned in the section 3.1.2. Consequently, we believe in the importance of presenting the rules by which these pieces of information are transformed into convenient and uniform values by which the table will be filled. Analyzing two parameters simultaneously is known as bivariate analysis. It looks at how two parameters are influencing each other. Bivariate analysis comes in three different types of parameters: (quantitative \ quantitative, quantitative \ qualitative and qualitative \ qualitative)

1) Quantitative parameter AND Qualitative parameter

Case 1: when the value is (+1), it means an increase between the two quantitative parameters. When Parameter A increases, then Parameter B increases, as well.

First example:

In the Figure 17, there is an influence between the relative density (on horizontal axis) and the energy absorption of lattice structure (on the vertical axis) [123]. Two pieces of information could be extracted from this figure. First, energy absorption increases with increase in relative density. The second information is that at the same value of relative density, the energy absorption of lattice structure increases with increase in the strain rate.

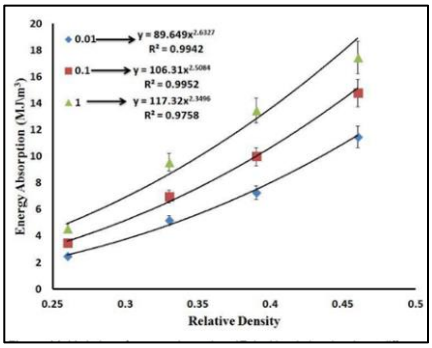


Figure 17: An example on Case 1

Second example:

By following the common physical low of density, ρ = $\frac{Mass}{Volume}$. In this mathematical equation, there is an influence between the following pairs: density and the mass, density and volume, and volume and mass, because all parameters appear in the same equation. From this equation, one can see that, at the constancy of one parameter, the other two parameters change. For example, when the Mass increases, the density increases, as well.

Case 2: when the value is (-1), it means a decrease between the two quantitative parameters. When Parameter A increases, then Parameter B decreases, as well. Two examples are given to illustrate this value.

First example:

To show the dependency of various features with each other, a data visualization technique namely heat map is used. The cluster heat map shown in Figure 18 provides clear visual hues about the clustering of phenomena. This heatmap is extracted from [124]. In this figure, there is an influence between strut length and stress (highlighted inside the white square). When the length increases, the stress decreases.

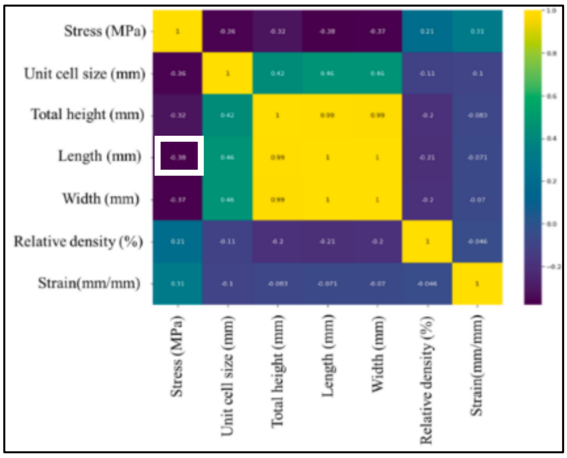


Figure 18: Heat map as an example on the correlation between parameters

Second example:

This example is one mathematical equation from a model called Gibson -Ashby model [24] to describe the mechanical behavior of cellular structures e.g., lattice structures.

$$\tilde{\varepsilon}_{\mathrm{d}} = 1 - 1.4\left(\frac{\tilde{\rho}}{\rho_{\mathrm{s}}}\right) \tag{2}$$

In the equation (2) there is an influence between the following pairs: the relative density $\frac{\tilde{\rho}}{\rho_{\mathrm{s}}}$ and densification strain $\tilde{\varepsilon}_{\mathrm{d}}$. When the relative density increases, the densification strain decreases.

Case 3: when the value is (0), it means no influence, e.g., no influence of the parameter A on the parameter B

Case 4: when the value is (X), it means that there is no information found in one or more of the sources of data, e.g., no information about the relation between Parameters A and $Parameter$ B

Case 5: when the value is (other), it means that there is another meaning. In other words, it means that there is extra information extracted from a source of data, which may enrich or affect the relation between the couple of parameters linked to this cell.

An example:

The graphical model in Figure 19 describes the relation between relative density and energy absorption of lattice structure is extracted from [125]. From this curve, at some degrees of temperature, the energy absorption increases dramatically with the relative density. However, at some other temperatures, the energy absorption shows a flat plateau. This means that the temperature is another

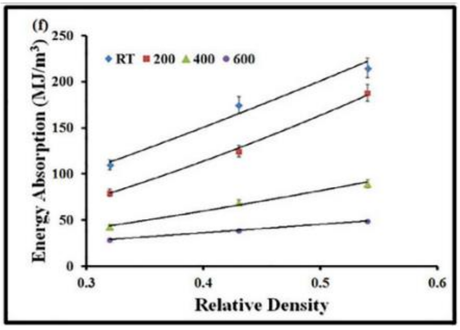


Figure 19: An example on (other) value in the GTP (from [125])

variable interferes with the relation between relative density and energy absorption. It means that the influence cannot be always (+1) but we give (other) to significant this interference of temperature.

2) Quantitative parameter AND Qualitative parameter

General rule: before extracting information, the values of the qualitative parameter are arranged in an order according to the ascending order of the values of the quantitative parameter corresponding to each value of the qualitative parameters, see Figure 20. For example, there is a relation between the material type and young’s modulus (MPa). However, the problem of following this concept of ordering is that the decision of ordering ascendingly- or the inverse- is an individual action from the person who is building the table, then, it is not a characteristic of the parameter. Consequently, ordering the qualitative parameter has no clear rules, at this stage of building the generalized table of parameters.

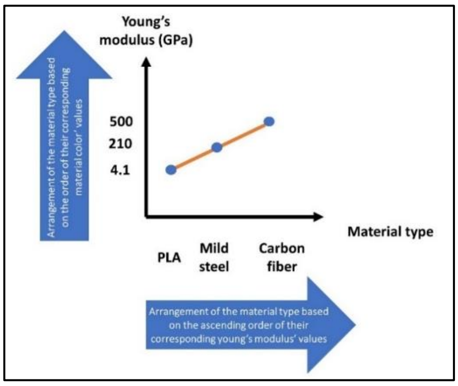


Figure 20: The influence between qualitative and quantitative parameters

Case 1: when the value is (0), it means no influence, e.g., no influence of the parameter A on the parameter B.

Case 2: when the value is (X), it means that there is no information found in one or more of the sources of data. For example, there is no information about the relation between Parameters A and $Parameter\ B$

Case 3: when the value is (other), It means one or more than one scenario. First: There is another meaning. In other words, it means that there is extra information extracted from a source of data, which may enrich or affect the relation between the couple of parameters linked to this cell. Second: The cell links qualitative parameter with quantitative parameter. An example to illustrate this value. In the Figure 21 from the scientific article [124], there is an influence between the optimization model “optimizer” on the horizontal axis which is a qualitative parameter, and the accuracy on the vertical axis which is a quantitative parameter.

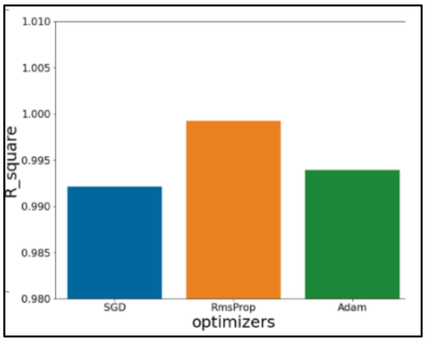


Figure 21: An example on the link between quantitative and qualitative parameters (from [124])

3) Qualitative parameter AND Qualitative parameter

General rule: before extracting information, the values of the qualitative parameter are arranged in an order according to the ascending order of the values of the quantitative parameter corresponding to each value of the qualitative parameters, see Figure 22. For example, there is a relation between the material type and the color of material. The problem of following this concept of ordering is that choosing the referral parameter has no clear rules, at this stage of building the generalized table of parameters.

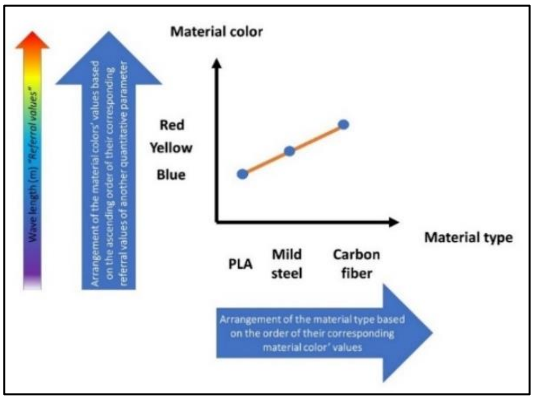


Figure 22: The influence between the two qualitative parameters and another third referral parameter

Case 1: when the value is (0), it means no influence, e.g., no influence of the parameter A on the parameter B. An example on this value is as follow:

In the Figure 23, there is no influence between the material type on the horizontal axis and the cellular shape on the vertical axis. The reason is that there is a possibility for each value of one parameter to combine with any value of the other parameter which indicates the full independence of both parameters.

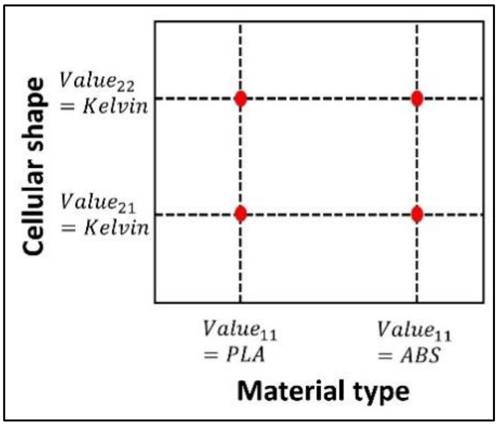


Figure 23: An example on the absence of the relation between two qualitative parameters

Case 2: when the value is (X), it means that there is no information found in one or more of the sources of data. For example, no information about the relation between Parameters A and $Parameter\ B$

Case 3: when the value is (other), It means one or more than one scenario. First: There is extra information extracted from a source of data, which may enrich the information of this cell. Second: The cell links qualitative parameter with another qualitative parameter. An example to illustrate this value is s follow. In the Figure 24, the material type is on the horizontal axis and the material color is on the vertical axis. The relation

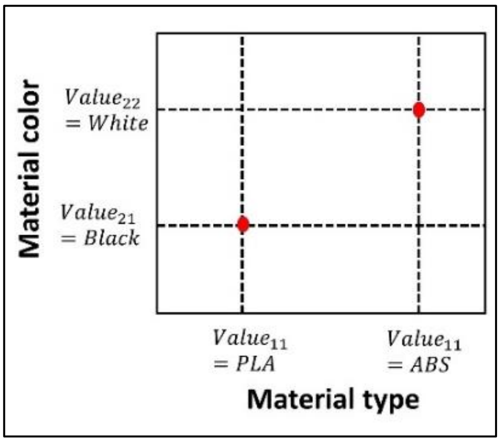


Figure 24: An example on the link between two qualitative parameters

between the two parameters comes from the fact that there is a distinguished color for each type of material. Hence, there is a relation between the two parameters.

3.2 Methods to obtain the table of parameters

In this thesis, three techniques were exploited, as follows, Scientific database (e.g., Research articles by other researchers, books, patents), interviewing experts, and performing experiments. In this section, we are going to propose individual methods to obtain information and data from each source and fill t. At the end, a unified approach would be proposed to merge all methodologies in one method to obtain information and data from different sources of knowledge.

3.2.1 Method to build the table of parameters from literature reviews

The first method is composed of six main steps, as shown in Figure 25, each step or sub-step will be explained and illustrated in this section:

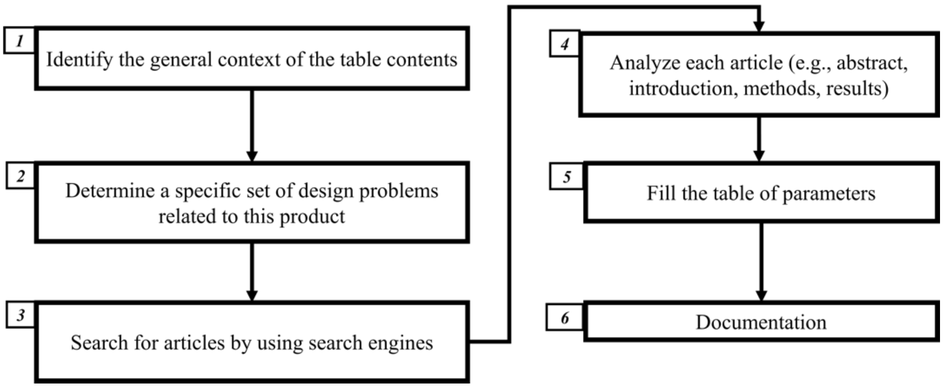


Figure 25: Method to fill the table from scientific databases such as literature reviews

Step 1: is to identify the general context of the table contents.

Step 2: once the general context of the table contents is identified, the researcher should determine a specific set of design problems related to be solved by the help of this table.

Step 3: The myriad available scientific resources online and offline is a distracting factor to achieve the relevant information. However, if one decides to start searching without a relevant set of keywords, it may risk collecting irrelevant sources and wasting time. For this reason, we will exploit the previous two steps to prepare a set of keywords. This set of keywords will be used when searching for the available literature reviews. To do this search, many search engines e.g., Google, science direct, Scopus, can be used to facilitate reaching out these literature reviews.

Step 4: This step concerns the analysis of each document (i.e., scientific articles). To respect analyzing articles in the order of this format i.e., IMRAD, step four will be composed of four sub-steps as follow; analyze the abstract, analyze the introduction, analyze the used methods, and analyze the results. The objective of each sub-step and the steps to implement this analysis will be discussed. For better illustration, we will present the different steps on a direct example, which is an article [126] in the topic of lattice structure. The upcoming part will show how each part was analyzed by authors, and sub-steps will be listed:

Step 4.1: Analyze the abstract

In this step, the abstract is analyzed by doing a careful reading of the entire abstract. Reading the first part of the article is useful to extract certain useful information such as the author’s name, journal and publisher name, publishing year, and the linked keywords. For example, in the article [126], one can extract the following information:

Article name	Exploiting negative Poisson's ratio to design 3D-printed composites with enhanced mechanical properties
Author(s)	Li, Tiantian et al.,
Date of publishing	2018
Publisher e.g., journal name	Materials and Design
Ressource type e.g., journal article, book	Journal article

Information such as the author’s name, journal and publisher name, publishing year, can be useful for evaluating the quality and performance of the collected data from scientific resources. However, analyzing the abstract and the keywords of the article should be performed by using the formulated list of keywords, prepared previously in the first three steps. This analysis will give a global vision if this article matches with the list of keywords prepared in priori. For illustrating analyzing the abstract better, an example will be given.

Let us suppose that the search operation is performed to collect articles about the energy absorption of lattice structure in the domain/field of mechanics. Consequently, the scientific article [126] will be collected and listed. In [126], there is a set of keywords used and mentioned in the beginning of this article. By putting a close focus on the list of keywords of this article, one can find the set of words below:

Keyword 1	Keyword 2	Keyword 3	Keyword 4	Keyword 5	Keyword 6
Auxetics	*3D printing*	*Stiffness*	*Energy*	*Composites*	*Lattice*

The keywords No. 1, 3, 4 and 6 directly correspond with the same words of the sentence ‘the energy absorption of lattice structure in the domain/field of mechanics. However, keywords No. 2 and 5 can be used to understand the manufacturing technology and the topology of the structures used in the article [126].

Step 4.2: Analyze the introduction

In this step, the introduction is analyzed by doing a careful reading of the introduction. Analyzing the introduction of the article should be performed by asking questions. Yet the answer to these questions will frame the objective analysis of this part. These questions and their objectives are as follow:

The question	The goal of question
Are there any cited literature work which sounds relevant to the prepared keywords out of step 2?	To update and enrich the list of collected scientific articles/books. This process stops when all keywords are absent in the new article.
Is there any potential case study or industrial application for the solved problem in this article?	Since the table of parameters is a generalized one, it could be used for multiple case studies. For this reason, it is important to list the possible case studies in which the table could be used.

Step 4.3: Analyze the used methods

As mentioned in [127], the goal of the used methods section is to provide enough information about what authors did and how they did it so that any average reader with the same resources at their disposal could duplicate and reproduce this research. Since every result included in the results section must have a technique defined in the methods section. This means that we can find detailed techniques, methods, and/or constitutive models, in this section, which could describe the relation between different input and output parameters i.e., mathematical equations. These models could be beneficial since they provide information about the design parameters and their interconnection relations. Therefore, these pieces of information could be added to the table of parameters with citing the article as a source of information. This information can be generalized enough to address more than one problem e.g., dimensions, or specific for a case study then it could be useful in case another person wanted to reproduce the same case study e.g., energy absorption.

Step 4.4: Analyze the results

The main objective of the results section is to describe what the authors observed from testing or experimentation process. In some research articles, this section can stand alone with no discussion, in others, authors follow the results with discussion or commentary. The part that we are concerned about in this section is the information necessary to be provided in the generalized table of parameters. For this purpose, we will concentrate on analyzing the results which are modeling the relation between input and output parameters. These models can exist in this section in more than one form, such as mathematical equation, graph, image with commentary and/or a table. From this section multiple information could be extracted, such as, potential parameters and their interconnecting relationships.

Step 5: By using the rules stated in the section 3.1.4, the pieces of data extracted from the previous step could be analyzed and transformed into the type of information valid for the GTP.

Step 6: it is the last step, and it is dedicated for keeping the collected information within a document while searching to keep the reproducibility of such information in the future for any kind of exploitation.

3.2.2 Method to build the table of parameters from experts' interviews

In this study, the goal of interviewing experts was to collect and grape a set of parameters attached to the same context of the GTP. Moreover, find relationships between each pair of these parameters. The second goal is to compare the information extracted from experts to others extracted from the scientific databases and the FEM and CAD software. To apply this method for our case study, a set of meetings were held with experts in the field of lattice structures and materials, besides one TRIZ expert. The method that authors followed to collect these pieces of information is chained in five steps, as shown in Figure 26.

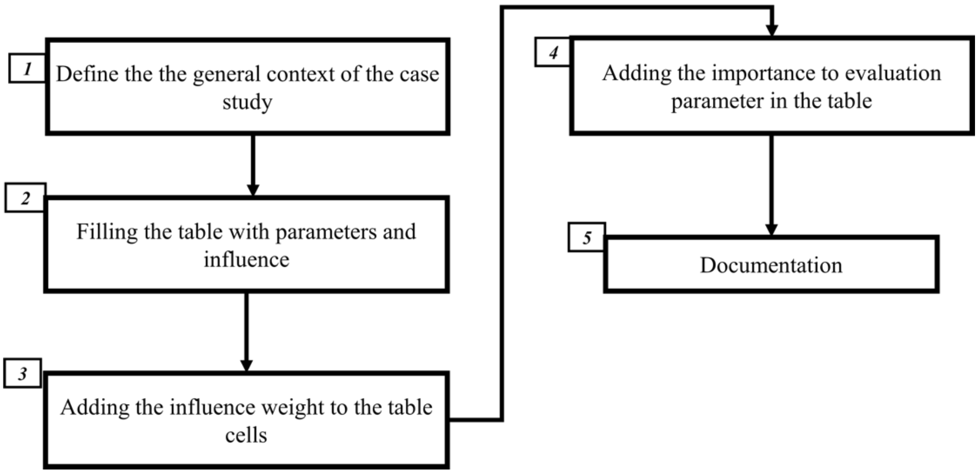


Figure 26: the proposed approach to build a table of parameters from expert's interviews

Step 1: The goal of this step is to frame the global context of the design problem for the expert. This step could be done successfully by elaborating problem definition, objectives, and expected results. To achieve this goal the researcher and the expert(s) should summarize some points by replying to certain questions clearly, such as:

What are the possible parameters that could act on the system of the product?
What are parameters to be measured to evaluate the performance of the system of the product?

As a result of this step, a list of parameters should be provided to the table, as shown in Table 3.

Table 3: The list of parameters based on the experts' opinions

Parameter name	Parameter family	Parameter type	Parameter name	Parameter family	Parameter type
Relative density	Material	Physical Parameter (PhP)	Young's modulus	Rigidity (main)	Performance parameter (PrP)
Periodicity or regularity	Topology	PhP	Deformation energy (absorbed energy)	Energy absorption (main)	PrP
Strut shape	Geometry	PhP	Plateau stress	Energy absorption (main)	PrP
Strut Thickness	Geometry	PhP	Densification Strain	Energy absorption (main)	PrP
Strut Section	Geometry	PhP	Storage modulus	Rheology (secondary)	PrP
Open or closed	Topology	PhP	Loss modulus	Rheology (secondary)	PrP
wall thickness	Topology	PhP	All geometry of thickness (after fabrication)	Tomography (experimental)	PrP
wall section	Topology	PhP	All geometry of section area	Tomography (experimental)	PrP
Young's modulus	Base material	PhP	Manufacturing defaults	Tomography (experimental)	PrP
Loss modulus	Base material	PhP	Interconnection	Rigidity (secondary)	PrP
Storage modulus	Base material	PhP	Relative density (after fabrication)	Weight (main)	PrP
interconnection	Topology	PhP			
Gradient of density	Topology	PhP			

Step 2: The step is the beginning of filling the table with parameters and values about the influence between each pair of parameters. In this step, the expert should presume a hypothesis to control the influence between each pair of parameters. An example on the influence between a set of quantitative parameters can illustrate this point better. Let us say that the equation (3) governs the relation between the volume, mass and density. One cannot decide the influence or the effect between the mass and density until a hypothesis is presumed that mass increases with the fix of volume value, so, the density increases, consequently. The output of this step is a positive sign (+ve) since the relation between the mass and density is directly proportional.

$$Density = \frac{Mass}{Volume} \tag{3}$$

Another example can be given on two parameters, one of them is a qualitative parameter. The influence of changing the material type on the modulus of elasticity. In this example, material type is a qualitative parameter, which can be described by a set of quantitative parameters within the context of the design problem such as density of bulk material which is a quantitative parameter if the context is in the mechanical field.

Step 3: By continuing the sample example, step three is to ask the expert to give a value for influence weight between each pair of parameters. The output of this step is a weight from 1 to 3 that the expert gives based on his experience.

Step 4: Step four is dedicated to ask the expert to decide which problem is prioritized to be solved in the frame of the sought product and the described design problem. The output of this step is a number from 1 to 10 that is given by the expert to each chosen EP. The last step is to add and update all this information in the indicated document in Figure 26 and save it with the record of the held sessions if exists.

Step 5: it is the last step, and it is dedicated for keeping the collected information e.g., records, documents, tables, to keep the reproducibility of such information in the future for any kind of exploitations.

3.2.3 Other techniques to extract certain information to contribute to building the table of parameters

There are certain techniques to collect information. Amongst these techniques, performing experiments. In this study, as we will see later, the numerical simulation by using the Finite Element Models (FEM) will be carried out to model the product system under certain conditions and parameters. To perform FEM models, Computer Aided Model (CAD models) should be prepared in priori. Therefore, both FEM and CAD software will be used for this study to implement the experimental tests and generate the necessary FEM/CAD models. The experimental trials and CAD preparation sections will be detailed in the next chapters; however, it is necessary to illustrate in this section, how can one exploit the available CAD software to extract some information to contribute to filling and building the table of parameters?

Certainly, CAD software is a powerful tool for product design and optimization, and engineers can extract various parameters from the software that can be used to affect the studied system. One such parameter is the product's dimensions, which can be easily manipulated and analyzed in CAD software. For example, engineers can vary the product's length, width, and height to optimize its performance, such as improving its strength or reducing its weight. In addition to utilizing CAD software to extract information, Finite Element Models (FEM) can also be used to contribute to filling and building the table of parameters. FEM is a numerical method that allows engineers to simulate the behavior of complex systems under certain conditions and parameters. This method can be used to identify stress concentrations, deformation patterns, and other critical factors that affect the product's performance. By using FEM software, engineers can create a digital model of the product system and apply loads and boundary conditions to simulate the real-world behavior of the system. The results obtained from the FEM software can then be used to optimize the design, identify potential problems, and evaluate different material options. For instance, by varying the material properties of the product, such as its Young's modulus or Poisson's ratio, engineers can study the effect of different materials on the product's performance and select the best option. Therefore, we can analyze each software that will be used in this study such as PTC Creo® and ABAQUS® to extract potential parameters which are attributed as physical or performance parameters.

3.2.4 Proposed approach to combine different sources of information

This table and its linked database are collected from three sources of knowledge: (1) Collecting information from scientific database, (2) Collecting information from experts' opinions, and (3) collecting information from the experimental approach. After, an approach was proposed to integrate between the three techniques, as shown in Figure 27. The method illustrated in Figure 27 comes in thirteen sequential steps.

Step 1: in this step, the studied system is defined whether it is a product or a process. In this study, the focus is on developing products, hence, the system is a product in our study. For our study, authors will use one TRIZ-based model which is Main Useful Function (MUF) diagram.

Step 2: is to identify the general context of GTP. As defined previously, the general context is a frame formed by a set of conditions, boundaries, requirements, and constraints and within this frame the system is located, and the problems should be solved. In case the system is a product, this context could be:

- The technology used for manufacturing (e.g., injection molding, additive manufacturing)
- The material used for manufacturing (e.g., polymer, metal)
- The composition of the expected developed product (e.g., composite, specific material)
- The expected applied deformation to this product (e.g., Quasi-static, dynamic)
- The concerned field (e.g., mechanical, thermal)
- The potential design problem(s) linked to the concerned field i.e., specific table

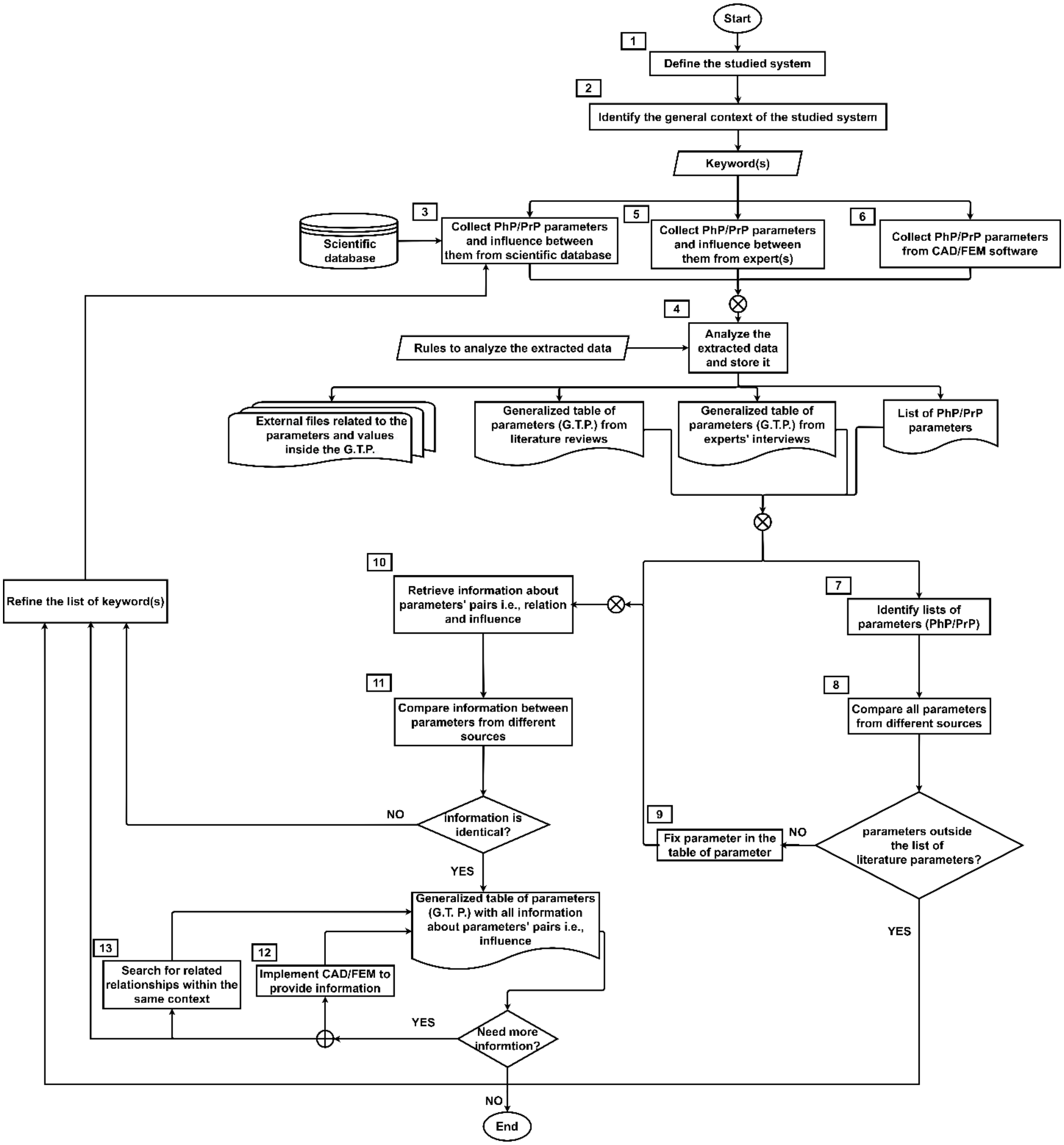


Figure 27: The proposed unified approach to fill the generalized table of parameters based on the integration between three methods of collecting information

Step 3: is to prepare a list of keywords that can be extracted based on the system definition and the general context of the studied system.

Step 4: is to search for relevant articles through scientific databases. This step could be implemented by executing two techniques:

- Use the keywords as input to search for relevant scientific articles/books from scientific database (e.g., science direct)
- Try composite different keywords together for widening the search process

Step 5: This step is to analyze the extracted data from scientific databases and store it. Some data and information are extracted from the scientific databases, such as context, graphs, and equations. Lots of these pieces of data can be transformed into useful information, for example:

1. *Parameters extracted*: PhP: physical parameter i.e., the linked parameter to the global form of lattice structure, material, experimental control parameters. PrP: performance parameter i.e., the linked parameters to the potential problem(s) to be solved.
2. The influence between each pair of these parameters.

The transformation of data is undergoing certain rules, mentioned in section 3.1.4.

Step 6: a set of questions, related to the system and general context, were asked to the expert(s) to determine the following data and information. The same rules, in section 3.1.4, were applied.

Step 7: The analysis was done for the software PTC Creo V6.0 and ABAQUS 2019.

The analysis of CAD software resulted in all potential physical parameters related to the design of lattice structure. On the other hand, the analysis of FEM software concerned the extraction of potential performance parameters.

Step 8: In this step, comparing all parameters from all sources is necessary. We go through all parameters in all lists, then we find the following scenarios:

- If parameter in list 1 is similar in functionality to a parameter in list 2, then, the two parameters are identical. In this case, we fix one parameter to put in the GTP
- If parameter exists in list 1, but does not exist in list 2, then, the two parameters are non-identical. In this case, we put both in the GTP

- If one cannot find any identical parameters between lists of parameters, then, one should think about different possibilities: (1) refine the studied system and its inherent context. (2) revising the selection criteria of experts. (3) Revising the asked questions during interviewing the expert. (4) Revising the efficient keywords used to collect literature reviews. (5) Refine the analysis of CAD software more carefully.

Step 9: for the purpose of filling one GTP, we identify identical and non-identical parameters to take the decision of continuing the process or refining the preliminary steps (as described in step 8).

Step 10: in this step, it is time to retrieve information about parameters' pairs from different sources i.e., influence. Once all parameters are listed in the G.T.P, we retrieve information related to each cell individually from each table of parameters/list of parameters, produced previously (the table/list of each source).

Step 11: The same as we did with parameters from different sources, we do the same with influence. We compare information between parameters from different sources. The comparison is based on two aspects:

- The information, e.g., influence, of a specific cell is said to be the same in all tables.
- The information, e.g., influence, of a specific cell is different at least in one table.

Consequently, some cells can contain identical information, and, in this case, one information can be raised in the cell. However, others can conflict, and, in this case, one can return to literature review by adding more keywords about the coupling parameters related to the conflicting information.

Step 12: At this stage, it is supposed that the work of filling the GTP is finished. However, there is some missing information about the influence of some pairs of parameters. To overcome this obstacle and increase the performance of the data inside the table, completing as much information as possible inside the GTP. For this reason, we propose steps 12 and 13.

In step 12, in case there is missing information between parameters in the table. One option is to implement a customized FEM model to provide information. An alternative option is to add keywords about the coupling parameters, then search again about relevant scientific articles through scientific databases.

Step 13: in this step, we propose exploiting the collected relationships e.g., mathematical models, graphs, experts' feedback to find missing information. We give an example for a better explanation.

If we have three parameters A, B and C (mentioning that (→) means the influence between parameters)

If A → B, which is given by a data source
And B → C, which is given by a data source
Then, A → C, which is missing in the GTP

3.2.5 Illustration of the method for lattice structure design problems

The purpose of this section is to illustrate the unified method for building the generalized table of parameters. This method is based on extracting the information from three sources, first, is the available scientific databases, second, is one or more experts in the same field of the treated problem [64], and third source is the FEM and CAD modelling software. This collected information is used to build a Generalized Table of Parameters GTP.

Recent applications, driven by industrial demands, necessitate innovation to fulfill specific requirements and desired properties. This innovation extends to the development of novel material structures. Among these innovations, lattice structures have emerged as cutting-edge solutions in the world of cellular materials. These structures are characterized by specific cell shapes that repetitively and seamlessly interconnect in either two or three dimensions. On the other hand, with the advent of additive manufacturing and advanced 3D printing techniques, lattice structures offered promising solutions in many domains, such as mechanical, thermal, chemical, electrical, physical, and many other domains.

Lattice skeleton structures excel in fulfilling core requirements such as energy absorption, cost reduction, unique deformation, rigidity, and durability. They also exhibit properties like acoustic and vibrational damping, high strength-to-weight ratios, and thermal management capabilities. Real applications include vehicular safety, airfoils, and blast resistance. Furthermore, lattice structures can provide unique mechanical, electrical, or magnetic properties either independently or as composites with other materials. They are known for their ability to absorb energy, making them suitable for shock absorbers and vibration attenuation. Additionally, lattice structures maintain relative strength compared to solid objects and offer thermal functionality. They are versatile, serving purposes like acoustic damping while ensuring crashworthiness. Among all previous applications and design problems that lattice structures try to tackle, we present a general case study in the mechanical domain of lattice structures that serve for one or more design problems. This section presents a general case study which aims to build a generalized table of parameters (GTP) that is versatile and applicable to a range of problems related to lattice structures.

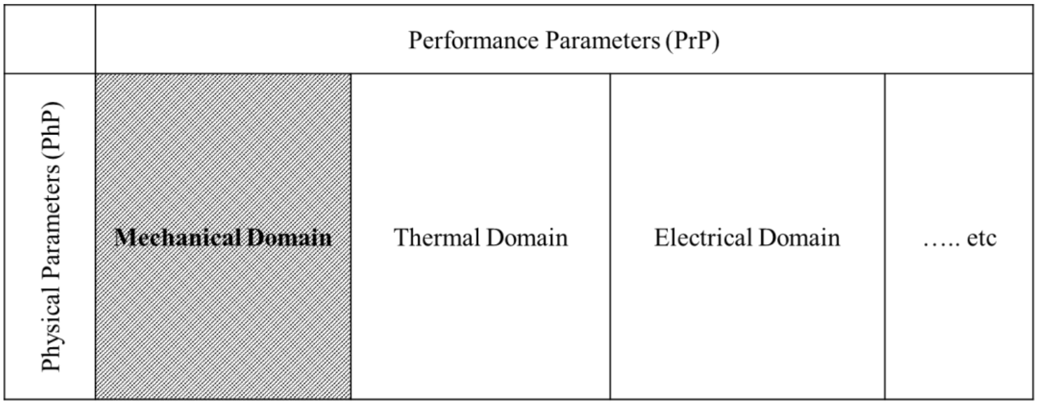
In this section, it is expected to present the output table -as a result- by using different sources to extract information. Steps of the applied method will be illustrated in this section, as follow:

Step 1: The following aspects are within the scope of this general case study:

Initial problem: compromising results between crashworthiness capabilities, rigidity, lightweighting, costing, and deformation for many of industrial mechanical systems, such as helmets, car bumpers, packages, and other applications which require improving all characteristics together.

Deformation: the table should encompass various types of applied deformation scenarios relevant to the mechanical behaviors.

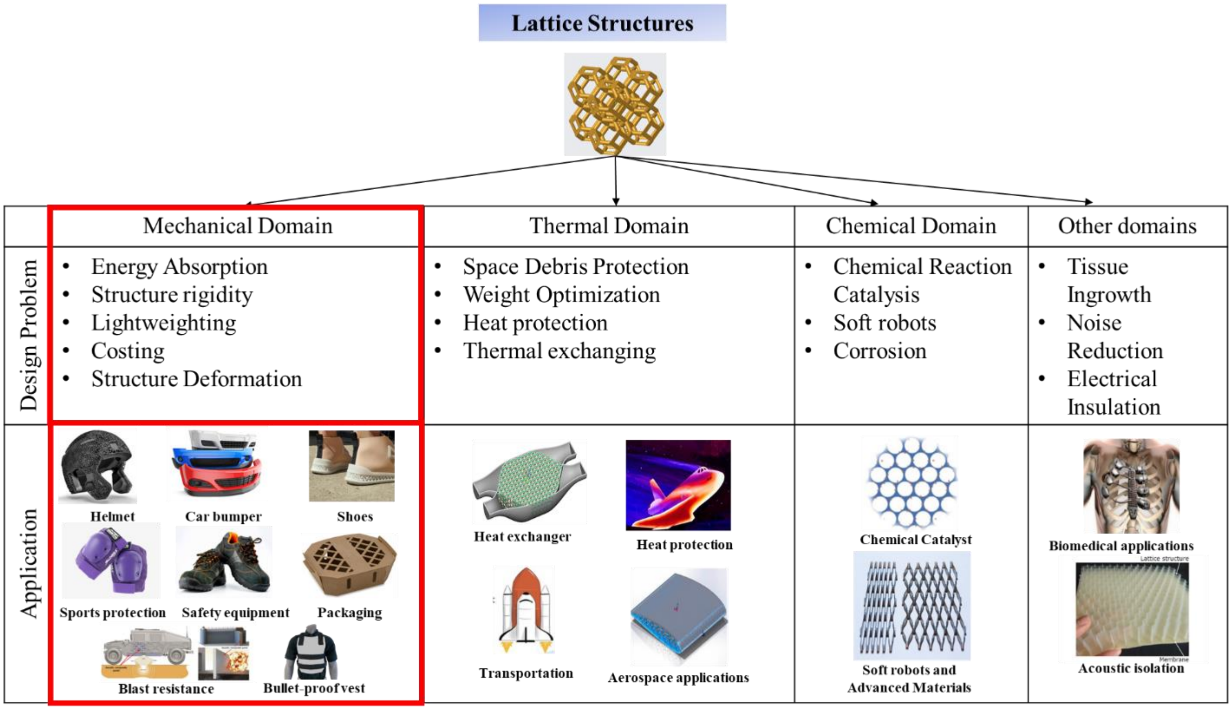
Application domain: One of the advantages of the proposed table is the ability for extension, dynamically, to represent multiple domains for solving multi-physical and coupling design problems such as thermomechanical, electromechanical, or thermochemical problems. However, in this thesis, we will concentrate on proposing the table and its connected database to serve the case studies in the mechanical domain, only, as shown in Figure 28.



	Performance Parameters (PrP)			
Physical Parameters (PhP)	**Mechanical Domain**	Thermal Domain	Electrical Domain	….. etc

Figure 28: Extension of the Generalized Table of Parameters to multiple domains

Possible industrial applications: this case study is general which means that it handles common design problems valid to one or more industrial applications e.g., products. The tackled design problems are common between a set of industrial systems such as helmets, car bumpers, packaging of precious objects, safety equipment, sports protections, and shoes soles, as shown in Figure 29.



Lattice Structures

	Mechanical Domain	Thermal Domain	Chemical Domain	Other domains
Design Problem	Energy Absorption Structure rigidity Lightweighting Costing Structure Deformation	Space Debris Protection Weight Optimization Heat protection Thermal exchanging	Chemical Reaction Catalysis Soft robots Corrosion	Tissue Ingrowth Noise Reduction Electrical Insulation
Application	Helmet Car bumper Shoes Sports protection Safety equipment Packaging Blast resistance Bullet-proof vest	Heat exchanger Heat protection Transportation Aerospace applications	Chemical Catalyst Soft robots and Advanced Materials	Biomedical applications Acoustic isolation

Figure 29: Some design problems and their relevant industrial applications of lattice structures

Fabrication technology: the lattice structures under consideration should be fabricated using additive manufacturing technology.

Used material: the lattice structures should be made from polymeric materials.

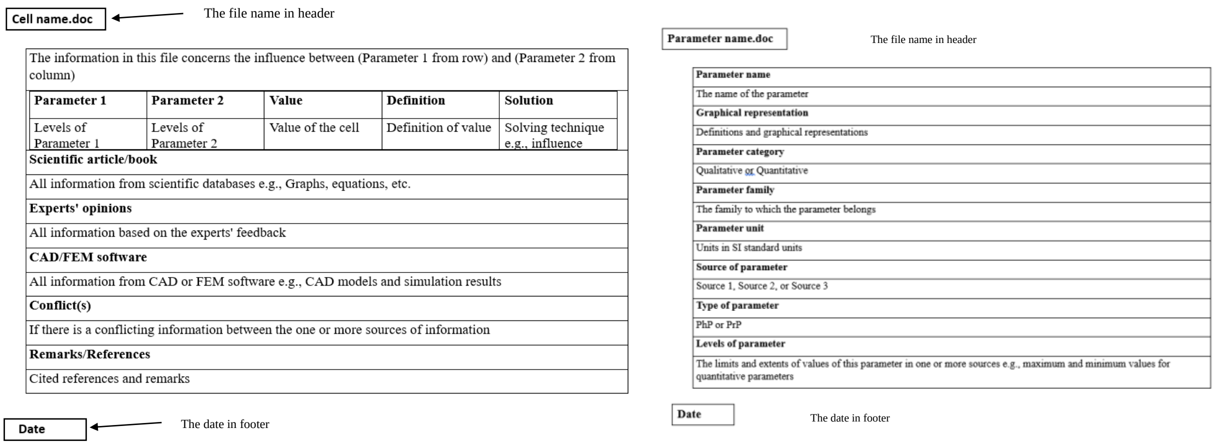
Step 2: the general context is determined in detail previously, which states that the generalized table of parameters is covering the following concerns:

- The structure should be fabricated by the additive manufacturing technology
- It should be made of polymeric materials
- This structure might be subject to different applied deformation
- The concerned field is the mechanical field
- The potential design problem(s) linked to the concerned field are: Energy absorption, Structure strength, Light weighting, Deformation, and Costing.

Step 3: This step is devoted to searching for information from the available literature reviews. This search process is implemented based on a set of keywords which will help in searching relevant scientific sources such as scientific articles, books, or websites. The set of keywords are *Lattice structure*, *Additive manufacturing*, *Polymeric lattice structure*, *Cellular materials*, *Material mechanics*, *Material of 3D printing technology*, *Rigidity*, *Light weighted lattice structure*, *Energy absorption*, *Deformation.*

Consequently, a list of references (e.g., scientific articles, books) was extracted and analyzed. Since this step is devoted to search for relevant articles through scientific databases, about 66 articles and 4 books were collected and numbered.

Step 4: Parameters extracted from scientific databases are classified as follows: PhP = 25 parameters and PrP = 16 parameters. The extracted data are stored in two documents; The first document is the table of parameters itself. The template of this document is illustrated previously in Figure 30.



Cell name.doc

The file name in header

The information in this file concerns the influence between (Parameter 1 from row) and (Parameter 2 from column)

Parameter 1	**Parameter 2**	**Value**	**Definition**	**Solution**
Levels of Parameter 1	Levels of Parameter 2	Value of the cell	Definition of value	Solving technique e.g., influence

Scientific article/book

All information from scientific databases e.g., Graphs, equations, etc.

Experts' opinions

All information based on the experts' feedback

CAD/FEM software

All information from CAD or FEM software e.g., CAD models and simulation results

Conflict(s)

If there is a conflicting information between the one or more sources of information

Remarks/References

Cited references and remarks

Date

The date in footer

Parameter name.doc

The file name in header

Parameter name

The name of the parameter

Graphical representation

Definitions and graphical representations

Parameter category

Qualitative or Quantitative

Parameter family

The family to which the parameter belongs

Parameter unit

Units in SI standard units

Source of parameter

Source 1, Source 2, or Source 3

Type of parameter

PhP or PrP

Levels of parameter

The limits and extents of values of this parameter in one or more sources e.g., maximum and minimum values for quantitative parameters

Date

The date in footer

Figure 30: on the left, the template of the file where the data and information about each parameter is stored. On the right-hand side, is the file where pieces of data and information about each intersecting cell between each pair of parameters are stored.

The second document is a set of external files. Each file is linked to a specific cell in the generalized table of parameters GTP. These files are divided into two templated, first template is built to organize all necessary information about each parameter in the GTP, which is indicated in Figure 30, as well. At the end of this document, some tables are provided to evaluate the quality and performance of the included information. As illustrated in Table 4, Table 5, and Table 6 the three tables are provided in each single file of the contextual database for the evaluation purpose.

Table 4: Measures to evaluate the quality of provided data and information from scientific databases

Source	Dimension	Indicator	Measure of indicator	Limits of measurement
Document 1	Credibility	The scientific source is in the predatory journals list (based on the database https://beallslist.net/) The document is well impacting	Existence of journal name in the list The impact factor of the document	Yes/No Number

	Accuracy	Type of this document is: Journal/Book/Patent	Type of document	Journal/Book/Patent
	Consistency	The generality of the information	Specific information for a specific case or General information	Specific/General
	Timeliness	The time interval between publishing and updating the table	The recent year- The publishing year	Number

Table 5: Measures to evaluate the quality of provided data and information from experts

Source	Dimension	Indicator	Measure of indicator	Limits of measurement
Expert 1	Credibility	Domain of work of the expert	The name of the domain of expertise of expert(s)	String
	Accuracy	Recurrence of provided information/data in one/more of data sources	Number of experts provided this piece of information	Number
	Consistency	The conflict about the same piece of data/information between one/more than source of data	Existence of conflict	Yes/No
	Timeliness	The time between the interview with the expert and updating the table with information	The recent day-The interview day	Number

Table 6: Measures to evaluate the quality of provided data and information from CAD/FEM software

Source	Dimension	Indicator	Measure of indicator	Limits of measurement
Software 1	Accuracy	Type of software	CAD (Computer Aided Design) software or FEM (Finite Element Modeling) software	CAD software/FEM software
	Consistency	The conflict about the same piece of data/information between one/more than source of data	Existence of conflict	Yes/No
	Timeliness	How many versions between the last version of software and the downloaded version	The number of the last version released – The studied version number	Number

Step 5: The expert(s) provided a list of design parameters composed of 24 design parameters. These parameters are divided up into 13 physical parameters, and 10 performance parameters. The expert(s)

provided relations and influences between each pair of parameters, as well. These pieces of data and information are stored in table-form documents (output document).

Step 6: The analysis of PTC Creo software resulted in a list of potential physical parameters (PhP) composed of 13 parameters. The list is provided with information about the flexibility of this parameter to be changed in value (changeable or not). Whereas the analysis of ABAQUS software resulted in a list of potential performance parameters (PrP) composed of 18 parameters.

Step 7: in this step, it was supposed to prepare one file containing all parameters from different documents for a further comparison. This step resulted in collecting the following quantities of parameters as indicated in Table 7.

Table 7: Quantity of parameters collected from different sources of data

Source	Type of Parameter	Quantity
Scientific databases	PhP	26
	PrP	17
Experts' opinions	PhP	13
	PrP	10
CAD software	PhP	14
FEM software	PrP	18

Step 8: in this step, all parameters from different sources are compared to distinguish identical from non-identical ones. All parameters are collected and listed in one file to be comparable. Number of PhP = 33 parameter and number of PrP = 24 parameter.

Step 9: This step resulted in one unified list of parameters, composed of:

Parameter type	Quantity	State of parameter
PhP	12	identical
PhP	21	non-identical
PrP	5	identical
PrP	18	non-identical

Where, the identical parameter refers to the parameter exists in all more than one source of information. Whereas the non-identical one refers to the parameters exists in one -and only one- source of information

Step 10: in this step, we list all parameters in the template on the GTP to start filling the table with transformed data and information.

Step 11: in this step, the data and information concerning each pair of parameters from different sources are retrieved. The data is analyzed based on certain rules mentioned in 3.1.4 and the influence between each pair is identified. To clarify this step, a real example from GTP would be explained. In the GTP the relative density of lattice structure is a physical parameter PhP and the energy absorption per unit volume of lattice structure is a performance parameter PrP. Some references such as [125] confirmed the increase of quantity of the absorbed energy with the increase of the relative density of lattice structure Figure 31. For this reason, the influence between this pair of parameters is (+1).

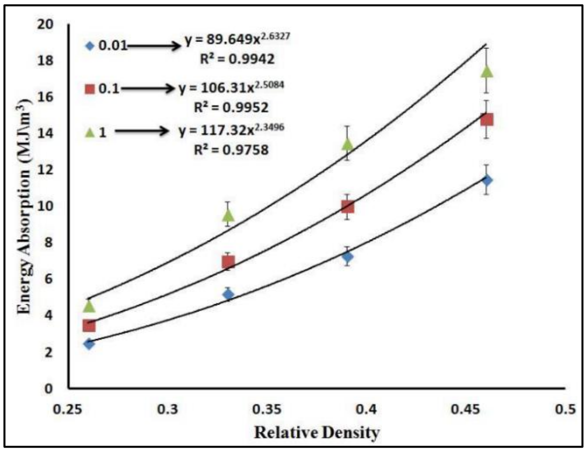


Figure 31: A graph to illustrate the relation between the relative density of lattice structure and the absorbed energy

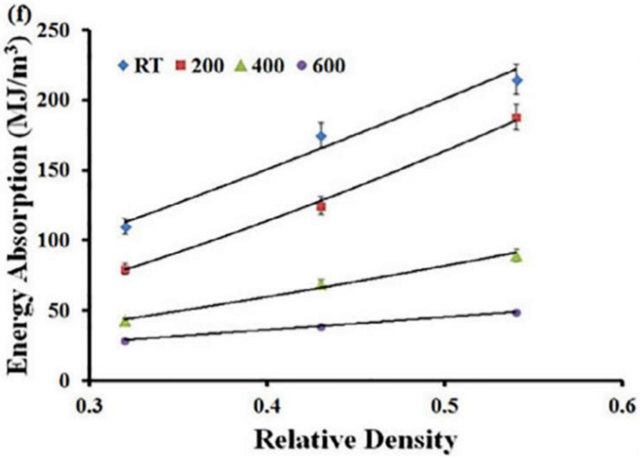


Figure 32: A graph to illustrate the relation between the relative density of lattice structure and the absorbed energy

Another reference [123] emphasized on the same fact as illustrated in Figure 32. In this figure, the energy absorption capabilities of cellular structure decrease with increasing temperature because of plateau and yield strength of cellular structure decrease with increases in temperature but the energy absorption is increasing with room temperature, at a constant value of relative density. However, the expert's feedback was on the contrary with references, as he mentioned the absence of the influence between the two parameters. That means the influence value is 0 in this case. At this stage the two sources conflict about this information. Therefore, we proposed updating the list of keywords to search further scientific articles/books. The keyword added was (relative density and energy absorption of lattice structure). By adding new keywords, the search process was carried out one more time starting from step 3. The reference [128] and [129] were added to the list of articles. The reference [128] confirmed the increase of the value of the absorbed energy with the increase of the relative density of cellular structure, at a constant value of displacement, as seen in Figure 33.

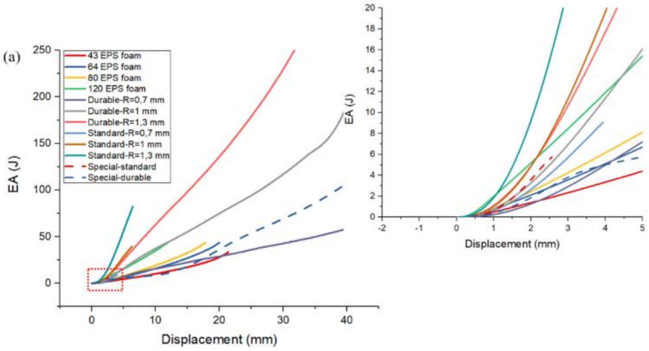
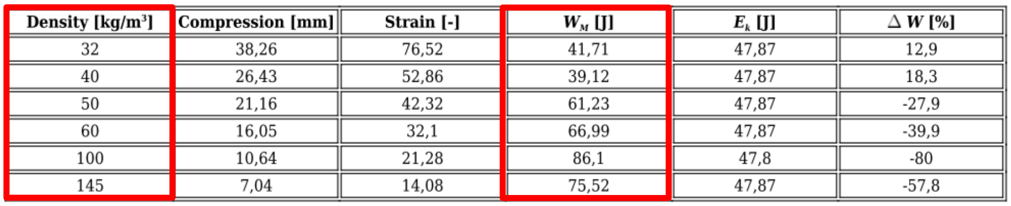


Figure 33: A graph to illustrate the relation between the relative density of lattice structure and the absorbed energy

Another reference [129] confirmed the same information as indicated in Table 8.

Table 8: The increase of energy absorption with the increase of relative density (from [129])



Density [kg/m³]	Compression [mm]	Strain [-]	W_M [J]	E_k [J]	Δ W [%]
32	38,26	76,52	41,71	47,87	12,9
40	26,43	52,86	39,12	47,87	18,3
50	21,16	42,32	61,23	47,87	-27,9
60	16,05	32,1	66,99	47,87	-39,9
100	10,64	21,28	86,1	47,8	-80
145	7,04	14,08	75,52	47,87	-57,8

As a result, this argument reinforces a final decision to put the value 1 in the generalized table of parameters. Worth mentioning that the total number of conflicting cells in the GTP is 12 cells.

Step 12: as mentioned before, this step is activated in case there is missing information between pairs of parameters in the table. To illustrate this step better, a real cell value was picked from GTP. The information between the parameters; Global dimensions and energy absorption per unit volume, was missing. For this reason, two CAD models were built to extract the information by using numerical simulation. we fixed values of all other parameters and created two models with two different values of global dimensions (mm). The first CAD model was a structure composed of 2x2 kelvin cells. The global dimensions of this model were 50x50x50 mm. The second CAD model was 3x3 kelvin cells. The global dimensions of this model were 75x75x75 mm. FEM model was built and numerical simulation runs were carried out by using ABAQUS® 2019. The two model are illustrated in Figure 34.

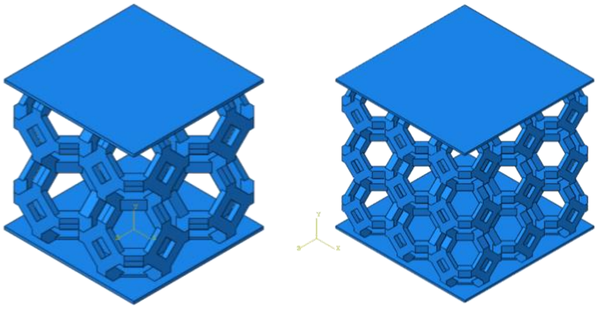


Figure 34: on the left the CAD model of size 2x2x2 cell, whereas, on the right, the CAD model 3x3x3 cell

Table 9: The numerical simulation results of the two FEM models, 2x2x2 and 3x3x3

	size (3x3x3)	size (2x2x2)
Young's modulus of lattice structure (MPa)	51	46.5
Densification strain	0.62	0.65
plateau stress (MPa)	2.9	3.26
Absorbed energy (MJ/m^3)	1.4	1.5

Global Dimensions (mm)	75x75x75	50x50x50
Strain (%)	Until 80%	Until 80%

From the results of the FEM models, in Table 9, one can conclude that when the global dimensions are increasing homogeneously, the young's modulus of lattice structure increases. Therefore, the influence of the dimension change parameter and young's modulus of lattice structure is +1 in the GTP. However, all of densification strain, plateau stress and the absorbed energy per unit volume decreases. Therefore, the influence of the dimension change parameter and mentioned parameters are -1 in the table of parameters. The change in the absorbed energy and plateau stress from one model to another are rather small, hence, the influence of the change in global dimensions on the two parameters could be either 0 or -1. Figure 35 indicates the comparison between the two-resulting stress-strain curves. The hashed area between the two curves represents the quantified difference in energy absorption between the two models 2x2x2 cells and 3x3x3 cells.

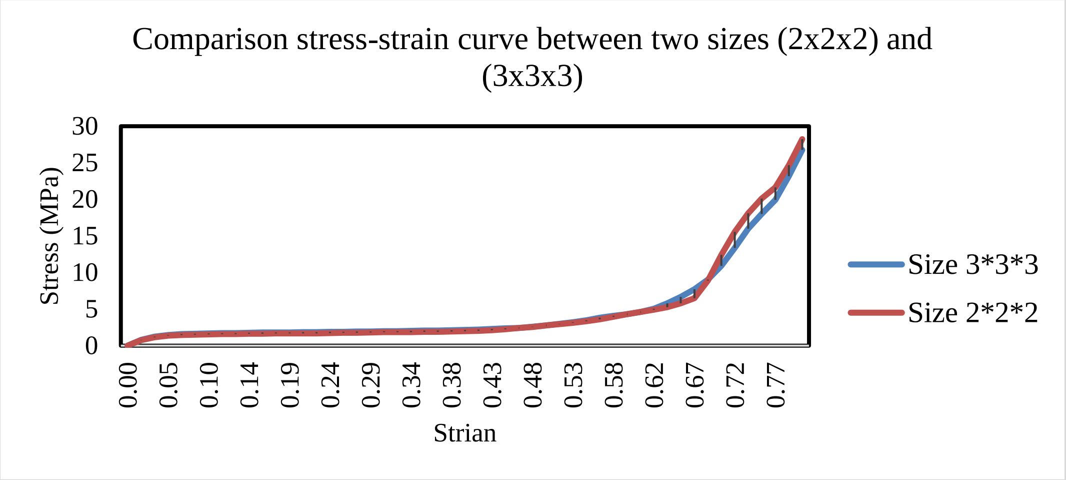


Figure 35: Stress-Strain curve of the two models, 2x2x2 cells, and 3x3x3 cells

Step 13: To illustrate this step more effectively, a real cell value from the GTP is selected when there is missing information between pairs of parameters in the table of parameters, triggering the activation of this step. Cell A-30 refers to the influence of increasing the relative density of lattice structure and the fracture toughness of lattice structure. However, there was no direct relation between the relative density of lattice structure and fracture strength of lattice structure, which is represented by cell A-34.

If the relative density of lattice structure is denoted by the equation (4):

$$\rho_{relative} = \frac{\rho_{Lattice}}{\rho_{base}} \tag{4}$$

Where $\rho_{relative}$ is the relative density of lattice structure. $\rho_{Lattice}$ is the density of lattice structure, whereas ρ_{base} is the denity of the base material from which the lattice is made. And fracture toughness of lattice structure is denoted by the equation (5) [130]:

$$K_{IC} = \alpha \rho_{relative} \sigma_{fs} \sqrt{l} \tag{5}$$

Where K_{IC} is the fracture toughness of lattice structure, $\rho_{relative}$ is the density of the base material from which the lattice is made and σ_{fs} is the fracture strength of lattice structure. Hence, the increase of relative density of lattice structure causes a decrease of the fracture strength of lattice structure. Therefore, the influence value of the cell A-34 is -1 and cell A-30 is +1.

Based on the previous literature articles, we selected six commonly used data-quality-measuring dimensions. We propose the dashboard indicated in the Table 10 to measure the quality of the data and information provided in the GTP.

3.3 Measuring data quality

Measuring the quality of the collected data forms a serious issue in the road of robust and relevant solution at the end of a design problem solving method. Data quality, precision and accuracy are generally thought of as having a major impact on the information that may be inferred from this data [131], [132]. In the article [133], authors developed a measurement framework to quantitatively assess the quality of Open Government Data (OGD) based on intrinsic quality characteristics. The authors of [134] proposed the establishment of a hierarchical structure of a data quality framework, which involves a dynamic big data quality assessment process with a feedback mechanism. Further data quality criteria and dimensions were presented in the article [135]. In a general context, authors of [136] provided examples of metrics that can be used to measure data quality, such as accuracy, completeness, consistency, and time-related dimensions. In [137] authors referred to some general data quality frameworks such as AIMQ, and others so specific in particular domains, such as AMEQ in manufacturing and product data. In the same reference, authors emphasized the fact that some dimensions appear very frequently in the frameworks.

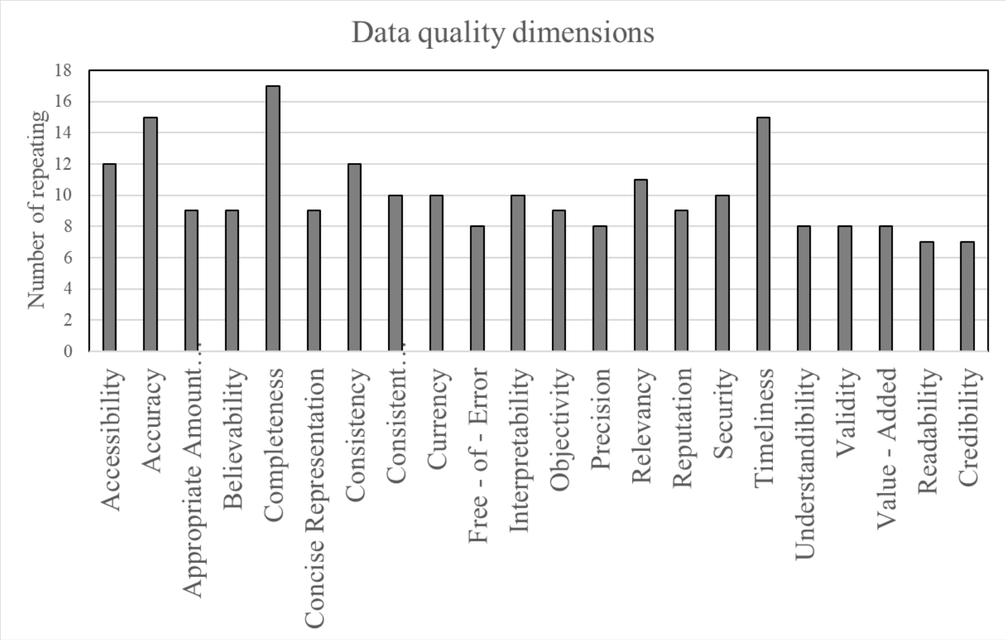


Figure 36: the frequently used data quality dimensions from literature

Based on these referential studies in data quality measuring, as shown in Figure 36, we drove six dimensions which are widely used in many studies to measure the data quality, and which are matching with the objectives of our table of parameters. These dimensions are Accessibility, Timeliness, Credibility, Consistency, Completeness, and Readability.

Table 10: Dashboard to measure the data quality of the entire GTP

Dimension	**Explain of dimension**	**Indicator**	**Measure of indicator**	**Limits of measurement**
Accessibility	(1) Data can be easily made public or easy to obtain?	1.open access sources of literature 2.possibility of getting a version of the software	1.The type of journal (open access/free book/paid book/paid article) 2.Availability of a trial version of the software	1.Paid articles (however, the university email was used to get access to these articles) 3 free books and one paid book 2.There is a trial version of PTC Creo and ABAQUS
Timeliness	(1) Within a given time, whether the data arrive on time? (2) Whether data are regularly updated?	1.The time between the interview with the expert and updating the table with information 2.How many versions between the last version of software and the downloaded version	1.The recent day-The day of first interview 2.The number of the last version released – The studied version number	1.(179 days) 2.(3)
Credibility	(1) Data is extracted from trustful scientific sources? (2) Data come from specialized experts? (3) Experts regularly audit and check the correctness of the data content?	1.The scientific source is in the predatory journals list 2.Domain of work of the expert 3.How many times the data is revised per month by an expert	1.Existence of journal name in the list 2.The name of the domain of expertise of expert(s) 3.Number of revision times per month	1.No 2.Cellular structures and foams 3.Randomly revised and not periodically (around 4 times per months)
Consistency	(1) The conflict about the same piece of data/information between one/more than source of data	1.Existence of conflict	1.Number of conflicts' cells with a dotted hash/total number of all informative cells in the table	1.(31cell /1612 cell) * 100 = 1.92 %
Completeness	(1) Deficiency of a component which will impact use of the data for inventive design	1.Missing pieces of data/information	1.Number of cells with (X) sign / total number of all informative cells in the table	1.(295 cell /1612 cell) x 100 =18.3%
Readability	(1) Data (content, format, etc.) are clear and understandable? Data provided can be easily accessible	1.The format of provided files are known formats 2.Readability and clearness of provided data in each cell 3.Cells are indexed/hyperlinked to access them easily	1.Format of the table file 2.Format of linked external files 3.Indicators for values inside cells are provided 4.Indices e.g., letters or numbers are provided to refer to cells 5.External files are linked to cells	1.Xlsx extension 2.Docx and Doc extensions 3.Provided 4.Provided 5.Linked (each cell is hyperlinked with an external file)

3.4 Discussion of results and feedback

The discussion of results will be divided in this section into two levels, one level is to discuss the general idea beyond proposing GTP. The second level is to discuss the resulting method proposed in the section 3.2.4.

3.4.1 General feedback and discussion

This research work exploited some of recently used methods for collecting data and a unified method to collect, transform, store data information, and hence, represent them in a generalized table of parameters. These methods and approaches are analyzing literature reviews, experts' interviewing, and CAD/FEM software analysis. This research work participated in building a generalized table of parameters, based on quantitative and qualitative data. This table is expected to integrate with the inventive design problem-solving process. The data and information provided by the table can be completed by performing a full factorial design of experiments (DoE). To frame the work presented by this study, the results should be analyzed in the light of some questions. In this study, transforming and analyzing the collected data from more than one source of data and integrating them in one tool such as the GTP, showed the strength of multiplying the sources of data and information. In the proposed GTP, each source of data provided unique information and data i.e., non-identical parameters in step 9, section 3.2.5. On the other hand, some parameters were common between more than one source i.e., identical parameters. This integrity between data sources showed the risk of dependence on one data source to achieve coherent information about the design system. This risk was unrevealed when conflicts between data sources appeared.

3.4.2 Method feedback and discussion

This feedback discussion of used method is demonstrated based on three main questions; first, what is the positive feedback observed on this method? Second, to what extent this table can be integrated in the inventive problem-solving method. Third, what are the potential limitations that are determined because of the application of the proposed method?

- The large number of design parameters is a way to treat with different design problems in one or more domain by using a holistic representation of these parameters and their influences e.g., mechanical field or coupling-field problems e.g., thermo-mechanical problems.
- Generalization can help effectively in treating more design problems on two levels, the level of quantity and the level of complexity of design problems.
- Each cell is hyperlinked to an external file which includes a highly performed data and information. This file contains solving techniques e.g., influence, which could be used for design process phases such as optimization. For example, quantifying the levels of each parameter.

- The completeness of some missing information in the GTP is thanks to the collected mathematical models about the relation between different parameters. This confirms the argument of [64] that the governing law between parameters could help in completing the information in such table. On the other hand, is thanks to the ease of computer modeling software such as PTC Creo and ABAQUS. These tools facilitated the completion of some information in the proposed table. However, for some parameters, modeling lattices structures based on the variation of some parameters is quite challenging and takes time. For this reason, the proposed method provides an option to update the list of keywords with new relevant keywords to the missing information and redo the search cycle for relevant scientific articles/books.
- VBA script, available in appendix A, was developed. It offered an automated and efficient solution to overcome the challenge of generating and linking customized files to a potentially large number of cells in such tables, significantly reducing manual effort and error.
- The provided design parameters by scientific databases are much more than those provided from experts and software, as seen in Table 7. We claim that the more scientific articles/books are collected, the larger quantity of parameters.
- The conflicting percentage is considered as a significantly low ration in comparison with amount of provided information. This fact brings out the robustness of the proposed approach.
- The used method in this chapter contributed to modelling the system and its performance through the determination of system parameters such as, physical and performance parameters. The generalized table of parameters could be a good practice to show to what extent such a representation approach can successfully integrate with inventive design problem-solving approach. In addition, the generalized table and its relevant documents can work such as an instant database in a specific field for solving a set of problems. Any researcher or user needs to solve one or more design problems in the same field, he/she can do it without referring again to a long list of references and repeating a long process of analysis for these scientific sources.
- However, some limitations are still inherent to the proposed method. Even though the generalized table of parameters is a powerful tool to model the designed system, accomplishing all pieces of data in this table is a considerably time-consuming process. Since this table depends on collecting, manually, all relevant information/data about each pair in the table PhP/PhP and PhP/PrP. The second limitation is that collecting the data and the analysis process depends strongly on the individual skills and competencies of the person who handles this mission (i.e., researcher). One more limitation is the limited number of extracted scientific sources since this process is a human-based one. This limitation can be treated by developing an automated tool to extract excessively the scientific sources e.g., literature reviews, patents and so on. Therefore, this tool can follow the rules of data analysis presented in this chapter.

- One more limitation concerns the availability of human experts. Since this study is conducted with the help of two experts, one is TRIZ expert, and another is cellular materials expert. However, authors made attempts to get access with four other experts to enrich the space of experts in the GTP, but unfortunately, one expert had scheduling conflicts and the other three showed no response to the invitation. This raise the difficulty of the massive dependence only on experts to conduct studies, as in [64] and [138]. This limitation argues the robustness of the proposed method.

3.5 Conclusion

In conclusion, this chapter proposes a method for constructing a generalized table of parameters (GTP) linked to a contextual database (CDB). This table can help to understand complex design problems by modeling and representing both quantitative and qualitative data from multiple sources such as, scientific databases, experts' interviews, and the analysis and usage of Computer-Aided Design (CAD) and Finite Element Modeling (FEM) software. The table model is based on the representation of collective information on system parameters, especially the influence between each pair of parameters. This model serves the extraction of system conflicts based on the TRIZ problem model, known as the 'contradiction system'. The analysis of this table can contribute to the development of a resolution strategy and provide a global understanding of the situation.

Chapter 4 Exploitation of the GTP (identifying the contradictions)

As mentioned in chapter 2 - section 2.2.3, the notion *contradiction* is used in the frame of TRIZ methods to formulate problems. One of the advantages of the generalized table of parameters and its linked contextual database is the capability of exploiting them for extracting and solving system contradictions. For this reason, in this chapter, we present a method to exploit the generalized table of parameters presented in chapter 3 for extracting generalized systems of contradictions related to inventive design problems and solve them. Moreover, we propose a way to replace complex generalized physical contradictions with a simpler one by using the same table and database.

This chapter starts with presenting a general case study for its solution, the table and database will be examined. Then, a developed method would be proposed for this exploitation. The next sections will be dedicated to applying the proposed approach for solving the case study that was presented in the preface of the chapter. This application would reveal the strengths and limitations of the proposed approach. The illustration would be followed with a feedback discussion, ended by a resuming conclusion.

4.1 Presentation of case study and problematic

After analyzing several studies on the desired performance for lattice structure ([135] - [12]), we propose as case study an energy absorber that can serve several applications in the mechanical domain. It focuses on the design of an energy absorber whose main component is a lattice structure. The challenge is to design a solution based on lattice structures to improve industrial mechanical energy absorbers found in various systems such as helmets or packaging. The "absorber" system will be manufactured using a lattice structure made from lightweight polymer materials. The main objective is to create a system that meets the criteria of shock resistance, rigidity and lightness. This system would be a crucial component in industrial applications in the mechanical field, aiming to improve these three characteristics simultaneously. The main function of an energy absorber is to efficiently absorb the kinetic energy generated during deformation, while preserving the structural integrity of systems. The central question here is how to create a lightweight, rigid system that excels in crashworthiness. The following aspects fall within the scope of this case study:

Domain of application: for this case study, the focus will be dedicated only for industrial applications within the mechanical domain.
Initial problem: energy absorbers have compromising results between crashworthiness capabilities, rigidity, and lightweighting for many of industrial mechanical systems, such as helmets, packages, and

other applications which require improving the three characteristics all together, as indicated in Figure 37.

Fabrication technology: the energy absorber under consideration should be fabricated using additive manufacturing technology.

Used material: the energy absorber should be made from polymeric materials.

Deformation: the structure of the absorber would be subjected to a static deformation, which is uniaxial.

Possible industrial applications: this case study is aiming to fabricate an energy absorber which could be a part of one or more industrial systems i.e., products. The tackled design problems are common between a set of industrial systems such as helmets, car bumpers, packaging of precious objects, safety equipment, sports protections, shoes equipment, and bullet-proof vest, as shown in Figure 37.

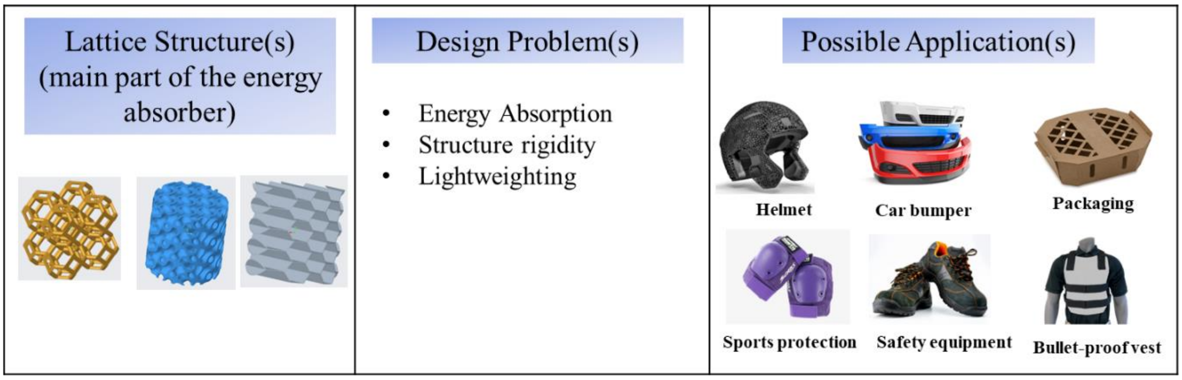


Figure 37: The core part of the designed energy absorber, its inherent design problems, and their relevant possible industrial applications of this energy absorber

To address this case study, by using the previously proposed GTP, a systematic method is proposed in the next section.

4.2 Method to integrate the GTP with the design process

In this section we propose a 10-steps method to exploit the GTP for extracting generalized systems of contradictions (GSC) [2] underlying a given inventive problem, as illustrated in Figure 38. This section is presenting the proposed method, while the next section will be presenting the application of this proposal on the case study mentioned in the section 4.1.

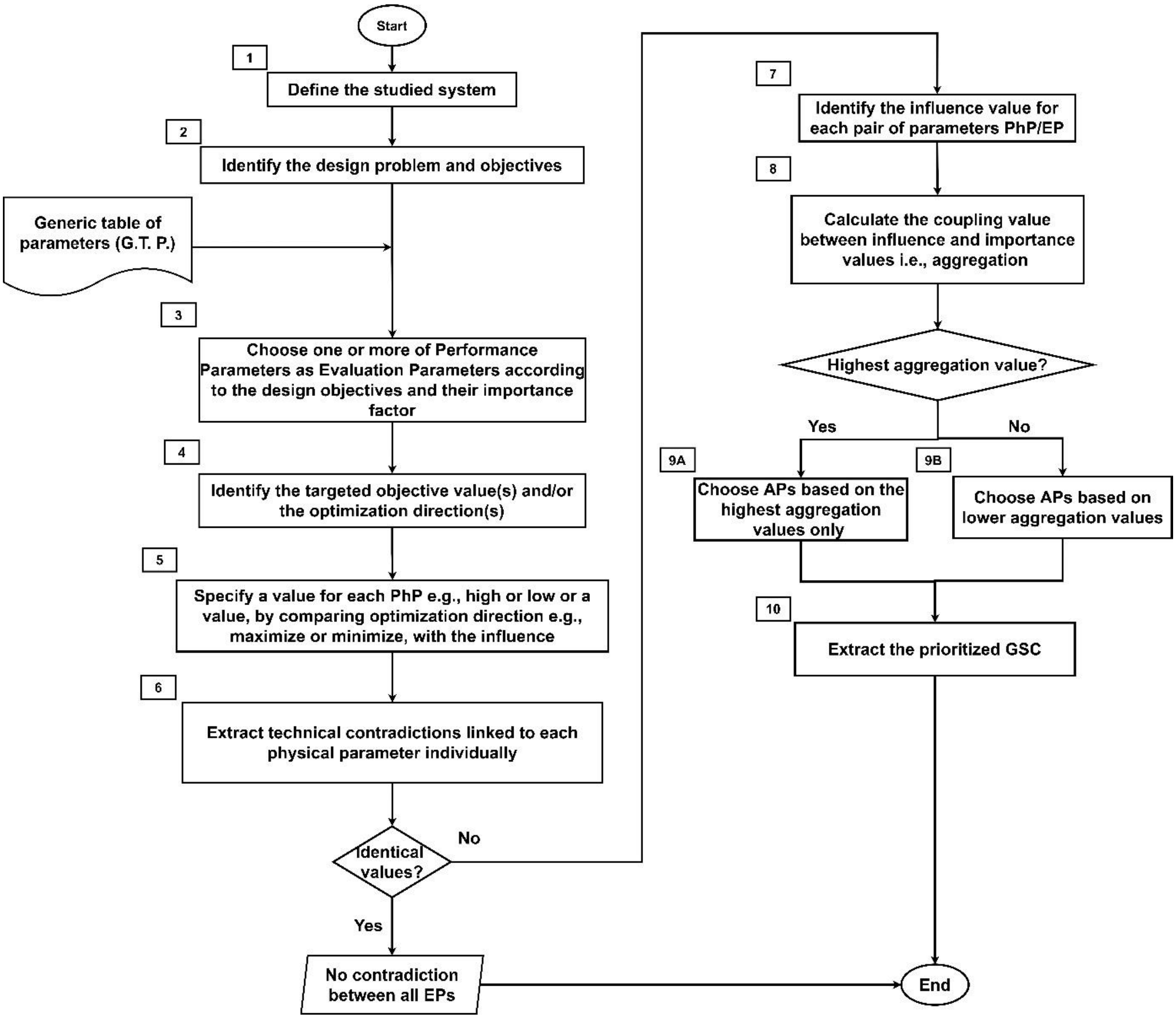


Figure 38: Proposed inventive design method to identify and solve the GSC from the GTP

Add the last part of solution for perspectives

4.3 Applying the method on the case study

The illustration of the method, mentioned in section 4.2, on the lattice case study, will be detailed within the next lines.

Step1: Define the studied system

In this step, the studied system is first defined as a product or a process. In this study, the focus is on developing products, hence, the system is a product in our study. The full definition of the studied system is detailed in section 4.1.

Step 2: Identify the design problem and objectives

The structure should be fabricated by the additive manufacturing technology

- It should be made of polymeric materials
- The structure is made of a specific material no a composite structure
- This structure might be subject to static load i.e., deformation
- The selected problem to be covered by this table are three:
    - Energy
    - Structure strength
    - Light weighting
- The concerned field is the mechanical field

The design objective of this case study is to enhance the lattice structure's ability to absorb mechanical energy arising from external solicitations, such as pressure, displacement, or applied force. The enhanced mechanical energy absorption capacity will render the lattice structure suitable for utilization as an energy absorber in a wide range of applications, including protective pads, car bumpers, and helmets, within a broad context. Furthermore, the structure must maintain both rigidity and lightweight characteristics. These objectives gain significance due to the challenges associated with conventional design and fabrication methods.

The initial problem is that energy absorbers have compromising results between crashworthiness capabilities, rigidity, and lightweighting for many of industrial mechanical systems, such as helmets, packages, and other applications which require improving the three characteristics all together.

Step 3: Choose one or more of Performance Parameters (PrPs) as Evaluation Parameters (EPs) according to the design objectives and their importance factor

In this step, one or more Performance Parameters can be selected from the Generalized Table of Parameters (GTP), according to the design objectives. In this method, experts are asked to give the importance value to each Performance Parameter (PrP). Hence, the most important PrPs can be considered as Evaluation Parameters (EPs) in the context of the design problem since they are modeling the design problem.

The choice of EPs can be facilitated by using the GTP by referring to the so-called “Parameter family”. The one parameter family is grouping one or a set of parameters, as indicated in Figure 39. In this case, specialists and non-specialists can refer to these families to select the appropriate EPs and/or

APs. An example on these families can be the family of energy which contains parameters energy absorption per unit volume, densification strain, and other parameters which can model problems of mechanical energy. For example, if the design problem is around (energy) then the family (energy) would be taken into consideration as a priority.

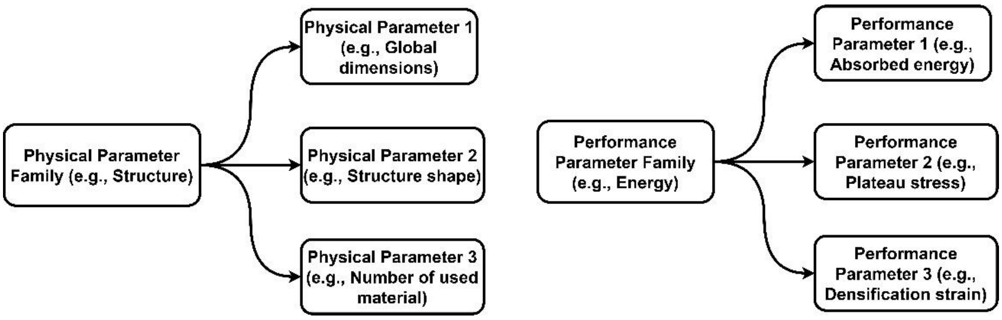


Figure 39: An indication of the parameter family

In this step, on the other hand, an “importance” factor within the range 1 to 10 is given to each EP to help the decision makers in prioritizing the problem to be solved. These values are given by stakeholders in the field of the ongoing problem i.e., lattice structures or cellular structures.

According to the design objectives, to be measured, five PrPs have been chosen to be considered as Evaluation Parameters EPs in the context of the design problem based on the importance values, determined by experts, in our case. These chosen EPs are related to specific families, which are energy, Rigidity of lattice structure, and Lightweighting. Moreover, the importance factor was determined to each chosen EP, as indicated in Table 11.

Table 11: The chosen EPs from the GTP and their relevant families, and importance factor

Evaluation Parameter (EP)	Importance factor of each EP	Parameter Family
Energy absorption per unit volume	10	Energy
Modulus of elasticity of lattice structure	10	Energy
Plateau stress	7	Energy
Densification strain	7	Rigidity of lattice structure
Mass	10	Lightweighting

Step 4: Identify the targeted objective value(s) and/or the optimization direction(s)

This step translates the objectives into expected values for the evaluation parameters, and the optimization direction of each EP. Two situations are distinguished:

- The target values are known. For example, the mass of the system designed must be less than 50 grams to limit weight; the range of target values is between 0 and 50.

- Target values are not (yet) known. In this case, objective values are defined in terms of minimum or maximum. For example, the mass of the designed system is to be as low as possible.

In this case study, an optimization direction was determined to each chosen EP, according to the desired targeted objectives, as indicated to Table 12.

Table 12: The chosen EPs from the GTP, and their relevant optimization directions

Evaluation Parameters (EPs)	Optimization direction of each EP
Energy absorption per unit volume (MJ/m3)	Maximize
Modulus of elasticity of lattice structure (MPa)	Maximize
Plateau stress (MPa)	Minimize
Densification strain	Maximize
Mass (g)	Minimize

Step 5: Specify a value for each PhP e.g., high or low or a value by comparing optimization direction e.g., maximize or minimize, with the influence

In this step, a new corresponding table is established. Each cell of this table contains information about the decision taken to change a Physical Parameter to satisfy one Evaluation Parameter and meet the optimization direction. As shown in Table 13, for this case study, some values e.g., high, low or a specific value, were specified for each physical parameter in order to satisfy each evaluation parameter individually. Worthy mentioning that the complete established table is provided in appendix B.

Table 13: An excerpt of the specific table which indicates the specific value for each PhP for each EP in respect with the objective direction

index		15	15.1	15.2	16	17
		Evaluation Parameters (EP)				
	Optimization direction	maximize	minimize	maximize	maximize	minimize
		Energy absorption per unit volume	Plateau stress	Densification Strain	Modulus of elasticity of lattice structure	Mass
A	Relative density of lattice structure	high	low	minimize	high	low
B	Global dimensions	low	high	low	high	low
..	..	..	..	..	..	..
ZZ.1	Type of base material	ABS	PLA	PLA	ABS	ABS

Step 6: Extract technical contradictions linked to each physical parameter individually

In the Table 14, PhP1 must be as high in value as possible to satisfy EP1 (in red color) and must be as low in value as possible to satisfy EP2 (in yellow color). This means that there will be a technical contradiction between both parameters EP1-EP2. Otherwise, there is no technical contradiction, as indicated in the same figure. By checking the identification of the value necessary of each PhP, the technical contradiction between EPs could be highlighted as explained previously. The specific extracted table of parameters were checked to highlight the possible contradictions between EPs. This resulted in the Table 14. However, the complete table is provided in appendix B.

Table 14: An excerpt of the specific table which highlights the possible contradictions between EPs for each AP

The contradictions table								
index			15	15.1	15.2	16	17	
	Parameter type		Evaluation Parameters (EP)					
		Optimization direction	maximize	Minimize	maximize	maximize	minimize	Contradictions
			Energy absorption per unit volume	Plateau stress	Densification Strain	Modulus of elasticity of lattice structure	Mass	
A	Physical Parameters (PP)	Relative density of lattice structure	high	low	low	high	low	Contradiction
B	Physical Parameters (PP)	Global dimensions	low	high	low	high	low	Contradiction
..	..	..	..	..	..	..	..	..
ZZ.1	Physical Parameters (PP)	Type of base material	ABS	PLA	PLA	ABS	ABS	Contradiction

Step 7: Identify the influence value for each pair of parameters PhP/EP

To identify the influence weight of each pair of parameters, we need to present the definition of this term first. The definition of the term "influence weight" can be presented as follow:

Influence weight: it is the degree of intensity of change (null, low, moderate, high) on a parameter e.g., evaluation parameter EP, that results from changing the value of one parameter e.g., physical parameter PhP. The influence (null, low, moderate, high) is coded with three values:

- if the influence between parameters is high, the weight is 3
- if the influence between parameters was moderate, then the weight is 2
- if the influence between parameters was low, then the weight is 1
- if there is no influence between parameters, then the weight is 0

The influence weight can be determined by different techniques. Those techniques are as follow:

- *Expert's feedback*

The expert, as a referring source of knowledge, can be interviewed to give his/her own opinion on the value of influence.

- *Equation*

The equation represents a mathematical model of a set parameters, inputs, and outputs.

- *Graph*

The results can be represented graphically by plotting the observed results. These graphs can be read and analyzed to extract information about the relation between two parameters as shown in, the interaction between two parameters and a third parameter, as shown in Figure 40.

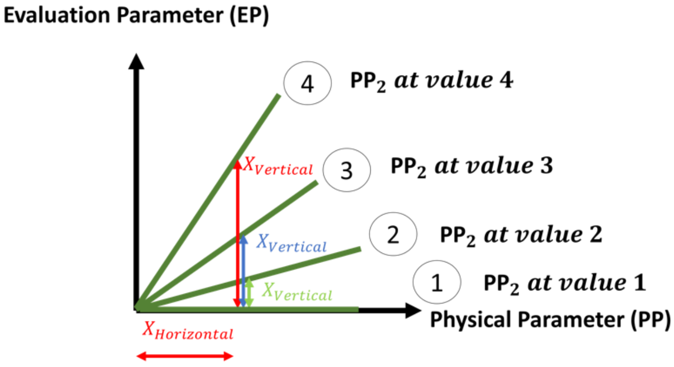


Figure 40: Indicative representation of the extracted information from a graph

For this case study, the influence weights were collected from experts, two experts, one expert in cellular materials and another one in mechanical design. An excerpt from the table of influence weights (IW) is indicated in Table 15.

Table 15: An excerpt of the table used to identify the influence weights (IW)

The influence weight (IW) table							
impact factor			10	7	7	10	10
	Parameter type		Evaluation Parameters (EP)				
		Optimization direction	maximize	minimize	maximize	maximize	minimize
			Energy absorption per unit volume	Plateau stress	Densification Strain	Modulus of elasticity of lattice structure	Mass
A	Physical Parameters (PP)	Relative density of lattice structure	3	3	3	3	3
B	Physical Parameters (PP)	Global dimensions	1	1	1	1	3
..	..	..	..	..	..	..	..

ZZ	Physical Parameters (PP)	Strut shape	1	2	2	3	3
ZZ.1	Physical Parameters (PP)	Type of base material	3	3	3	3	3

Step 8: Calculate the coupling value between influence and importance values i.e., aggregation

The aggregation value is the summation of multiplying the importance factor (IF) of the most important EPs (highlighted in green and grey in Table 16, multiplied by the corresponding influence weight (IW) and identified by calculated aggregation (highlighted in yellow and orange colors), in the same table. The aggregation is following the formula of equation (6):

$$\text{Aggregation} = \sum_{n=1}^{N} IF_n * IW_k \quad for\ each\ K \tag{6}$$

By applying this rule on the study case, the Table 16 will be obtained. In this step, the choice of Action Parameters APs is based on choosing those ones with an aggregation more than or equals to 90 (highest aggregation values). This led to prioritizing 3 APs out of 32 PhPs in total.

Table 16: The calculated aggregation values for each EP in the specific table. This table will lead to the selection of Action Parameters APs out of the entire set of Physical Parameters PhPs

			AP1	PhP2	PhP3	PhP4	PhP5	PhP_n
			Relative density of lattice structure	Global dimensions	Shape of structure	Number of used materials	Gradience	….
EP1	10	Energy absorption per unit volume	3	1	3	3	2	….
EP2	7	Plateau stress	3	1	0	3	2	….
EP3	7	Densification Strain	3	1	0	3	1	….
EP4	10	Modulus of elasticity of lattice structure	3	1	3	3	1	….
EP5	10	Mass	3	3	2	2	3	….
			90	50	80	80	60	….

Step 9: Choose APs based on the highest aggregation values

In this step, the choice of APs is based on choosing those ones with an aggregation more than or equal to 90. This led to prioritizing 3 APs out of 32 in total. The chosen APs are illustrated in the Table 17.

Table 17: The chosen APs with their aggregation values which helps in prioritizing the selected APs to formulate the prioritized problem to be solved

			AP1	AP11	AP32
			Relative density of lattice structure	Cell size	Type of base material
EP1	10	EP1	3/(high)	3/(low)	3/(ABS)
EP2	7	EP2	3/(low)	3/(high)	3/(PLA)
EP3	7	EP3	3/(low)	3/(high)	3/(PLA)
EP4	10	EP4	3/(high)	3/(low)	3/(ABS)
EP5	10	EP5	3/(low)	3/(high)	3/(ABS)
			90	90	90

Value	Explanation
3/(high)	Influence weight / value of action parameter to satisfy the evaluation parameter

Step 10: Extract the prioritized GSC

The proposed method specified APs linked with a chosen EPs. This may result in potential system of contradictions based on the previous *step*. In this step, the prioritized generalized system of contradictions (GSC) could be extracted from the Generalized Table of Parameters (GTP). The contextual GSC is as in the Figure 41:

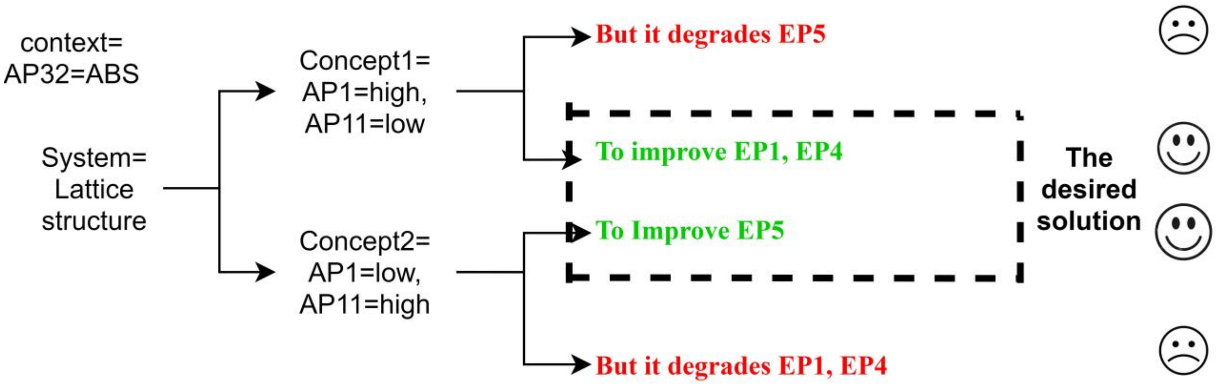


Figure 41: The formulated contextual GSC out of the table of parameters

This GSC is true under the context of having the type of material is ABS. states that the system of lattice structure needs to be in two concepts. The first concept is to have a lattice structure with a high relative density and low cell size to satisfy the energy absorption and modulus of elasticity. The same structure should have a low relative density and a high cell size to provide a lightweighted structure.

4.4 Discussion of results and feedback

This feedback discussion of used method is demonstrated based on two main questions; first, what is the positive feedback observed about the proposed method? Second, what are the potential limitations that are determined because of the application of the proposed method?

Answering the first question could be resumed in the following bullet points:

- The proposed method is a systematic approach, which is not loaded, heavily, on the level of experience of users, hence, using the proposed approach can be possible by non-experts in the domain of the treated design problem.
- Presenting a systematic inventive design method less dependent on the experience level of the user, can reduce the subjectivity in the decision- making process.
- The proposed approach could give a holistic vision on the core problem of the system and contributed in re-formulating the design problem to facilitate solving this problem after.
- The method could reveal some design parameters related to the design conflict. These parameters and their relation to the design conflict were not well-explained by the interviewed experts. This shows the strength and robustness of the proposed approach.
- In contrast with some existing methods e.g., IDM method, our method an inclusive to all design problems in one conflict model i.e., GSC model. Moreover, it presented feasible and applicable direct solution concepts which are very coherent to the design problem, and less dependent on the experience of users.
- As a perspective of this method, solving the Generalized Physical Contradiction could be possible by using units of parameters. Such as anticipating the parameter(s) which can substitute a set of APs by multiplying or dividing the units of these parameters. This approach was proposed initially by other research, as mentioned in section 2.2.4. Hence, this approach could be developed more in the light of more complex contradictions.

Answering the second question, this proposal is promising, even though it suffers from some limitations. The influence weights and importance values given within this method are still, partially, based on the experience of the user and, therefore, this could be a subjective step in the process of decision making. To overcome some limitations of this process, and/or apply some promising perspectives, the next chapter will be presenting a further development to enhance the inventive process in this thesis.

4.5 Conclusion

In this chapter, chapter 4, we present a method to exploit the built generalized table of parameters GTP in the inventive design process to extract and prioritize the generalized system of contradictions (GSC). The new method is presented as a systematic approach, which is not loaded, heavily, with the level of experience of users. Hence, using the proposed approach can be possible by non-experts in the domain of the treated design problem, and decrease the subjectivity in the decision- making process. A case study was treated to illustrate the strengths and limitations of the proposed method. This case study was to fabricate an energy absorber with lattice structure as a core component. This structure must have a high crashworthiness, rigidity, and lightweighted. As a result of applying the method, one prioritized GSC were extracted to be solved. Finally, in the next chapter, developments will be proposed to present specific solutions of the technical-system problems within a specific context by applying the experimental approach (DoE-based).

Chapter 5 Invention through Design of Experiments (DoE)

In cases where the bibliography and available expert opinions are not sufficient to understand the problem and initiate the modeling process, we propose the use of an alternative method based on Design of Experiments (DOE) that highlights the boundaries between multi-objective optimization and invention. These experiments can be conducted either through physical experimentation or by utilizing models and numerical simulations. Initially, a Design of Experiments is planned, considering the system parameters and the desired performance measures. Nevertheless, this step can still utilize GTP (Generalized Table of Parameters) (see chapter 4) to better select the parameters for the plan and avoid neglecting certain ones that may have a significant influence on the system's behavior. Conversely, once implemented, this method can also be used to fill in empty cells of the GTP, as it allows for the clarification of relationships between the system parameters. The Design of Experiments (DoE)-based method aims to define a set of experiments to be conducted by varying the parameter levels to collect data on the system's behavior. Based on the obtained results, modeling allows for the understanding of relationships between parameters and performances and the identification of potential contradictions. The objective contradictions "technical contradictions" may arise due to the need for trade-offs among different sought-after performances. For this reason, a multi-objective optimization is undertaken to find solutions lying on the Pareto front, meaning solutions that represent the best compromises between competing objectives. Multi-objective optimization seeks to find a set of optimal solutions rather than a single optimal solution since objectives may be contradictory and cannot be simultaneously optimized.

We proposed introducing a threshold or "Binarization threshold" for extracting the system conflicts. This threshold represents a variation in the values of the optimization constraints. It can lead to a simplification of the model adjustment process by reducing the number of physical parameters considered in resolving contradictions, making problem-solving easier (or resulting in minor changes in the initial model, enabling short-term solutions). The use of the threshold also prompts users of the method to carefully consider the initial constraints' values in the system and observe the effect of a small variation in these constraints on the final resolution. They can assess the impacts on the model's complexity, solution feasibility, expected performance, costs, etc.

Thus, by assisting the many problem-solving steps suggested in this novel approach, design of experiments (DoE) can play a vital role in the inventive design process. In order to make this method easier to understand, the discussion progressively builds up to a concrete example employing lattice structures. This chapter aims to develop a DoE-based methodology that aims to define a set of experiments to be conducted by varying the parameter levels to collect data on the system's behavior.

Based on the obtained results, modeling allows for the understanding of relationships between parameters and performances and the identification of potential contradictions. A specific example of applying this method to solve design problems related to the mechanical behavior of lattice structures is presented, to illustrate the applicability of the proposed method. This method is composed of 16 sequential steps, as shown in Figure 45, which will be explained in detail through this chapter. On the other hand, the performed DoE will be analyzed by using multiple methods such as, Regression model, RSM model, and Analysis of variance -ANOVA-. This analysis will help in completing information of modelling the problem situation in the Generalized Table of Parameters (GTP), and understanding better the problematic situation, therefore, overcoming some limitations of the proposed method in chapter 4. PTC CREO® software will be used to construct CAD models for the purpose of the design of experiments. ABAQUS® software will be used to perform non-linear numerical simulations. Minitab® software will be used for two things: first is to perform the analysis of the obtained results from DoE, the second thing is to apply the Reduced Gradient Algorithm (RGA) for a multi-objective optimization. NSGA-II (Non-dominated Sorting Genetic Algorithm) will be exploited, as well, by using the python-based package Pymoo®. At the end of the proposed method, a set of contradictions will be chosen to be solved by using TRIZ-based inventive methods i.e., separation principles and standard SI units. The new changed models and proposed solution concepts will be tested by using numerical approach i.e., finite element software ABAQUS®. The new models will be evaluated to examine their performance and hence knowing whether the design goals are achieved or not. The sequence of the proposed approach is illustrated in the Figure 42. A part of this work was presented in [139].

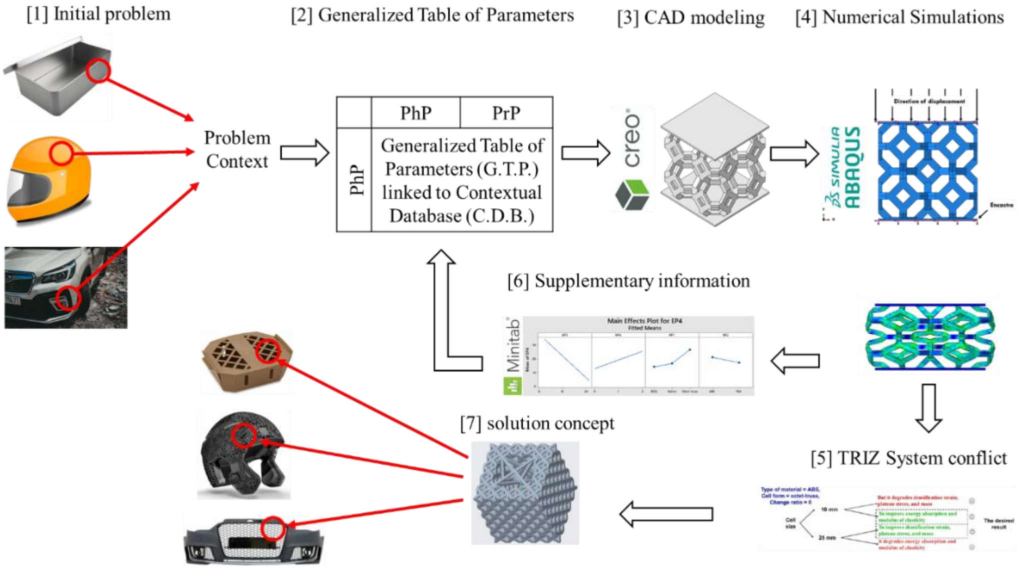


Figure 42: An illustration of the proposed method to evolve from an existing system to a new developed system

5.1 Presenting the developed method

We proposed introducing the "threshold" as a technique to extract information about the contradictions of the system, within a developed systematic inventive method. The extraction and resolution of the generalized contradictions from the experimental data is a main step in the proposed method. This extraction is achieved by comparing all the rows in the experimental plan. Both action parameters (inputs) and evaluation parameters (outputs) for each row are analyzed. The goal of this analysis is to sort the experimental plan based on action parameters and their levels and then observe the outputs to detect any potential technical contradictions in the system. Contradictions can be linked to one action parameter or several action parameters at once. The extracted contradictions in the proposed method, in this chapter, will be based on varied number of physical parameters and varied values of threshold. Solving design problems should be because we have no idea whether this problem is inventive or not. For this reason, trying to solve the design problem by using optimization is an option to investigate the optimization solutions. This optimization could be done by performing the DoE and detecting the "best" solutions can be achieved within the available data, see Figure 43 (a). However, inventive methods explore new problem spaces in the general solution space when optimization methods do not allow for the finding of a satisfying concept solution i.e., highly complex problems. In other words, TRIZ enables the model of the problem to be changed, moving from one space to another by only changing the action parameters and relationships. This model change occurs when no optimal solution (Pareto solutions) satisfies the concept of a solution. The model change is executed based on defined threshold values which could be minimal change with one physical parameter or more complex change based on more than one parameter. The proposed method is based on exploring the first conflict(s) appear when changing a specific number of physical parameters. The more changing physical parameters in the system, the closer to the desired ideal solution. Here, we should present the "ideality" within the context of this method. Ideality is the desired value of each evaluation parameter (EP) to evaluate achieving the desired development of the system. In this method, in case the ideal results are unknown, the best results of each EP will be selected to be the ideal result of this EP. The selected value would be binarized to show this value as a solution within a specific experimental configuration. For this reason, we should present the term "binarization" in the context of this method. This term refers to the transformation of a quantitative parameter to a qualitative one. In other words, it converts values into colors (green) and (red). The goal of binarization is to highlight that some values of DoE are higher or lower by a specific predefined threshold value. A result from combining "threshold" with "binarization", we would present the terminology "binarization threshold". This term, expressed as a percentage, defines the limit for evaluation parameter values during binarization, varying from ideality (0%) to complete deviation from ideality (100%). This method offers both global and individual thresholds for evaluation parameters. In Figure 43 (a), the "binarization threshold" could be global, which means a global deviation of all performance parameters e.g., Evaluation Parameters, for example, corresponding values of $EP_1=EP_2=10\%$ far from the ideal desired solution. In the same figure, the "binarization threshold" could be individual, which means a change of the constraining value for each performance parameters individually, for example, objective value of EP_1 = 10% far from the desired solution, corresponding value of $EP_2=20\%$ far from the desired solution.

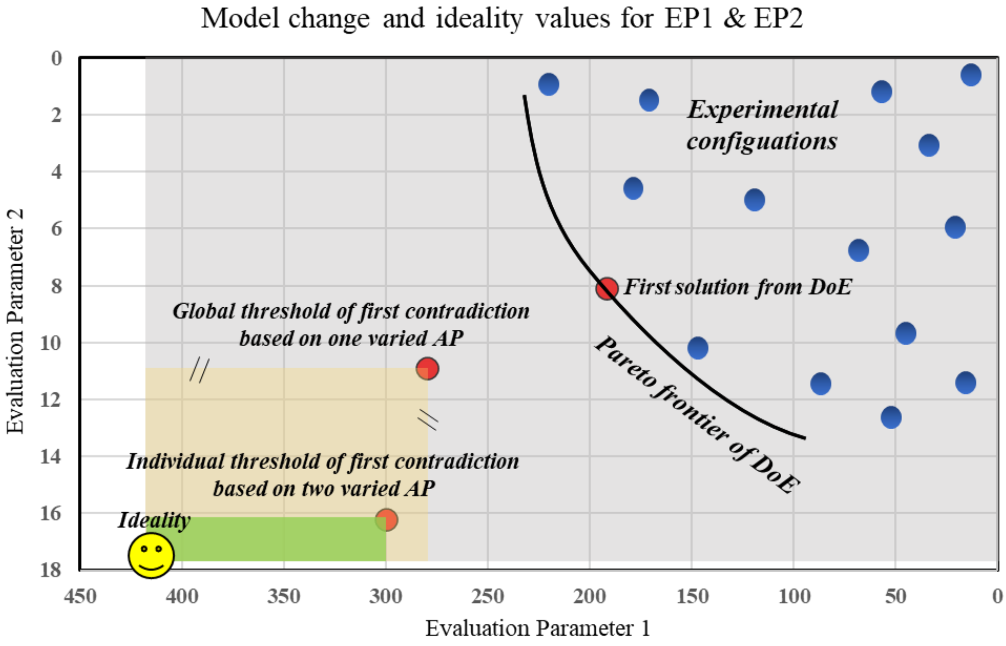


Figure 43: an example on solution found out of optimization process

As a result, from determining a "binarization threshold", solutions could appear, which is called "Binarization zone solution". This term refers to the satisfaction of evaluation parameters with a set binarization threshold value. It can be a final solution if all evaluation parameters are satisfied or partial if only a few are. In the Design of Experiments (DoE), this solution is highlighted in green, distinguishing it from others. It is not the ideal final problem solution but rather an intermediate step in the optimization process, indicating parameter satisfaction under the specified binarization threshold within a specific iteration.

Hence, one can see that by determining the value of "threshold" technical contradictions could appear. To illustrate the definition of "binarization threshold", an example would be given. Three experiments exp1, exp2, and exp3 are performed. Three Evaluation Parameters EPs are measured EP1, EP2, and EP3. Two Action Parameters APs are changing AP1 and AP2. For example, EP1 is a parameter favorized to be at its maximum value. EP1 has boundary values which are the maximum value Y7 and minimum value Y1. In this example, the binarization threshold is framed with values from the maximum value Y7 and only this value can be the objective value.

From this explanation, one can conclude that the objective value in this case is defined in regards of the experimental boundary values i.e., maximum, and minimum, the optimization direction, and the "threshold". Hence, the corresponding value of a specific threshold is calculated by using these formulas:

- For the optimization direction = "Maximize"

$$\text{Objective value } = (ABS(maximum\ value - minimum\ value) * (1 - objective\ threshold)) + minimum\ value$$

- For the optimization direction = "Minimize"

$$\text{Objective value } = (ABS(maximum\ value - minimum\ value) * (objective\ threshold)) + minimum\ value$$

In the same example, the best objective value of EP2 is where the maximum value is located, which means Y8. However, the best objective value of EP3 is Y3 where the minimum value is located. To explain better this definition of "binarization threshold", EP2 will be illustrated. In this case, Y8 and Y5 are green because they are accepted values within the threshold zone and close to the objective values which range from Y8 to 40% of the entire values of EP2 i.e., Y5. In the case of EP3, all cells are accepted and colored green, since the binarization threshold is accepted from the minimum to the maximum value of EP3. This means that any value within this zone is accepted and solves the problem linked to EP3.

Exp no.	AP1	AP2	EP1	EP2	EP3
exp1	X1	Z1	Y1	Y2	Y3
exp2	X1	Z2	Y4	Y5	Y6
exp3	X1	Z3	Y7	Y8	Y9
		Min. val.	Y1	Y2	Y3
		Max. Val.	Y7	Y7	Y9
		Threshold (%)	0-40	0-40	0-40
		Obj. Val.	Y1 to Y4	Y2 to Y5	Y6
		Opt. Dir.	max	max	min

As a result, from sorting this table, contradiction could be extracted as follow in Figure 44:

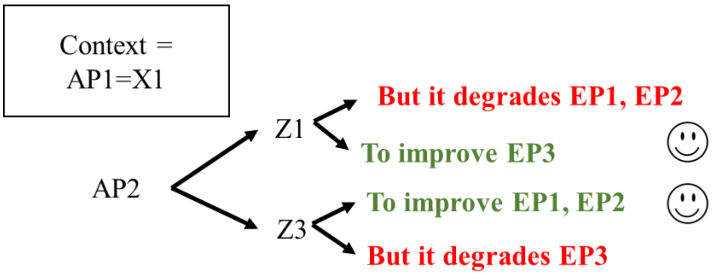


Figure 44: an example on the extracted contradiction based on sorting the physical parameters

This change of the number of varied physical parameters results in a deviation from the desired ideal solution. This deviation reflects the threshold percentage. The deviation represents the percentage by which the problem constraint is far from the desired solution e.g., the deviation at the desired solution is 0%. Applying the concept "binarization threshold" to change the system model with the possibility of the minimum change of the system, is presented in this chapter. Moreover, to treat with limitations of previous studies, completely or partially, the proposed method in this section is presented. The method is based on exploiting the results out from Design of Experiments DoE, as shown in Figure 45.

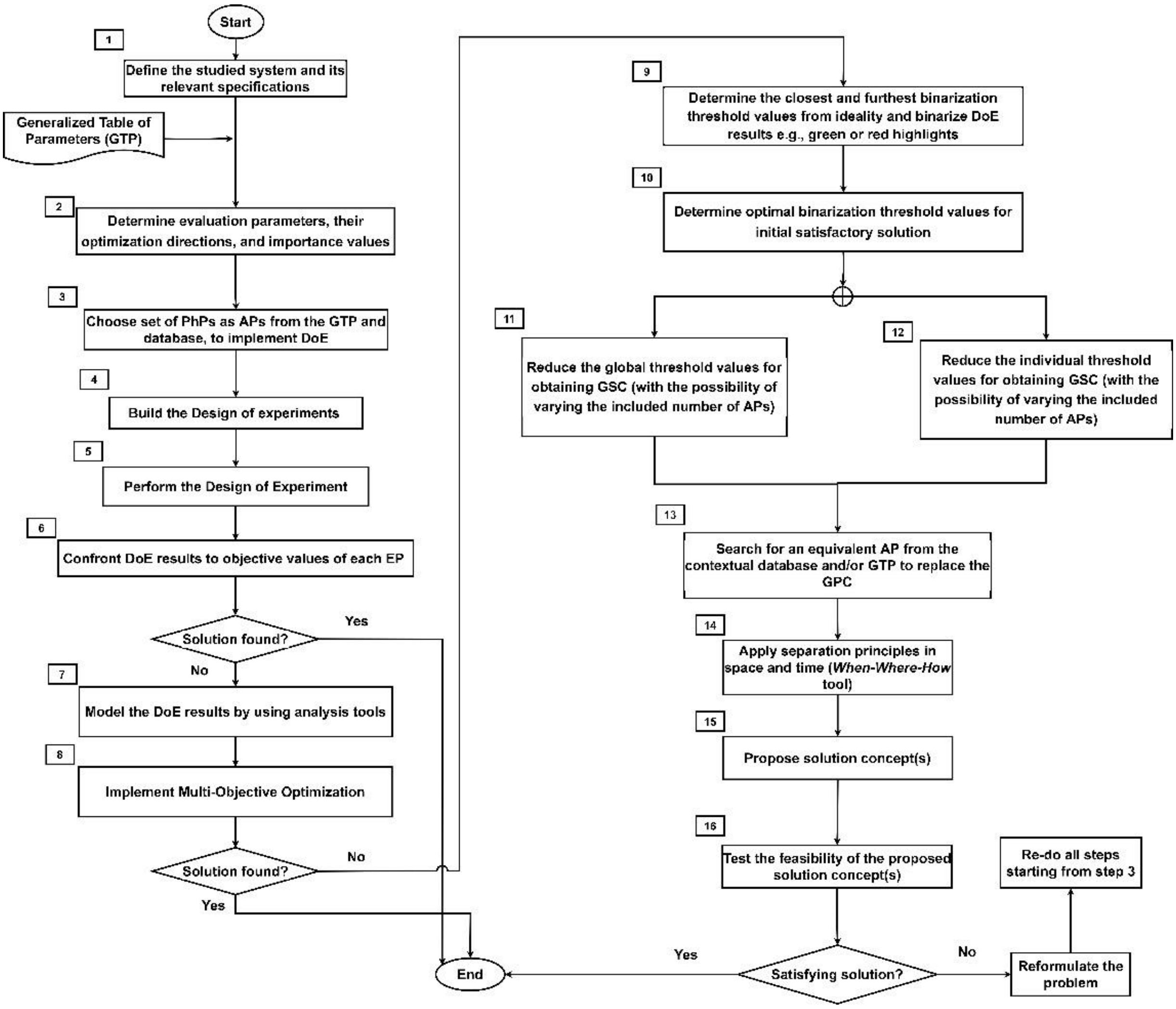


Figure 45: the proposed method to identify Generalized System of Contradictions (GSC) from the Design of Experiments (DoE)

5.2 Illustration of the proposed method on lattice structure

The case study is general, and it was previously presented in the section 4.1. The following aspects fall within the scope of this case study:

Domain of application: for this case study, the focus will be dedicated only for industrial applications within the mechanical domain.

Initial problem: energy absorbers have compromising results between crashworthiness capabilities, rigidity, and lightweighting for many of industrial mechanical systems, such as helmets, packages, and other applications which require improving the three characteristics all together.

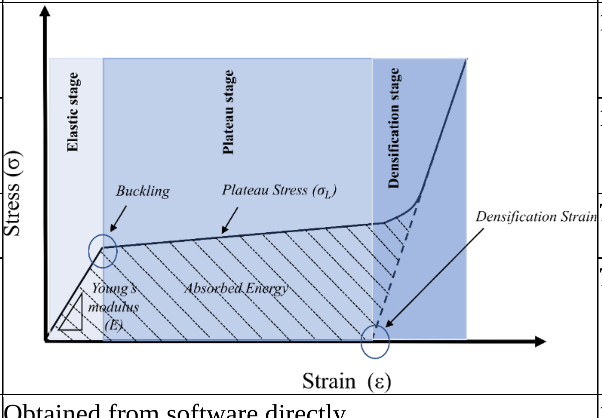
Fabrication technology: the energy absorber under consideration should be fabricated using additive manufacturing technology.

Used material: the energy absorber should be made from polymeric materials.

Deformation: the structure of the absorber would be subjected to a static deformation, which is uniaxial.

Possible industrial applications: this case study is aiming to fabricate an energy absorber which could be a part of one or more industrial systems i.e., products. The tackled design problems are common between a set of industrial systems such as helmets, car bumpers, packaging of precious objects, safety equipment, sports protections, shoes equipment, and bullet-proof vests.

Step 2: in this step, the evaluation parameters, their optimization directions, and importance values are specified from the generalized table of parameters GTP. Here, we present the results of this step:

symbol	Evaluation Parameters (EP)	Optimization direction	Definition	Importance value
EP1	Energy absorption per unit volume	Maximize		10
EP2	Modulus of elasticity of lattice structure	Maximize		10
EP3	Densification strain	Maximize		7
EP4	Plateau stress	Minimize		7
EP5	Mass	Minimize	Obtained from software directly	10

Step 3: Choose set of PhPs as APs from the GTP and database, to implement DoE

Choosing the APs, used to build the Design of Experiments (DoE), was based on three criteria: first, choosing the most influencing APs, and ss a result, four APs were chosen and listed in Table 18.

Table 18: List of action parameters APs of the case study

Action Parameters (AP)	Parameter type
Cell form	Qualitative
Type of material	Qualitative
Cell size	Quantitative
Change ratio of strut thickness	Quantitative

To satisfy the third criteria, GTP was used, especially the intersection between physical parameters and themselves. Based on searching information provided by the GTP, there was a dependence between two APs provided by the specialist. This dependency is indicated in Table 19.

Table 19: Dependency between some APs that the specialist chose

Action Parameters (AP)	Dependency
Cell form	Independent
Type of material	Independent
Cell size	Independent
Change ratio of strut thickness	Independent

The quantitative parameter so-called, change ratio of strut thickness (unitless), needs some illustration. To illustrate this parameter, Figure 46 shows the dimensional change of the strut thickness.

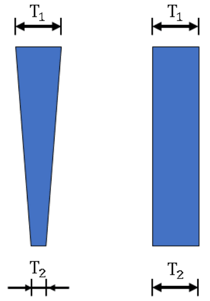


Figure 46: Indicative figure on the parameter change ratio of strut thickness

Where, T_1 is the large thickness of strut element at the top first cell of the structure, and T_2 is the small thickness of the strut element at the bottom last cell of lattice structure, when $\frac{T_2}{T_1}$ is the change ratio of strut thickness. Change ratio of strut thickness is given by the formula (7):

$$\text{Change ratio of strut thickness (\%)} = \frac{T_1 - T_2}{T_1} \qquad (7)$$

The choice of action parameters levels was implemented in referring to the presented database to choose a reasonable number of levels to reduce the total number of experiments. Worth keeping in mind that the resolution of one FEM model can vary from 30 minutes to 6 hours. The reason beyond the choice of the qualitative parameter (cell form) was the need to select different cellular forms undergo the classification of Ashby [140], [141]. Authors argued that to study the mechanical behavior of lattice structures, these cellular structures are divided into two main important classifications, *stretching-dominated* and *bending-dominated*. For this reason, and according to Maxwell's criterion [140], we chose Octet-truss and BCCz cells as stretching-dominated forms, meanwhile, Kelvin cell is a bending-dominated form (see Figure 50). The values of quantitative parameter (cell size) were chosen to match with the global dimensions of the system which is 50x50x50 mm. The qualitative parameter (material type) is set to be either ABS or PLA. The choice of these two polymeric materials is based on the availability of these raw materials, easily, especially at INSA Strasbourg. Moreover, these materials are printable widely by using additive manufacturing technology. PLA material with $\rho = 1240\ \mathrm{kg/m^3}, \mathrm{E} = 1826\ \mathrm{MPa}$ and $v = 0.3$, whereas ABS material has $\rho = 1040\ \mathrm{kg/m^3}, \mathrm{E} = 3354\ \mathrm{MPa}$ and $v = 0.36$, where ρ, E and v designate respectively the density, Young's modulus and Poisson's ratio of the material [142], [143]. The behavior of the material is set to elasto-plastic for all the simulations. The Figure 47, shows a comparison of the stress-strain curve of two examined thermoplastic materials. This figure is the result of calibrating engineering stress-strain curves to true values. The engineering values of deformation is calculated by using the equation (8):

$$\varepsilon_{\mathrm{engineeering}} = \frac{\Delta \mathrm{L}}{L_0} \tag{8}$$

The true deformation is also calculated, defined by the equation (9):

$$\varepsilon_{\mathrm{true}} = Ln(1 + \varepsilon_{\mathrm{engineeering}}) \tag{9}$$

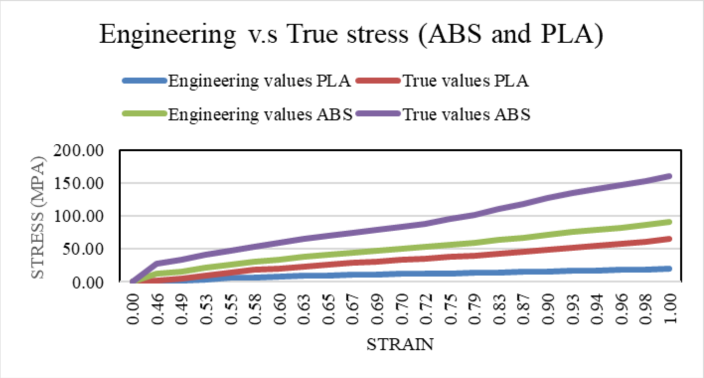


Figure 47: Average tensile strength values for ABS and PLA thermoplastic material

In regard of the quantitative action parameter (Cell size) is set to two values, 25 mm and 10 mm, as illustrated in Figure 48. Concerning the quantitative action parameter (Change ratio of strut thickness), it is set to two values, 0 and 1, as illustrated in Figure 49.

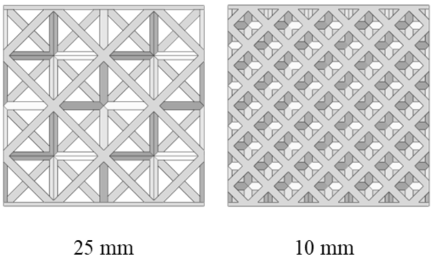


Figure 48: Quantitative action parameter (cell size) and its two values

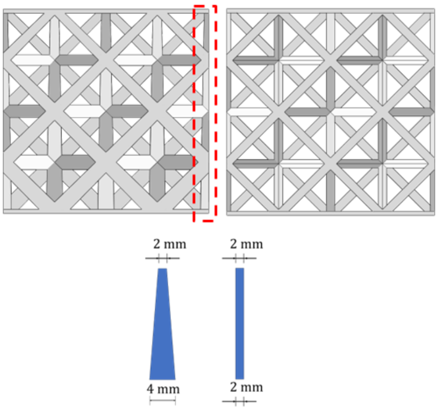


Figure 49: Quantitative action parameter (Change ratio of strut thickness) and its two values

Step 4: Build the Design of experiments

A full factorial design of experiments was conducted [144], which is one of the most common experimental designs that gives a full image on all possible cause-effect relations between action and evaluations parameters. The full factorial design requires several tests (runs) = 2^p (where P is the number of action parameters). In this study a combination of a two-level and three-level full factorial design was carried out, when the number of experiments is calculated by N= $2^p * 3^p$. By taking the expense of numerical simulation into account, a combination of 24 configurations were carried out.

The planning to perform the design of experiments was set as indicated in the following Table 20 and Table 21:

Table 20: The expected levels of each selected Action Parameter AP

Action Parameter	No. of levels	Level (-2)	Level (-1)	Level (+1)
Cell form	3	BCCz cell	Octet-truss cell	Kelvin cell
Type of material	2	ABS		PLA

Cell size (mm)	2	10		25
Change ratio of strut thickness	2	0		1

Table 21: The plan of the Design of Experiments (DoE)

Test No.	Cell form	Type of material	Cell size (mm)	Change ratio
1	Kelvin	PLA	25	0
2	Kelvin	ABS	10	0
3	Kelvin	PLA	25	1
4	BCCz	ABS	10	0
5	Kelvin	PLA	10	1
6	BCCz	ABS	25	2
7	Kelvin	ABS	10	1
8	Kelvin	PLA	10	0
9	Octet-truss	ABS	10	1
10	Octet-truss	PLA	25	1
11	BCCz	ABS	10	1
12	BCCz	PLA	10	1
13	Octet-truss	ABS	25	0
14	Kelvin	ABS	25	0
15	Octet-truss	ABS	25	1
16	BCCz	PLA	10	0
17	Octet-truss	PLA	10	1
18	Octet-truss	PLA	25	0
19	Octet-truss	ABS	10	0
20	BCCz	PLA	25	0
21	BCCz	PLA	25	1
22	Octet-truss	PLA	10	0
23	BCCz	ABS	25	0
24	Kelvin	ABS	25	1

Based on this planning of DoE, CAD models were built, this is dedicated to build CAD models by using the extracted list of Action parameters from phase two. All CAD models of lattice structures were built by using PTC CREO® software. Figure 50 shows a sample of the built CAD models, to be used after for performing the numerical simulations.

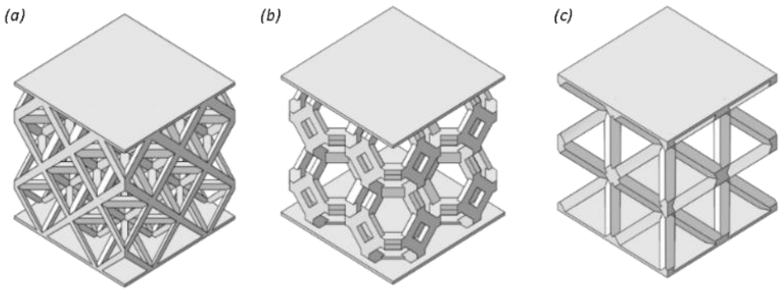


Figure 50: (a) Octet-truss cell, (b) kelvin cell, (c) BCCz cell

The Figure 51 indicates an example on the geometrical construction of one CAD model, the experiment No.1 (ep.1) which is the highlighted one in Table 21. Apart from the fact that all models are provided with a 1-mm exterior shell, made of the same material of the structure, experiment 1 is based on cell form of Kelvin, material type is PLA, cell size is 25 mm, and non-graded (uniform density). The global dimension of the system is 50x50x50 mm, with a relative density of 0.08, and a strut diameter of 2 mm.

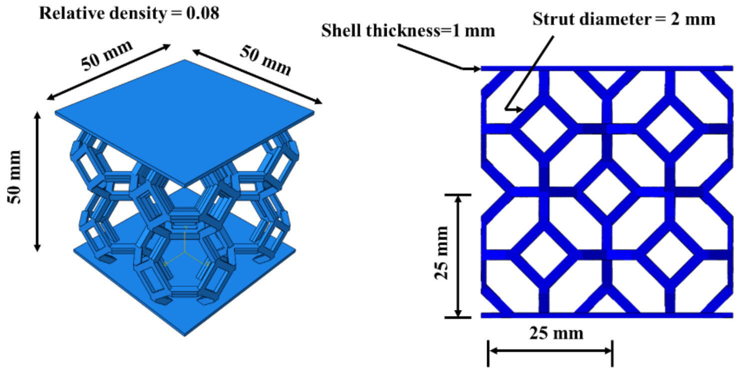


Figure 51: Geometrical details of the CAD model of the experiment no.1

Step 5: is dedicated to run the design of experiments (see Table 23). The setup of these experiments must be further detailed. In this study, the experimental runs were conducted by using the finite elements method, as shortened FEM. For this purpose, the software Abaqus® was used. All numerical simulations are carried out using Abaqus® and all SI units were used as input throughout this research work. Abaqus® is a finite element analysis software and a multi-physics engineering simulation software as well. The reason to use this software, that it is a powerful simulation tool to perform multitasks and can solve both routine and sophisticated engineering problems. In addition, it presents vast advanced strong capabilities in structural analysis, composite analysis, contact analysis and many other types of simulations. Abaqus® showed a good performance and it has been used successfully from many of researchers [12], [145]. Abaqus® was used to complete numerical simulation analysis to investigate the mechanical properties of cellular structures (lattice structures). The software and test settings were set as follow in the Table 22:

Table 22: ABAQUS® settings for running the experiments (1st design loop)

FEM software	Solver algorithm	Type of mesh element	Test type	Contact property	Longitudinal deformation
ABAQUS® 2019	Dynamic explicit	Tetrahedron elements (C3D10M)	Mechanical static deformation	Tangential behavior with a friction coefficient of 0.2	From 0 to 80%

24 experiments were conducted through performing a non-linear analysis by applying a uniaxial compressive loading deformation as shown in Figure 52.

Table 23: Results of the performed DoE

Test No.	Cell form	Type of material	Cell size (mm)	change ratio	Energy absorption (MJ/m3)	Modulus of elasticity (MPa)	Densification Strain	Plateau Stress (MPa)	Mass (g)
1	Kelvin	PLA	25	0	17.63	413.45	0.59	54.30	72.78
2	Kelvin	ABS	10	0	11.05	412.35	0.56	32.68	60.65
3	Kelvin	PLA	25	1	12.52	232.50	0.67	29.10	36.03
4	BCCz	ABS	10	0	15.23	140.31	0.68	37.01	54.74
5	Kelvin	PLA	10	1	13.80	173.78	0.62	44.62	86.77
6	BCCz	ABS	25	1	7.61	265.32	0.59	27.47	72.90
7	Kelvin	ABS	10	1	9.35	121.80	0.72	19.94	36.17
8	Kelvin	PLA	10	0	1.37	22.45	0.77	6.37	21.40
9	Octet-truss	ABS	10	1	0.24	11.13	0.75	0.79	13.27
10	Octet-truss	PLA	25	1	0.26	20.98	0.72	0.68	11.04
11	BCCz	ABS	10	1	0.70	35.22	0.72	2.14	16.26
12	BCCz	PLA	10	1	0.73	6.19	0.72	2.56	21.40
13	Octet-truss	ABS	25	0	0.42	33.24	0.72	1.48	19.54
14	Kelvin	ABS	25	0	1.21	20.11	0.72	3.54	21.40
15	Octet-truss	ABS	25	1	1.63	38.05	0.74	5.72	18.01
16	BCCz	PLA	10	0	0.20	7.21	0.69	0.37	10.87
17	Octet-truss	PLA	10	1	6.20	98.28	0.72	15.74	43.47
18	Octet-truss	PLA	25	0	8.63	159.46	0.69	24.38	43.30
19	Octet-truss	ABS	10	0	7.17	70.38	0.70	23.60	52.38
20	BCCz	PLA	25	0	0.10	4.79	0.67	0.21	13.07
21	BCCz	PLA	25	1	2.16	67.86	0.64	4.88	29.03
22	Octet-truss	PLA	10	0	1.15	47.60	0.64	3.05	34.89
23	BCCz	ABS	25	0	6.55	93.73	0.56	18.41	77.58
24	Kelvin	ABS	25	1	10.14	241.92	0.58	26.06	65.07

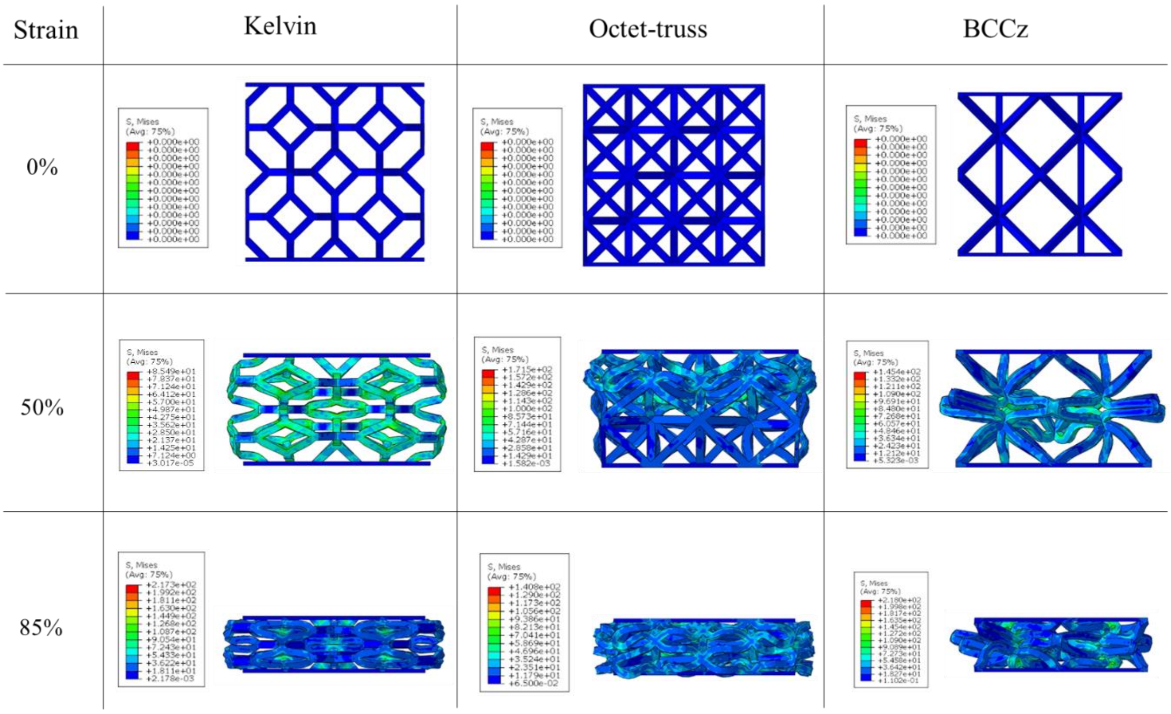


Figure 52: FEM simulations for the three cell types, as an example, when applying a uniaxial compression displacement in the Y-direction, by using ABAQUS® software

After completing the simulations, a post-processing on the raw data was done, involved extracting specific values from the raw simulation data. Advanced post-processing tools were used to perform mathematical calculations and specific analyses on the raw data, allowing for precise quantification and characterization of each lattice structure's behavior under different conditions. Post-processing entails plotting the stress-strain curve of the structure and absorbed energy quantities. These curves facilitate the extraction of four evaluation parameters, which are energy absorption, modulus of elasticity, densification strain, and plateau stress. The fifth evaluation parameter (Mass) is directly obtained from PTC Creo software.

Step 6: Confront DoE results to objective values of each EP

This step serves for two purposes in two cases, first case is when the objective value is known, and this step will help in searching for the final solution of all EPs directly from the available data. The second case is when the objective values are unknown, and in this case, this step will help in identifying the ideal results out of the available data. For this case study, there are no specific objective values, consequently, the best result(s) of each evaluation parameter is selected to be the objective value, hence, the ideal result(s), as shown in Table 24.

Table 24: the ideal results of the design problem based on the best results of each EP (highlighted in green color)

EXP No.	AP1	AP2	AP3	AP4	EP1	EP2	EP3	EP4	EP5
9	Octet-truss	ABS	10	1	17.63	413.45	0.59	54.30	72.78

21	BCCz	PLA	25	1	1.37	22.45	0.77	6.37	21.40
1	Kelvin	PLA	25	0	0.10	4.79	0.67	0.21	13.07
14	Kelvin	ABS	25	0	0.20	7.21	0.69	0.37	10.87

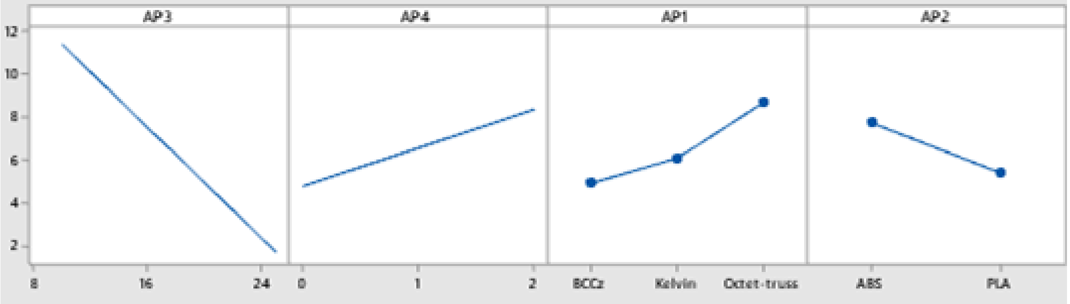
Step 7: Model the DoE results by using analysis tools (optional)

Notations

AP1	*Cell form*
AP2	*Type of material*
AP3	*Cell size (mm)*
AP4	*Change ratio of strut thickness*
AP5	*Strut thickness (mm)*
EP1	*Energy absorption per unit volume*
EP2	*Modulus of elasticity*
EP3	*Densification Strain*
EP4	*Plateau Stress*
EP5	*Mass*

In this step, the performed DoE is analyzed through using multiple methods such as, Regression model, RSM model, and Analysis of variance -ANOVA-. This analysis will help in understanding the relationships between the action and evaluation parameters. Therefore, understand better the system, help in choosing the most impacting contradiction(s), predicting the system responses by using MOO methods, as we will see later. Moreover, it helps complete information of modelling the problem situation in the generalized table of parameters, in the context of a particular case study. Minitab® software was used to perform this analysis. A linear regression analysis was established for each evaluation parameter. The second type of analysis is the main effect plots. These plots are showing the effect on various action parameters (cell form, material type, cell size, and change ratio of strut diameter) on each of evaluation parameters (Energy absorption, Modulus of elasticity, Densification Strain, Plateau Stress, and Mass). A third analysis is carried out which is the multi-objective optimization by using the RSM model. Optimization is a mathematical technique to find the most appropriate value from a set of input variables. In fact, the multi-objective optimization technique will search for the best value for each action parameter, so that the combination of these values will produce the best configuration to solve the design problem. The coefficient of determination R^2, this value is used to indicate how much of variation in response can be explained by the regression model, see Table 25. The higher this value, the better this response model fits data. The rest is a value of variation in response but unexplained by the model and is random. The value of R^2 of the model is 96.75%, which means that 96.75% of the energy absorption per unit volume is explained by this model, however, 3.25% is random and unexplained by the model. For the EP2, R^2 is 91.27%, EP3 is 60.29%, EP4 is 97.67%, and EP5 is 97.01%. The plots in the Table 25 shows the main effect plots, as an example, of each Action Parameter AP on Evaluation Parameter EP1, and the regression models which represents the relationship between all parameters. The remaining results are listed in appendix C. For example, the first plot shows that the cell size has a great effect on the value of energy absorption per unit volume about 10 times between the highest and lowest values of this EP. The gradience, AP2, has a reasonable effect on the ability of the structure to absorb mechanical energy. The ability of absorbing energy was enhanced by around 30%, which is according with [146], [147]. BCCz cell had the lowest ability to absorb the energy, next, Kelvin cell, and the Octet-truss was the highest. Structures fabricated from ABS showed higher ability to absorb the mechanical energy than others fabricated from PLA.

Table 25: Main effect plots and regression models of action parameters and EP1

	AP3	AP4	AP1	AP2
EP1				

AP1	AP2	Equation model of EP1	R^2 (%)
BCCz	ABS	EP1 = 15.88 - 0.6111 AP3 + 0.906 AP4	96.75
Kelvin	ABS	EP1 = 20.90 - 0.8210 AP3 + 0.722 AP4	
Octet-truss	ABS	EP1 = 21.75 - 0.8931 AP3 + 3.738 AP4	
BCCz	PLA	EP1 = 8.91 - 0.3468 AP3 + 0.906 AP4	
Kelvin	PLA	EP1 = 13.93 - 0.5566 AP3 + 0.722 AP4	
Octet-truss	PLA	EP1 = 14.78 - 0.6287 AP3 + 3.738 AP4	

This type of analysis is beneficial for four reasons. The first reason is the capability of having a visualized representation of the main effect of each AP on EP. Second, having a mathematical model could be used as an input equation for MOO algorithms, as will be the case later. Third, this regression model could be used to predict the performance of such a system without repeating the experiments. And finally, the fourth reason is, as a result of this analysis, the analyzed information could be added to the generalized table of parameters (GTP), for this specific case. This information could be useful for treating similar design problems. Table 26 is figuring out the potential information to that could be added to the generalized table of parameters (GTP) from the analysis process of DoE's resulting data.

Table 26: The added information to the GTP out of the DoE for a specific case study

		Evaluation Parameters (EPs)				
		Energy absorption per unit volume	Modulus of elasticity	Densification Strain	plateau stress	Mass
Action Parameters (APs)	Cell form	other	other	other	other	0
	Type of Material	other	other	other	other	other

	Cell size	(-)	(-)	(+)	(-)	(-)
	Change ratio of strut thickness	(+)	(-)	(-)	(+)	(+)

Step 8: Implement Multi-Objective Optimization (optional)

In this case study, the best configuration will be to maximize the energy absorption, maximizing the rigidity, and minimizing the mass. To search for a satisfying solution for the entire set of objective parameters, or to search for the compromise of solutions between the set of EPs, we will use multi-objective optimization methods. In order to apply the MOO methods, we choose two algorithms to apply, Reduced Gradient Algorithm (RGA) [148] by using Minitab® software and NSGA-II (stands for: Non-dominated Sorting Genetic Algorithm) [149] by using python-based package Pymoo® 0.6.0. (open-source package).

The first algorithm to exploit was NSGA-II, and the compromise between objectives appeared as shown in Figure 53. By applying this algorithm, the results were so useful to visualize the compromise between the objectives. This visualization could show the pareto front which is formed by set of solutions. Performing the Multi-Objective Optimization process by using Minitab® and Pymoo® could be summarized in the following steps:

1. Performing the Design of Experiments (DoE)
2. Analyze the resulting configurations of DoE for getting the regression model by using Minitab®
3. Treat the regression model and desired optimization constrains as an input to Multi-Objective Optimization process
4. Use Pymoo® package to perform the NSGAII algorithm and visualize results

The resulting configurations of each pair of objectives are plotted in one scattered matrix, as illustrated in Figure 53. As a result of applying this algorithm, it gave several solutions which can help in optimizing the existing system and visualizing the pareto front. However, none of these solutions can achieve the best desired results of all EPs together. Moreover, this algorithm gave too many solutions which make the results difficult to compare with results of system performance after changing the model.

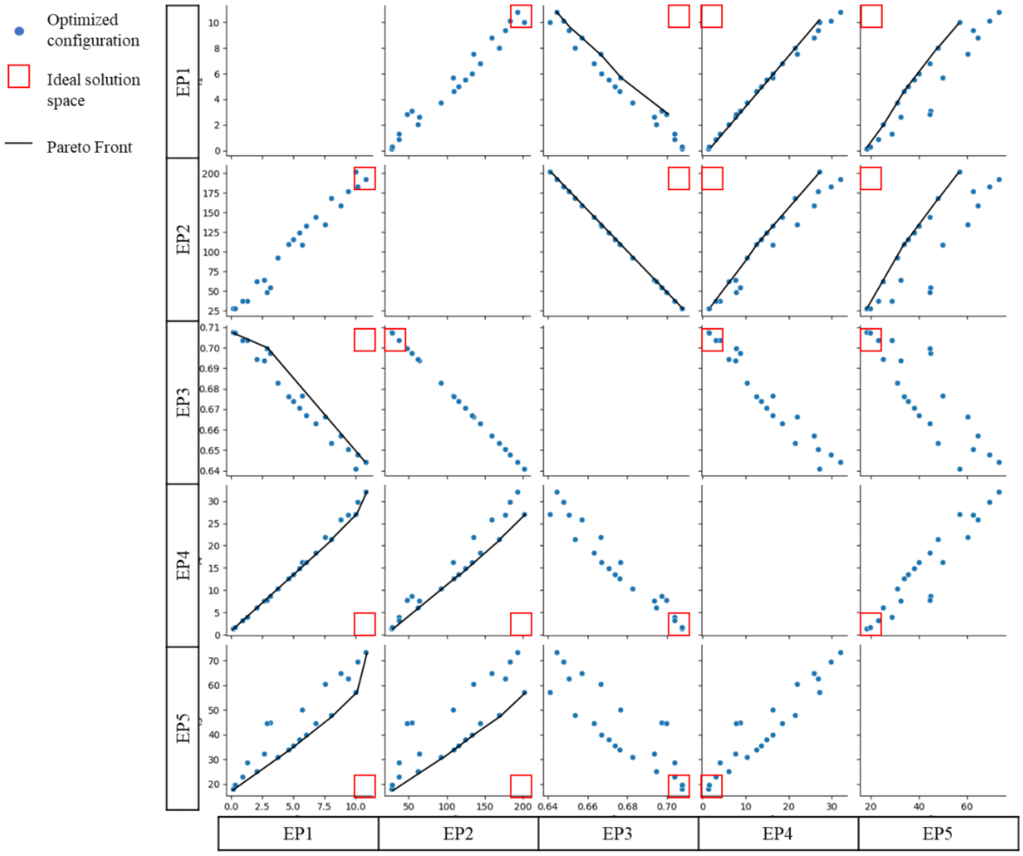


Figure 53: The compromise between objectives and formed pareto front are plotted in one scatter plot matrix

Despite the promising solutions appear from using this algorithm to optimize the existing system, the Figure 53 shows that there is no one satisfactory solution(s) for the entire set of EPs' values. For obtaining a smaller number of solutions for comparing with the results of system performance after changing the model, Reduced Gradient Algorithm will be applied.

The second algorithm to be exploited and applied is Reduced Gradient Algorithm (RGA) by using the software Minitab®. The interest of applying this algorithm is the possibility of obtaining fewer number of solutions, hence, it could be comparable to results of model change (see Table 27).

Table 27: the resulted proposed solution by using the response surface optimization

	AP1	AP2	AP3	AP4	EP1	EP2	EP3	EP4	EP5
Solution of MOO (RGA algorithm)	Kelvin	ABS	10	0	12.69	209.11	0.69	29.25	34.05
Ideal results					17.63	413.45	0.77	0.21	10.87

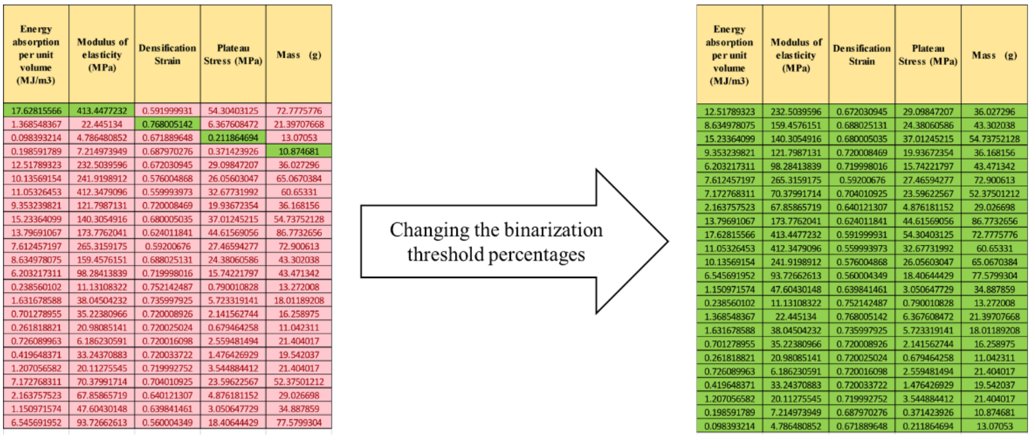
Nevertheless, optimization methods gave a solution with a compromise and not satisfactory. For this reason, extracting the system of contradiction, which reflects the core problem of the system, is a need. To do so, we continue the process with the next steps.

Step 9: Determine the closest and furthest binarization threshold values from ideality and binarize DoE results e.g., green or red highlights

For this case study, we varied the threshold starting from 0%, to identify the ideal results, to 100%, to identify the furthest threshold value from ideality where we have all EPs are satisfied. At this step, we set one threshold value, at which all EPs are considered, as illustrated in Table 28. Worth noting that the DoE results are binarized based on the determined binarization threshold by using colors. Green color means that the EP is satisfying for this specific threshold. Whereas the red color means that EP is not satisfying for the specific threshold value.

Table 28: The global threshold values for all EPs together, and the resulting values for each EP in corresponding to this global threshold

Threshold/EP	EP1	EP2	EP3	EP4	EP5	
0-0%	17.63	413.45	0.77	0.21	10.87	Best scenario
0-10%	15.88	372.58	0.75	5.62	18.46	
0-20%	14.12	331.72	0.73	11.03	26.05	
0-30%	12.37	290.85	0.71	16.44	33.64	
0-40%	10.62	249.98	0.68	21.85	41.23	
0-50%	8.86	209.12	0.66	27.26	48.82	
0-60%	7.11	168.25	0.64	32.67	56.41	
0-70%	5.36	127.38	0.62	38.08	64.00	
0-80%	3.60	86.52	0.60	43.49	71.59	
0-90%	1.85	45.65	0.58	48.89	79.18	
0-100%	0.10	4.79	0.56	54.30	86.77	Worst scenario



Energy absorption per unit volume (MJ/m3)	Modulus of elasticity (MPa)	Densification Strain	Plateau Stress (MPa)	Mass (g)
17.62815566	413.4477232	0.591999931	54.30403125	72.7775776
1.368548367	22.445134	0.768005142	6.367608472	21.39707668
0.098393214	4.786480852	0.671889648	0.211864694	13.07053
0.198591789	7.214973949	0.687970276	0.371423926	10.874681
12.51789323	232.5039596	0.672030945	29.09847207	36.027296
10.13569154	241.9198912	0.576004868	26.05603047	65.0670384
11.05326453	412.3479096	0.559993973	32.67731992	60.65331
9.353239821	121.7987131	0.720008469	19.93672354	36.168156
15.23364099	140.3054916	0.680005035	37.01245215	54.73752128
13.79691067	173.7762041	0.624011841	44.61569056	86.7732656
7.612457197	265.3159175	0.59200676	27.46594277	72.900613
8.634978075	159.4576151	0.688025131	24.38060586	43.302038
6.203217311	98.28413839	0.719998016	15.74221797	43.471342
0.238560102	11.13108322	0.752142487	0.790010828	13.272008
1.631678588	38.04504232	0.735997925	5.723319141	18.01189208
0.701278955	35.22380966	0.720008926	2.141562744	16.258975
0.261818821	20.98085141	0.720025024	0.679464258	11.042311
0.726089963	6.186230591	0.720016098	2.559481494	21.404017
0.419648371	33.24370883	0.720033722	1.476426929	19.542037
1.207056582	20.11275545	0.719992752	3.544884412	21.404017
7.172768311	70.37991714	0.704010925	23.59622567	52.37501212
2.163757523	67.85865719	0.640121307	4.876181152	29.026698
1.150971574	47.60430148	0.639841461	3.050647729	34.887859
6.545691952	93.72662613	0.560004349	18.40644429	77.5799304

Binarization threshold = 0%
(closest to ideality)

Energy absorption per unit volume (MJ/m3)	Modulus of elasticity (MPa)	Densification Strain	Plateau Stress (MPa)	Mass (g)
12.51789323	232.5039596	0.672030945	29.09847207	36.027296
8.634978075	159.4576151	0.688025131	24.38060586	43.302038
15.23364099	140.3054916	0.680005035	37.01245215	54.73752128
9.353239821	121.7987131	0.720008469	19.93672354	36.168156
6.203217311	98.28413839	0.719998016	15.74221797	43.471342
7.612457197	265.3159175	0.59200676	27.46594277	72.900613
7.172768311	70.37991714	0.704010925	23.59622567	52.37501212
2.163757523	67.85865719	0.640121307	4.876181152	29.026698
13.79691067	173.7762041	0.624011841	44.61569056	86.7732656
17.62815566	413.4477232	0.591999931	54.30403125	72.7775776
11.05326453	412.3479096	0.559993973	32.67731992	60.65331
10.13569154	241.9198912	0.576004868	26.05603047	65.0670384
6.545691952	93.72662613	0.560004349	18.40644429	77.5799304
1.150971574	47.60430148	0.639841461	3.050647729	34.887859
0.238560102	11.13108322	0.752142487	0.790010828	13.272008
1.368548367	22.445134	0.768005142	6.367608472	21.39707668
1.631678588	38.04504232	0.735997925	5.723319141	18.01189208
0.701278955	35.22380966	0.720008926	2.141562744	16.258975
0.261818821	20.98085141	0.720025024	0.679464258	11.042311
0.726089963	6.186230591	0.720016098	2.559481494	21.404017
0.419648371	33.24370883	0.720033722	1.476426929	19.542037
1.207056582	20.11275545	0.719992752	3.544884412	21.404017
0.198591789	7.214973949	0.687970276	0.371423926	10.874681
0.098393214	4.786480852	0.671889648	0.211864694	13.07053

Binarization threshold = 100%
(furthest from ideality)

Figure 54: Closest and furthest values of binarization thresholds from ideality

The application of the ranges of threshold values, were applied from 0% to 100%, as indicated in Figure 54.

Step 10: Determine optimal binarization threshold values for initial satisfactory solution

The second step is to determine the binarization threshold that yields the first solution satisfying all evaluation parameters. This step is performed for global binarization threshold values, as shown in, Table 29, It is essential to note that this test corresponds to the optimal point in our binarization space, which will serve as the starting point for subsequent contradiction exploration.

Table 29: The first optimal solution appears at global binarization threshold values

Test No.	AP1: Cell form	AP2: Type of material	AP3: Cell size	AP4: Change ratio of strut thickness	EP1: Energy absorption per unit volume	EP2: Modulus of elasticity	EP3: Densification Strain	EP4: Plateau Stress	EP5: Mass
2	Kelvin	ABS	10	0	8.16	192.77	0.66	29.42	51.86
				Global binarization threshold values	54%	54%	54%	54%	54%

However, the global binarization threshold is considered far from the ideality. For this reason, to approach more to ideality, the binarization threshold values are determined individually, as shown in Table 30. As noticed, there is a considerable change in the values in which is concerning EP1, EP2, EP3 and EP5. This leads to extracting a system of contradictions closer to ideality and therefore getting solutions closer to ideality, as well.

Table 30: The first optimal solution appears at individual binarization threshold values

Test No.	AP1: Cell form	AP2: Type of material	AP3: Cell size	AP4: Change ratio of strut thickness	EP1: Energy absorption per unit volume	EP2: Modulus of elasticity	EP3: Densification Strain	EP4: Plateau Stress	EP5: Mass
2	Kelvin	ABS	10	0	12.02	229.55	0.67	29.96	36.68
				Individual binarization threshold values	32%	45%	47%	54%	34%

Step 11: Reduce the global threshold values for obtaining GSC (with the possibility of varying the included number of APs)

In this step, we set the global binarization threshold to the highest value among the previously extracted individual evaluation parameter thresholds, which is 0-54% in our case. Then, we gradually decrease the global binarization threshold until contradictions emerge in our system. It's worth noting that we have the option to specify the number of action parameters included in the contradiction. As mentioned before, resolving contradictions with just one action parameter is easier.

For this reason, in our case, extracting the contradictions will start by specifying one AP, and fixing all other APs. Like that, we guarantee sorting the experimental configurations line by line for extracting a GSCs that have one fixed AP, all other APs are fixed, and these configurations satisfy all EPs together. As a result, the binarization threshold values were reduced, globally, to 38% instead of 54%. Two contradictions were extracted based on one varied AP as indicated in Table 31. These couples of experiments are highlighted with red rectangular in the same table (experiment 4&19) (experiment 13&19).

Table 31: The extracted systems of contradiction from DoE results at a global threshold value of 38%

EXP No.	AP1	AP2	AP3	AP4	EP1	EP2	EP3	EP4	EP5
19	Octet-truss	ABS	10	0	11.05	412.35	0.56	32.68	60.65
4	BCCz	ABS	10	0	9.35	121.80	0.72	19.94	36.17
13	Octet-truss	ABS	25	0	0.70	35.22	0.72	2.14	16.26

Threshold (%)	38	38	38	38	38
Value(s)	10.97	258.16	0.69	20.77	39.72
Opt. Direction	Max	Max	Max	Min	Min

Step 12: Reduce the individual threshold values for obtaining GSC (with the possibility of varying the included number of APs)

To fine-tune individual contradiction thresholds and get closer to ideality, the values of each individual threshold can be reduced towards the ideal results to ensure obtaining a contradiction. The following Table 32 presents two sets of individual threshold values, resulting some contradictions based on one varied AP. The first set of threshold values provides one contradiction, and the second, generates two contradictions.

Table 32: The extracted systems of contradictions based on one varied AP at an individual binarization threshold

EXP No.	AP1	AP2	AP3	AP4	EP1	EP2	EP3	EP4	EP5
13	Octet-truss	ABS	25	0	0.70	35.22	0.72	2.14	16.26
19	Octet-truss	ABS	10	0	11.05	412.35	0.56	32.68	60.65

Threshold (%)	38	1	24	5	8
Value(s)	10.97	409.36	0.72	2.92	16.95
Opt. Direction	Max	Max	Max	Min	Min

EXP No.	AP1	AP2	AP3	AP4	EP1	EP2	EP3	EP4	EP5
13	Octet-truss	ABS	25	0	11.05	412.35	0.56	32.68	60.65
19	Octet-truss	ABS	10	0	0.70	35.22	0.72	2.14	16.26
4	BCCz	ABS	10	0	9.35	121.80	0.72	19.94	36.17
				Threshold (%)	38	1	25	37	34
				Value(s)	10.97	409.36	0.72	20.23	36.68
				Opt. Direction	Max	Max	Max	Min	Min

By comparing the different values of binarization threshold, Figure 55 would be resulted.

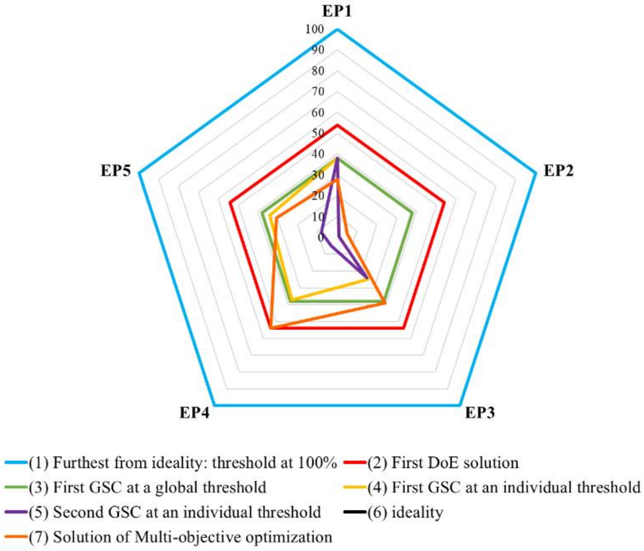


Figure 55: Comparison between different values of binarization threshold

This graph is useful to show the convergence towards ideality with the dynamic change of binarization threshold values. In this radar graph, line 1 corresponds to binarization zone solution at 100%, at which all DoE values are green and accepted as solutions. Line 2 corresponds to the first complete solution that appears from the available data of DoE. Line 3 is referring to the global threshold values at which the first GSC appears from the DoE data, based on one varied action parameter AP. Line 4 is referring to the individual threshold values at which the first GSC appears, based on one varied AP. Line 5 is referring to individual threshold values at which a second set of GSC appears, based on the variation of one action parameter. Line 6 reflects the threshold values of ideality. Line 7 is referring to the threshold values corresponding to the multi-objective solution values. Besides the usefulness of this graph in visualizing the appropriate binarization threshold value at which the system is approaching the ideality, this graph could be used to prioritize the choice of GSC.

In the Table 32, the first GSC is based on action parameter AP3, and the second GSC is based on AP1. Hence, the binarization thresholds are more advantageous in resolving the contradiction with parameter AP3 than with AP1, since the relevant values of EP3, EP4, EP5 are closer to ideality. We observe that the evaluation parameter carrying the global threshold is evaluation parameter EP1 which is equal to 38%, followed by EP3 which is equal to 24%. This means that even if we resolve this contradiction, a second inventive design loop will be necessary to improve this parameter to get closer to ideality. Subsequently, in the resolution and model change section, we will address some presented contradictions. Before that, we suggest studying cases where there are multiple action parameters in the contradiction, as well as the effect of the number of action parameters in the contradiction on getting closer to ideality. It is essential to note that we prioritize contradictions with a minimum of action parameters for ease of resolution and model change.

The previous steps were applied to search for first GSCs at different global binarization threshold values and based on one or many varied APs. The Table 33 illustrates the impact of the number of action parameters in the contradiction on approaching ideality when the contradiction is resolved. It is observed that a higher number of action parameters leads to a closer system to ideality. However, as mentioned earlier, a high number of action parameters in the contradiction increases the complexity of resolution. Worth mentioning that all extracted contradictions at global and individual thresholds are detailed in appendix D.

Table 33: The impact of the number of action parameters APs in the contradiction on approaching ideality

No. of varied AP / Threshold (%)	1	2	3	4
0%	0	0	0	0
8%	0	0	0	1
14%	0	0	1	1
16%	0	1	1	1
38%	2	6	7	3

From the Table 33, one can anticipate that there is a strong link between the binarization threshold value and the number of varied APs inside the extracted contradiction (GSC). This link could be visualized in the Figure 56.

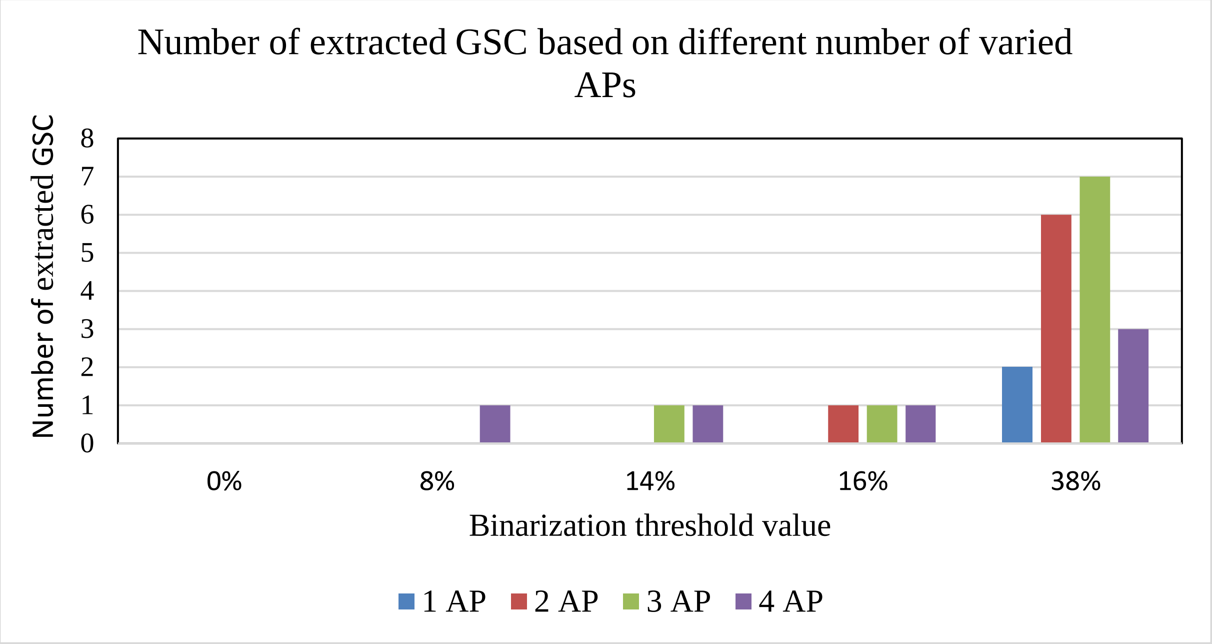


Figure 56: Number of extracted GSC based on different number of varied APs

Step 13: Proposed method of solving GSC based on more than one varied AP: Search for an equivalent AP from the CDB and/or GTP to replace complex GPC

This step is activated under two conditions; first, if there is more than one varied AP in the physical contradiction, second, if the varied parameters are quantitative. Referring to the extracted contradictions, there is only one generalized contradiction which is covering these two conditions, which is in Figure 57:

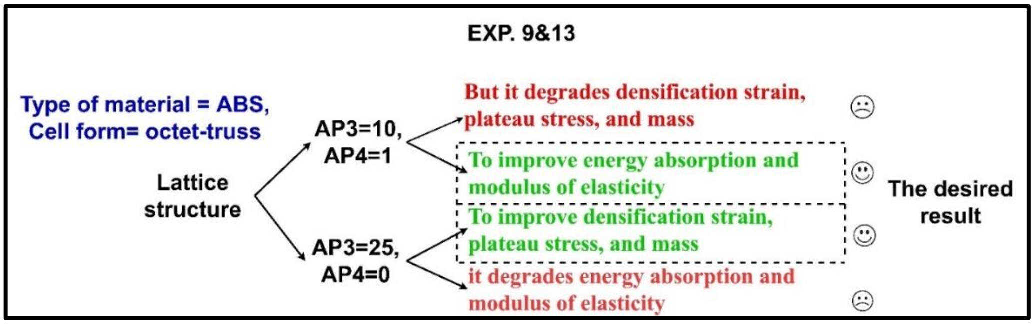


Figure 57: First GSC appears based on two quantitative APs (at a global threshold value)

This contradiction exists when the threshold is varying globally for each EP, with the following values: $EP_1 = EP_2 = EP_3 = EP_4 = EP_5 = 24\%$.

From the last contradiction, one can anticipate the need of substituting the concept of the GPC with one AP, to ease the model change. To substitute AP3 and AP4, using Generalized Table of Parameters (GTP) and the contextual database (CDB) could be useful and helpful. We search for equivalent parameters whose physical units can replace the units of both parameters, in other words, when the relative density is needed to be high in value as much as possible and cell size is needed to be low in value as much as possible, this third parameter can satisfy both conditions. This process can be implemented in few simple steps, as follow:

1. Units of AP4 is no unit, or unitless, because it is a ratio
2. Units of AP3 is millimeter
3. The division of the two physical units results in the physical unit Millimeter. The reason of dividing the two units is because the increase of AP4 would develop EP1 and EP2, but deteriorates EP3, EP4, and EP5. On the other side, increasing AP3 has the inverse effect. Therefore, it is necessary a third parameter that equilibrate with AP3 and AP4 and in the same time can keep the formulation of the contradiction.
4. From the GTP, we search for parameters which can replace physically the functions of AP3 and AP4, and have the unit of Millimeter
5. Two parameters could be extracted which can replace the previous concept; this parameter is (Strut thickness) and (Distance of variation of gradience)

The choice of these two parameters could be approved mathematically by using the formulas collected in the CDB, as in the equations (10) and (11).

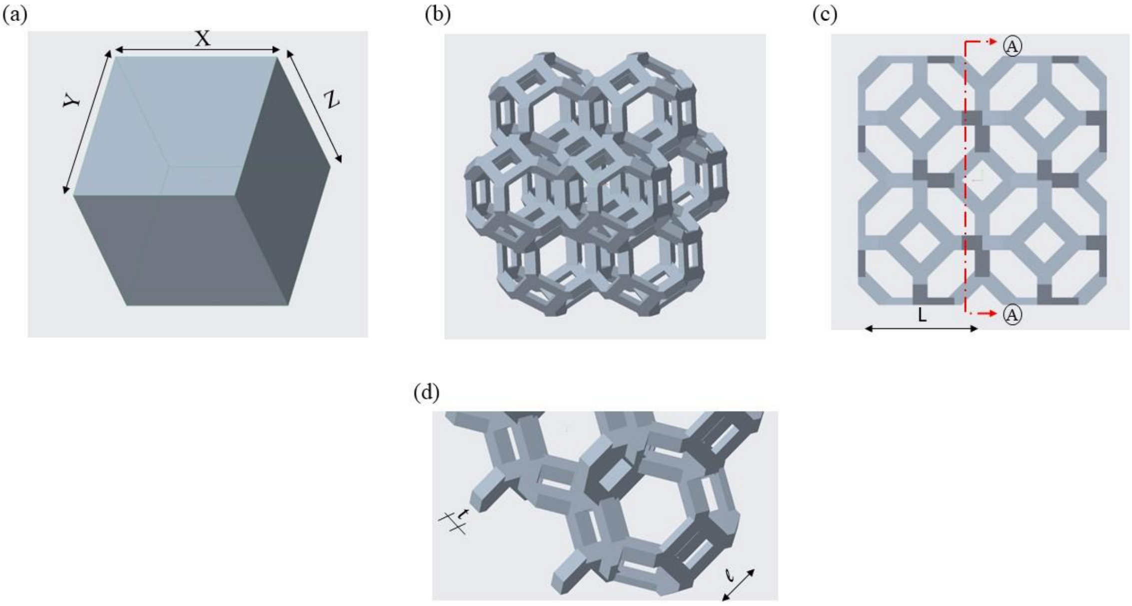
When:

$$\rho_{relative} = \frac{\rho_{Lattice}}{\rho_{base}} = \frac{Volume_{Lattice}}{Volume_{base}} \tag{10}$$

$$\frac{Volume_{Lattice}}{Volume_{base}} = \frac{\mathrm{n} * \mathrm{t}^2 * \mathrm{l}}{\mathrm{X} * \mathrm{Y} * \mathrm{Z}} = \frac{\mathrm{n} * \mathrm{t}^2 * \mathrm{l}}{\mathrm{N} * \mathrm{L} * \mathrm{Y} * \mathrm{Z}} \tag{11}$$

Where:

$\rho_{relative}$ is the relative density of lattice structure, $\rho_{Lattice}$ is the density of lattice structure, ρ_{base} is the density of the base material from which the lattice structure is made, $Volume_{Lattice}$ is the volume of lattice structure, $Volume_{base}$ is the volume of the base structure, n is the number of struts, t is the strut thickness, l (or l) is the strut length, X, Y, Z are the global dimensions of base structure, N is the number of cells, and L is the cell size. All parameters are illustrated in Figure 58:



Section A-A

Figure 58: (a) the global dimensions of the bulk structure, (b) the lattice structure which is filling this bulk structure in 3D view, (c) 2D view of this lattice structure and an indication of the cut section A-A with an illustration of the cell size, and (d) an illustration of the strut length and strut thickness

When dividing the units of AP3 and AP4, the resulting equation (12) could be obtained:

$$\frac{n * t^2 * l}{N * L * Y * Z} * L = \frac{n * t^2 * l}{N * Y * Z} \qquad (12)$$

Hence, the possible parameters from this equation are strut length, strut thickness, global dimensions of structure. Therefore, physically, there is difficulty to change the global dimensions with time or in space because it is one of the design constraints. One possible parameter to replace AP3 and AP4 is strut thickness, and from the CDB, we can use the distance of variation of gradience to replace both parameters, as well. Likewise, strut thickness is satisfying the same EPs by changing its value, as same as the technical contradiction linked to the GPC, as follow:

		Energy absorption per unit volume	Plateau stress	Densification Strain	Modulus of elasticity of lattice structure	Mass
AP5	Strut thickness	high	low	low	high	low

As a result, the contextual GSC could be re-formulated as shown in Figure 59:

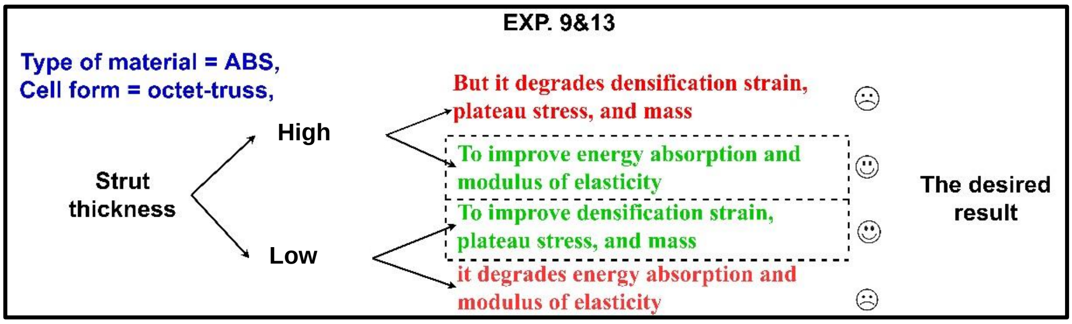


Figure 59: The re-formulated contextual contradiction

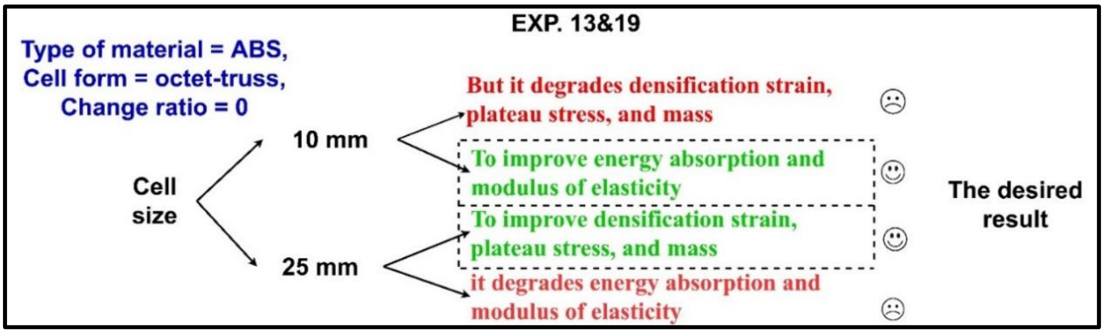
The binarization threshold at which the contradiction (GSC) in the Figure 57 appears, is quantified in the Table 34, as follow:

Table 34: the quantified values of binarization threshold which are corresponding to the contradiction in Figure 57

EXP No.	AP1	AP2	AP3	AP4	EP1	EP2	EP3	EP4	EP5
13	Octet-truss	ABS	25	0	0.70	35.22	0.72	2.14	16.26
9	Octet-truss	ABS	10	1	17.63	413.45	0.59	54.30	72.78
				Threshold (%)	24	24	24	24	24
				Value(s)	13.42	315.37	0.72	13.19	29.09
				Opt. Direction	Max	Max	Max	Min	Min

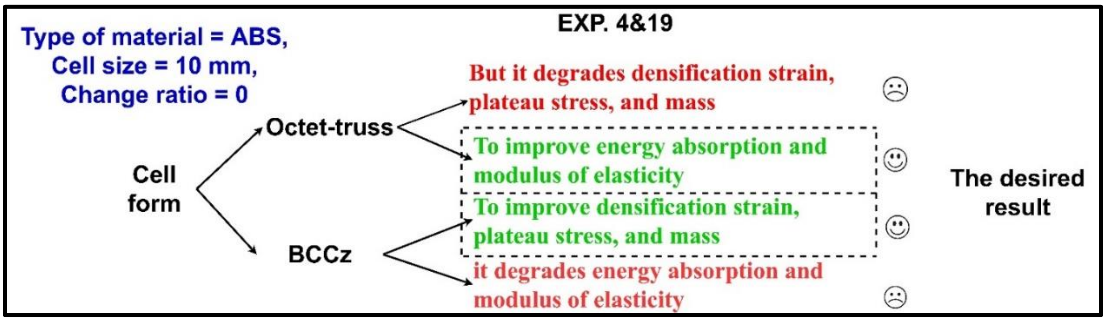
Finally, among all extracted contradictions, we chose three contradictions to be solved, one contradiction is based on one action parameter. The first contradiction appears when the binarization threshold are at these values:

Evaluation parameter	EP1	EP2	EP3	EP4	EP5
Binarization threshold	38%	1%	24%	5%	8%



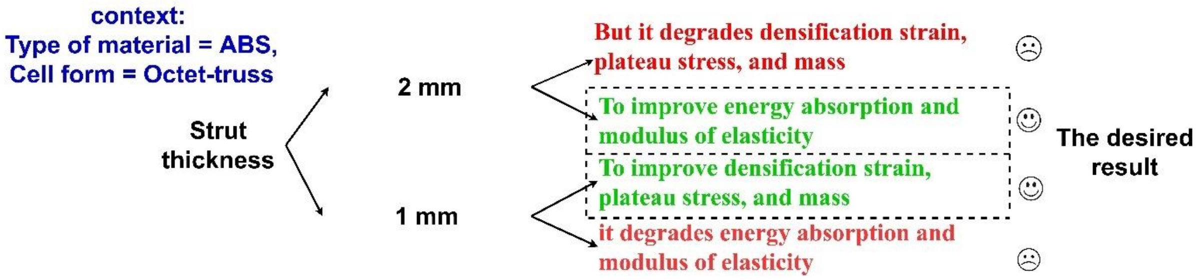
The second contradiction appears at threshold values as follow:

Evaluation parameter	EP1	EP2	EP3	EP4	EP5
Binarization threshold	38%	1%	25%	37%	34%



The third is based on two action parameters, after replacing the two parameters with one replacing parameter for the ease of changing the existing model. This contradiction exists when the threshold is varying globally for all EPs, with the following values:

Evaluation parameter	EP1	EP2	EP3	EP4	EP5
Binarization threshold	24%	24%	24%	24%	24%



Step 14: Analyze the system in space and time

As illustrated before, the system will be discretized in time and space. In this example, EPs from EP_1 to EP_5, can be separated in space from Operational Zone $(OZ)_1$ to OZ_3. The separation in space can be performed by asking a question concerning each EP: *Where do we need this evaluation parameter to perform its function?*

Answering this question can be realized after an analysis of the studied system. This analysis could help in understanding the parts where one can need each EP to perform its function. By doing this analysis on the recent system of the study case, the system is divided into three main parts; the sides, the core, and the top-bottom faces, as illustrated in Figure 60.

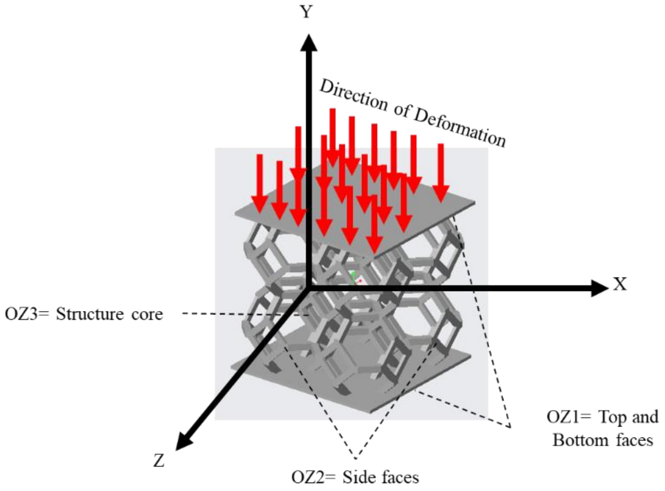


Figure 60: The analysis of the studied system in space

The same thing is done with space, from Operational Time (OT)$_1$ to OT$_2$. The separation in time can be performed by asking a question concerning each EP: *When do we need this evaluation parameter to perform its function?*

Answering this question can be realized after an analysis of the studied system. This analysis could help in understanding the time periods when one can need each EP to perform its function. By doing this analysis on the recent system of the study case, the system is divided into two main periods; the period starts by the beginning of the compression test and before the deformation until the start of the conflict (deformation). The second period starts with the start of the conflict and ends with the end of the conflicts and the entire process. The Figure 61 illustrates the timeline of the two periods, OT1 and OT2.

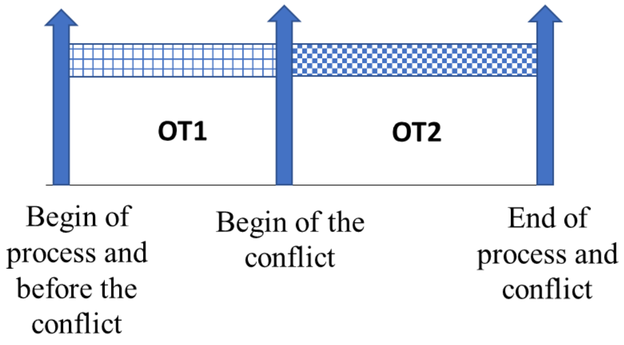
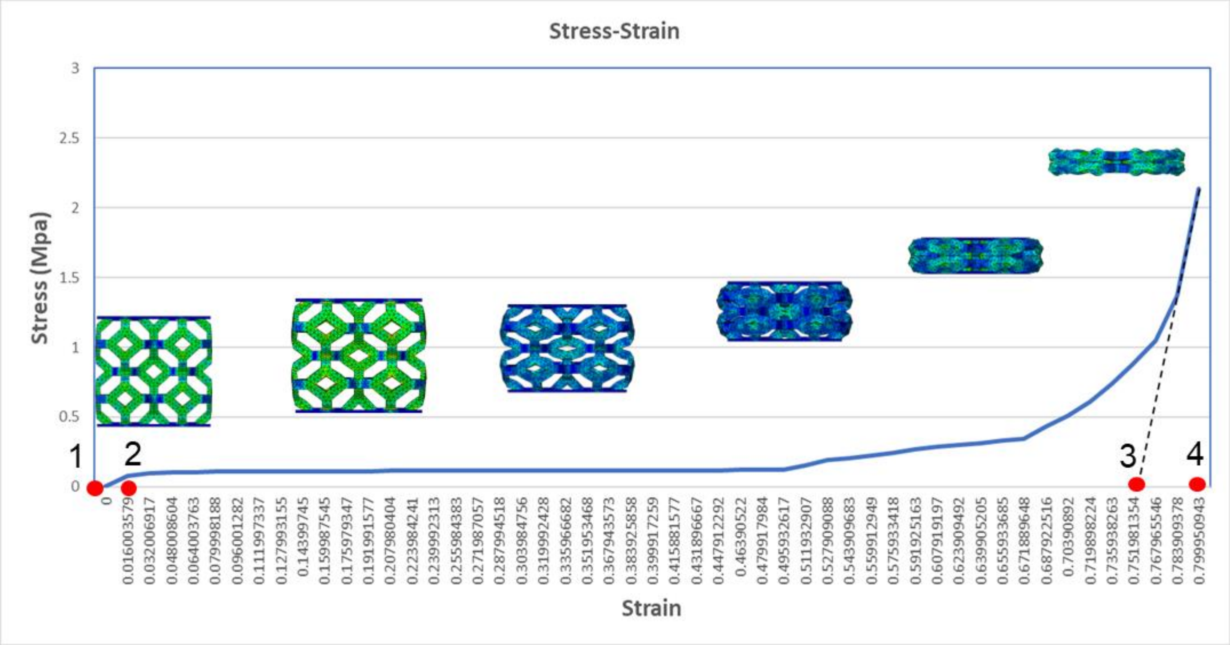


Figure 61: The analysis of the studied system in time

To understand the operational time periods within the context of studies case study, we needed to analyze the typical stress-strain curve of lattice structure under a uniaxial compression. This deformation curve gives a good vision on the moments where we can need each EP, as shown in Figure 62.



1	Begin of the deformation
2	Limit of elasticity
3	Limit of densification
4	End of deformation

Figure 62: The typical stress-strain curve of a uniaxial compression test of lattice structure (performed by using FEM) and the indication of each deformation point on the curve

The Table 35 illustrates the results of the process of separation in time and space. This table shows “when” and “where” we need each EPs to perform its function in the studies system, exactly.

Table 35: The table used to analyze the separated EPs in time and space

Evaluation Parameter(s)	When	Where	How
Energy absorption per unit volume	From point 1 to point 2	OZ 2	Octet-truss cell 10 mm cell size Strut thickness high
Plateau stress	From point 2 to point 3	OZ 1	BCCz cell 25 mm cell size Strut thickness low
Densification strain	From point 2 to point 3	OZ 3	BCCz cell 25 mm cell size Strut thickness low
Modulus of elasticity of lattice structure	From point 1 to point 2	OZ 2	Octet-truss cell 10 mm cell size Strut thickness high
Mass	OT1 only	OZ 1 and OZ 2	BCCz cell 25 mm cell size Strut thickness low

Step 15: Propose solution concept(s) (SC)

By taking separating in time and space principles into consideration, two solution concepts were proposed. The first concept is based on separating two cell forms. Such concepts have been defined as illustrated in Figure 63. This concept is based on providing cell form type octet-truss at the perimetric zone of the structure to provide a good energy absorption, rigidity. While maintaining another cell form type BCCz at the core of the structure to provide better densification strain, plateau stress and lower global mass.

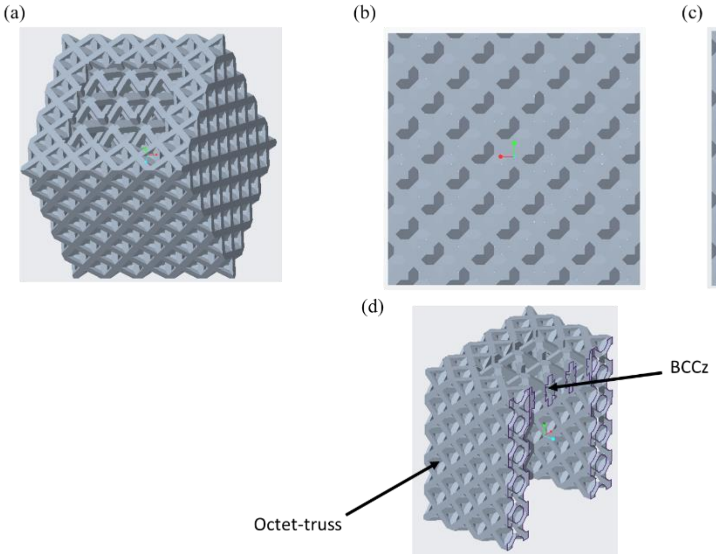


Figure 63: Solution concept no.1 (separating two cell forms)

The second concept is based on separating two cell sizes, and this concept is shown in Figure 64. This concept is providing small cell size of a size of 10 mm at the perimetric zone of the structure to provide a good energy absorption, rigidity. While maintaining larger cells of a size 25 mm at the core of the structure to provide better densification strain, plateau stress and lower global mass.

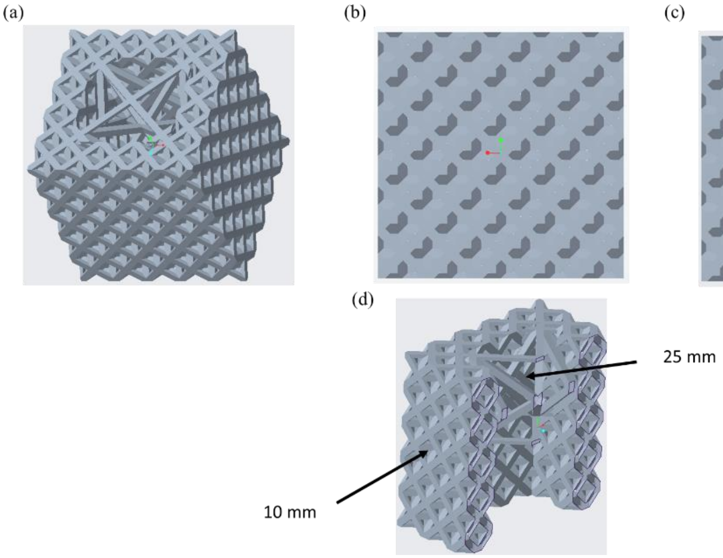


Figure 64: solution concept no.2 (separating two cell sizes)

These two solution concepts were prototyped, as seen in Figure 65, by using the additive manufacturing technology. The used technology to print this solution is FDM technology (Fused Deposition Modeling), and the used printer is INTAMSYS® FUNMAT HT. This printer is one of the resources at the research team CSIP and it is a high-performance printer which can achieve 50-micron high-resolution industrial quality 3D printing, as seen in Figure 65.

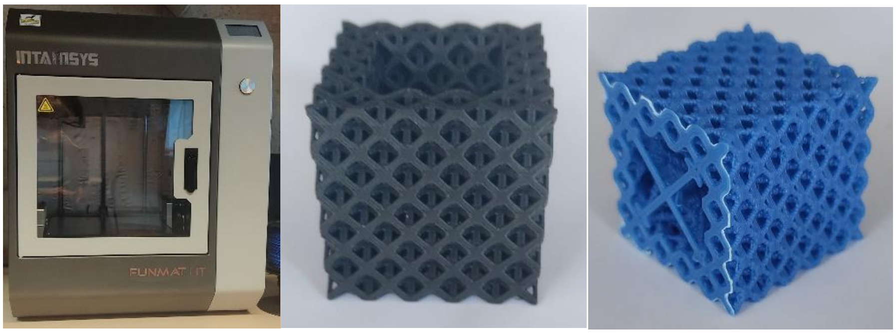


Figure 65: One the left side, the used FDM printer. In the middle, the prototype of SC no.1. On the right-hand side, the prototype of SC no.2

Step 16: Test the feasibility of the proposed solution concept(s)

This step is dedicated to validating the feasibility of the proposed solutions and knowing to what extent the model approached the desired ideal results. This step will help in checking the applicability of such solution concepts, in addition to quantifying the results. Such tests can validate the performance of the system to help in taking decisions whether to stop the process with a satisfying performance or re-model the system and redo the design loop (modeling-optimization-invention) one more time. To test the feasibility of the two solution concepts, we used CAD modeling software PTC Creo® and numerical simulation software by dedicating the software ABAQUS®. In the Table 36, the performance results of the proposed solutions are compared to the ones resulted from the multi-objective optimization methods. This comparison shows the superiority of the output results of inventive process than routine optimization process, to solve complex problems.

Table 36: Convergence of performance results towards the Ideal results

Evaluation parameter	Energy absorption per unit volume	Modulus of elasticity of lattice structure	Densification strain	Plateau stress	Mass
Ideal results	17.63	413.45	0.77	0.21	10.87
MOO solution	12.69	209.11	0.68	29.25	34.04
Proposed SC 1(AP1)	13.21	271.74	0.7	17.16	39.49
Proposed SC 2 (AP2)	13.57	284.03	0.68	19.59	39.54

A comparison is shown in Figure 66 between the stress-strain curves of both proposed SCs.

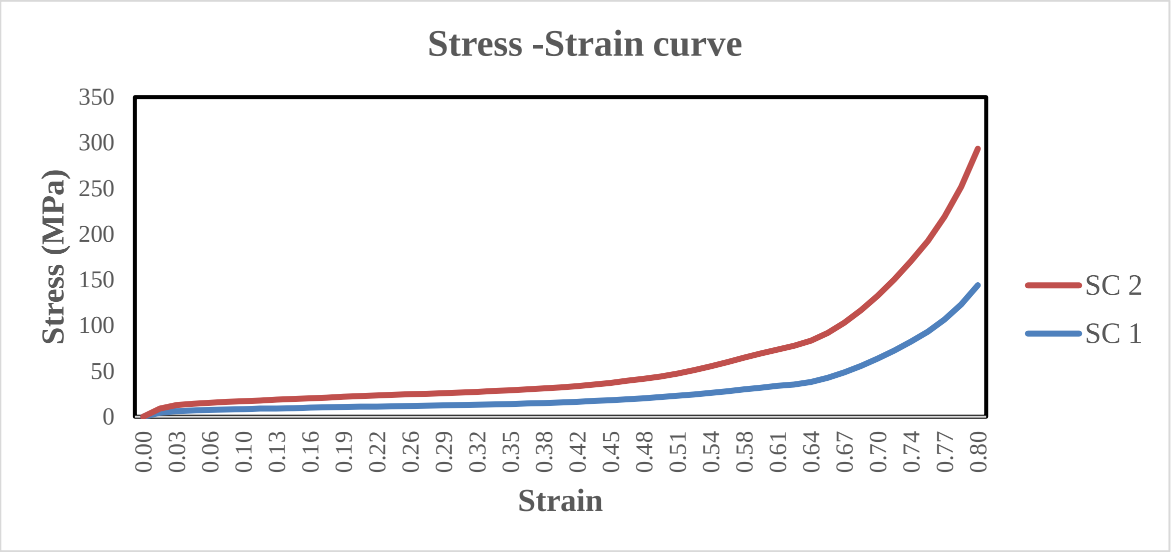


Figure 66: Comparison between the stress-strain curves of the two solution concepts (SC) to solve conflicts based on one AP

We did the model by using the design of experiments, then the optimization was performed. However, this MOO brought a compromise of results. When this result was not satisfactory for decision makers, the contradictions were extracted to highlight the system conflict and the model was changed to resolve this conflict. This change of model can be based on one changing parameter, with certain threshold values. However, we can do better with two changing parameters. As a result, we choose the reformulated contradiction based on two changing action parameters which highlights the conflict between experiments 9 and 13, as indicated in Figure 67.

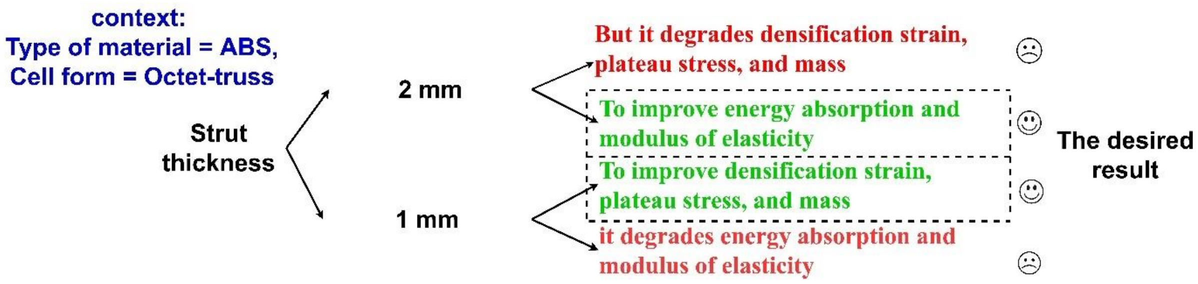


Figure 67: The reformulated contradiction based on two changing action parameters which highlights the conflict between experiments 9 and 13

By taking the separation principle between the parts and the whole, and separation in space in consideration, two solution concepts were proposed. The first concept is based on separating two strut thicknesses in space. Such concepts have been defined as illustrated in Figure 68. This concept is based on providing cells at a strut thickness of 2 mm at the perimetric zone of the structure to provide good energy absorption and rigidity. While maintaining cells at a strut thickness of 1 mm at the core of the structure to provide better densification strain, plateau stress and lower global mass.

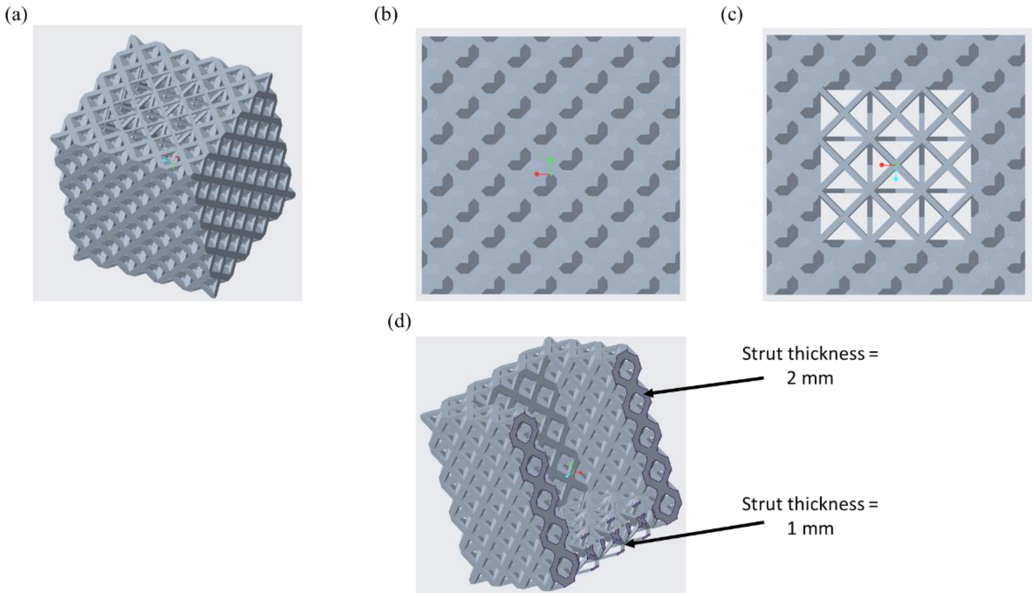


Figure 68: solution concept no.3 (separating two strut thicknesses) based on separation in space principle

The second solution concept is proposed, as well, to solve the system of contradictions based on two varying APs. This concept is based on separating two strut thicknesses between whole and parts. Such concepts have been defined as illustrated in Figure 69. This concept is based on providing the strut thickness of 2 mm at the macro level of the structure to provide good energy absorption and rigidity. While dividing up the thickness of same struts to form sub-elements of 1 mm at the micro level of the structure to provide better densification strain, plateau stress and lower global mass.

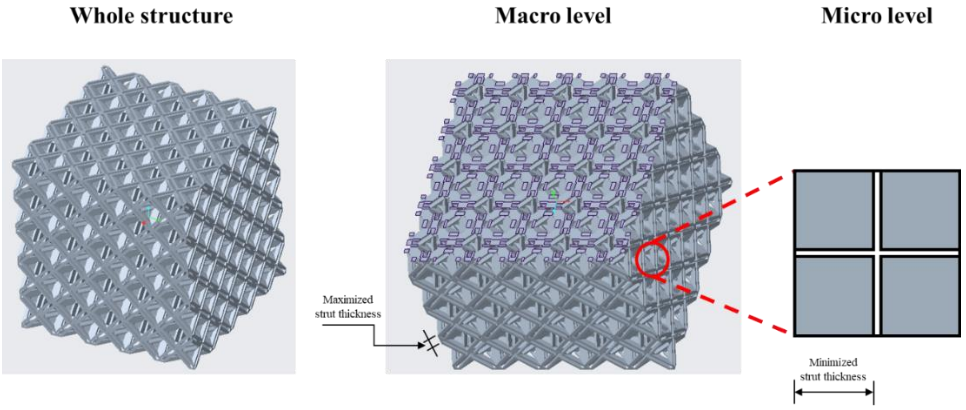


Figure 69: solution concept no.4 (separating two strut thicknesses) based on separating the parts of the whole

In the Figure 70, the performance results of the proposed solutions are showing a convergence towards the ideal results more than the ones proposed previously i.e., concepts 1 and 2. This comparison shows that changing the model based on more varying APs could help in getting closer to better performance. A comparison is shown in Table 37 between the stress-strain curves of both proposed SCs.

Table 37: Increasing the performance results towards the Ideal results

Evaluation parameter	Energy absorption per unit volume	Modulus of elasticity of lattice structure	Densification strain	Plateau stress	Mass
Ideal results	17.63	413.45	0.77	0.21	10.87
Proposed SC 3(AP5)	12.68	292.37	0.72	9.75	32.1
Proposed SC 4(AP5)	14.45	368	0.70	13.13	35.5

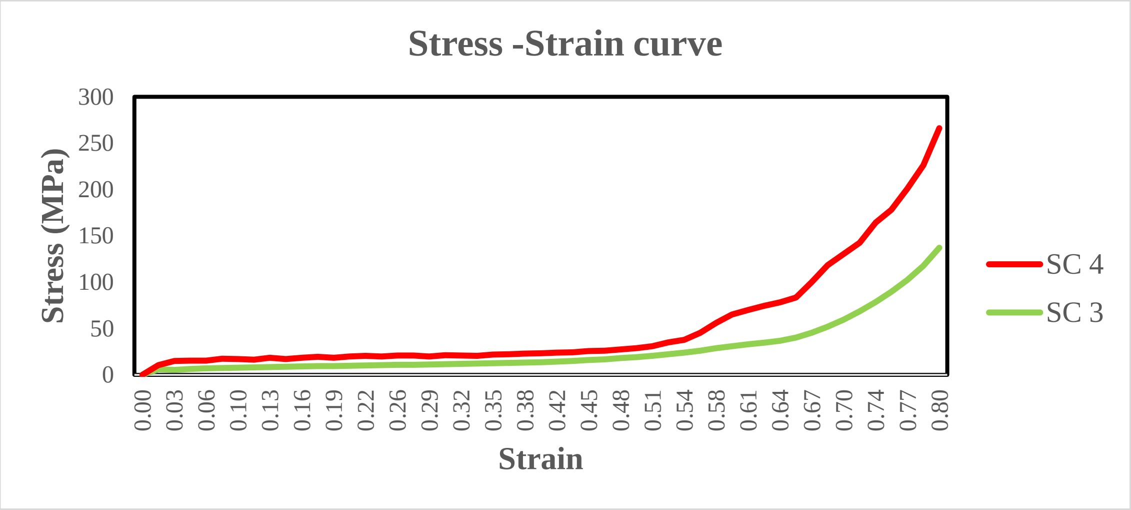


Figure 70: Comparison between the stress-strain curves of the two solution concepts (SC) to solve conflicts based on two APs

At the end of this section, the Figure 71 shows a comparison between the binarization threshold values of the four solution concepts (SCs) and the threshold of ideality, is necessary. This comparison brings the contribution of each SC to converge or diverge from the ideality.

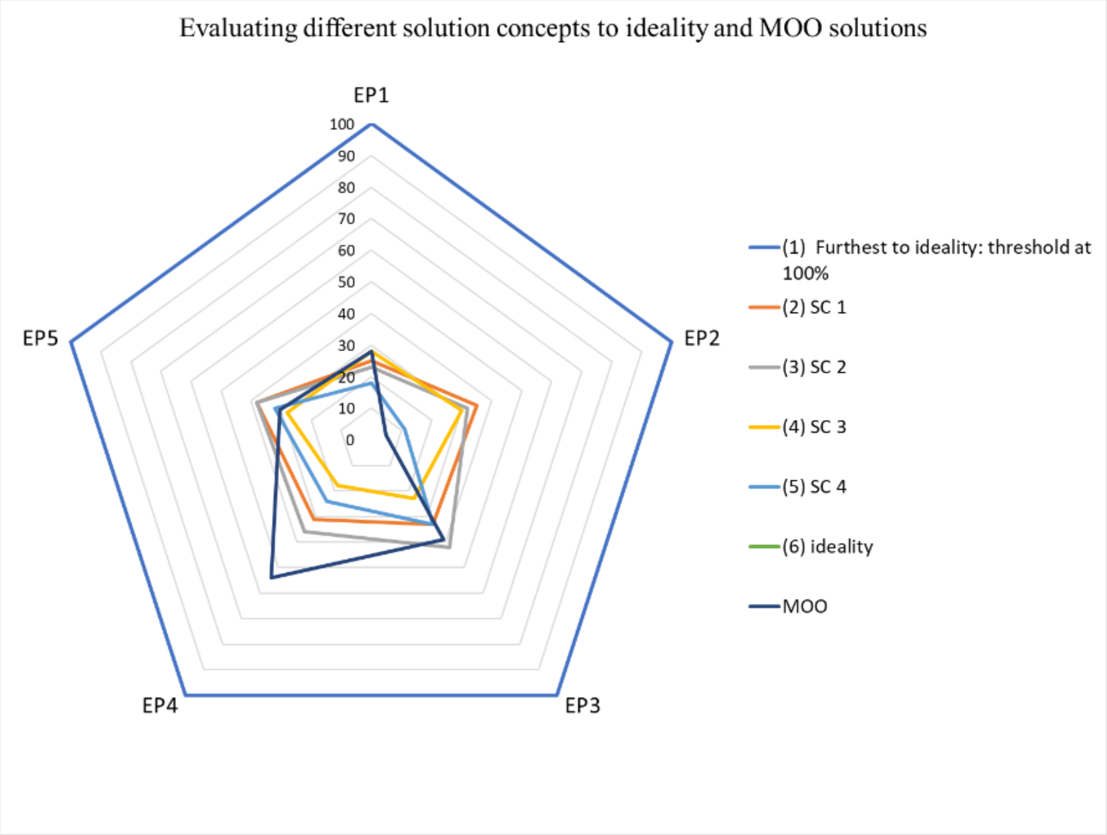


Figure 71: Comparing the threshold values of different solutions with ideality and MOO solutions

5.3 Performing a second design loop

An iterative technique is suggested to get closer to the ideal final results, as per Figure 72:

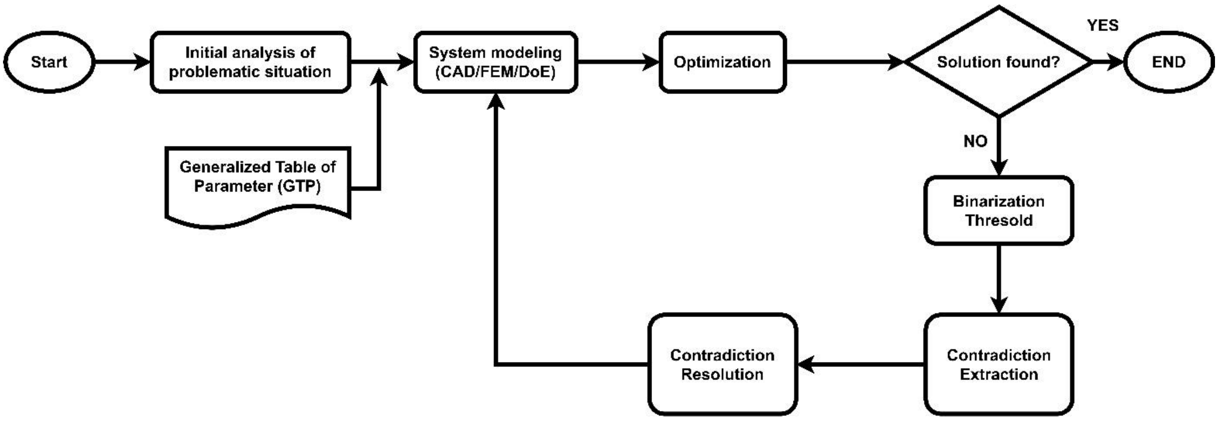
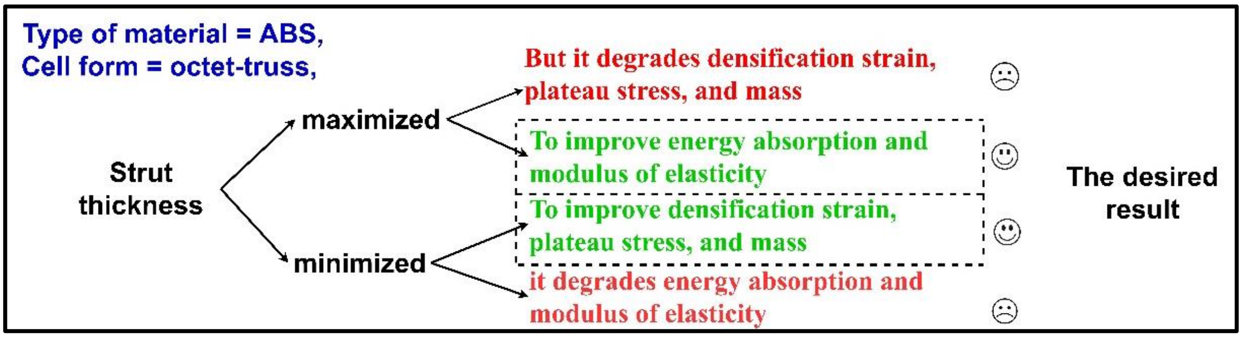


Figure 72: Proposed iterative inventive design process

To achieve a first inventive solution, the binarization threshold is established during the first iteration. It is crucial to keep in mind that when there is a conflict, the focus is on reducing the number of conflicting action parameters. Conflicts involving a single action parameter are often the easiest to resolve. For this reason, the binarization threshold is then steadily decreased in the second iteration until an overall solution is presented with at least one varying action parameter. For this case study, in this chapter, a second loop would be performed to examine this hypothesis. Several design steps would be performed as follow:

Starting from the identified contradiction, extracted from the first loop, based on two quantitative APs, as follow:

Evaluation parameter	EP1	EP2	EP3	EP4	EP5
Binarization threshold	24%	24%	24%	24%	24%



Step 1: Identify the list of APs

A new design model should be performed based on the new action parameter which is the strut thickness (*AP5*), by replacing two action parameters, which are cell size (*AP3*), and change ratio of strut thickness (*AP4*). By presenting this new AP, new APs would be listed, as follow (in Table 38):

Table 38: new list of APs within the second design loop

Action Parameters (AP)	Parameter type
Cell form	Qualitative
Type of material	Qualitative
Strut thickness	Quantitative

Step 2: Build the Design of experiments

A full factorial design of experiments was conducted, same as the first loop of design. By taking the expense of numerical simulation into account, a combination of 12 configurations were carried out. The choice of action parameters levels was implemented in referring to the presented database to choose a reasonable number of levels to reduce the total number of experiments. The new design of experiments includes a new parameter which is the strut thickness. This parameter is presented in two levels, struts of 1.5 mm, and struts of 3 mm, as shown in the example of Figure 73.

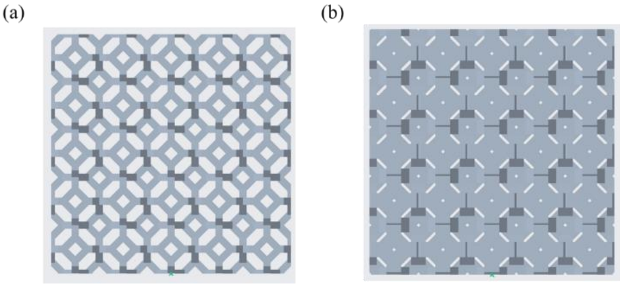


Figure 73: the figure (a) is representing a kelvin-based structure of 1.5 mm-strut-thickness, on the right, figure (b) is showing the same cell form with 3 mm-strut-thickness

Figure 74 shows a sample of the built CAD models, to be used after for performing the numerical simulations.

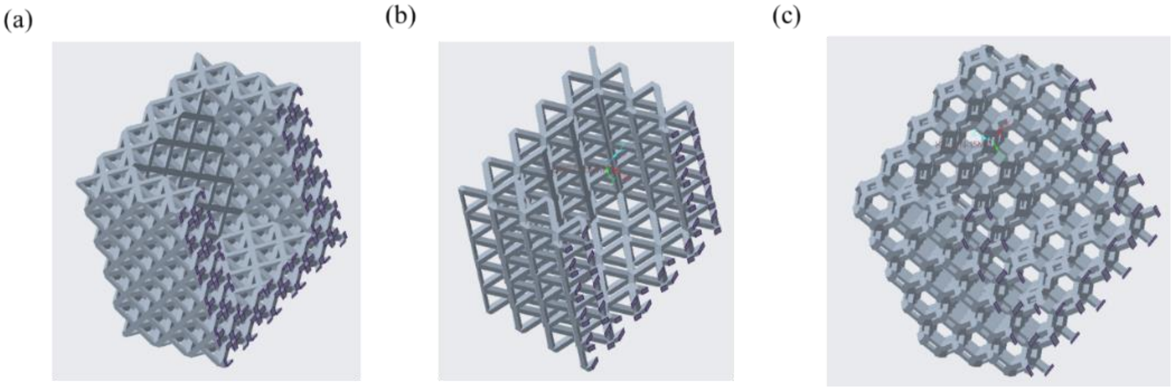


Figure 74: (a) Octet-truss cell, (b) BCCz cell, (c) Kelvin cell, of the 2nd design loop

The planning to perform the design of experiments was set as indicated in the following Table 39 and Table 40:

Table 39: The expected levels of each selected Action Parameter AP (2nd design loop)

Action Parameter	No. of levels	Level (-2)	Level (-1)	Level (+1)
Cell form	3	BCCz cell	Octet-truss cell	Kelvin cell
Type of material	2	ABS		PLA
Strut thickness (mm)	2	1.5		3

Table 40: The plan of the Design of Experiments (DoE)

Test No.	Cell form	Type of material	Strut thickness (mm)
1	kelvin	PLA	1.5
2	octet-truss	PLA	3
3	BCCz	PLA	1.5

4	octet-truss	PLA	1.5
5	kelvin	ABS	1.5
6	octet-truss	ABS	3
7	BCCz	PLA	3
8	kelvin	ABS	3
9	BCCz	ABS	1.5
10	kelvin	PLA	3
11	BCCz	ABS	3
12	octet-truss	ABS	1.5

Step 3: this step is dedicated to run the design of experiments (see Table 41 for the experimental results). The setup of these experiments is identical with the setup of the first design loop. In this study, the experimental runs were conducted by using the numerical methods (FEM), and the same software Abaqus® was used, for this purpose.

Table 41: the experimental results within the 2nd design loop

Test No.	Cell form	Type of material	Strut thickness (mm)	Energy absorption per unit volume (MJ/m3)	Modulus of elasticity (MPa)	Densification Strain	Plateau Stress (MPa)	Mass (g)
1	kelvin	PLA	1.5	1.48	38.86	0.72	1.51	14.24
2	octet-truss	PLA	3	15.10	224.21	0.71	17.37	82.47
3	BCCz	PLA	1.5	1.56	30.14	0.72	2.12	16.38
4	octet-truss	PLA	1.5	4.23	89.71	0.72	3.53	26.29
5	kelvin	ABS	1.5	2.03	56.73	0.72	2.42	16.98
6	octet-truss	ABS	3	19.35	415.32	0.70	25.45	69.17
7	BCCz	PLA	3	15.13	205.44	0.70	16.37	43.83
8	kelvin	ABS	3	16.38	321.09	0.70	21.90	27.15
9	BCCz	ABS	1.5	2.02	48.80	0.69	2.99	13.73
10	kelvin	PLA	3	12.00	201.63	0.70	15.22	51.59
11	BCCz	ABS	3	20.32	324.73	0.70	25.21	43.83
12	octet-truss	ABS	1.5	6.99	134.44	0.72	7.21	31.35

Step 4: Implement Multi-Objective Optimization

In this case study, the best configuration will be to maximize the energy absorption, maximizing the rigidity, and minimizing the mass. To achieve the design objectives and satisfy the entire set of objective parameters, we will use multi-objective optimization methods.

The algorithm Reduced Gradient Algorithm (RGA) by using the software Minitab®, will be exploited only. The results from the optimization chart are inserted directly in Table 42, in a comparison with their corresponding values from the first loop, and ideal results.

Table 42: Comparing the results of MOO process out of first and second loop with the ideal results

	AP1	AP2	AP3	AP4	AP5	EP1	EP2	EP3	EP4	EP5

Solution of MOO (1st loop)	Kelvin	ABS	10	0	-	12.69	209.11	0.69	29.25	34.05
Solution of MOO (2nd loop)	BCCz	ABS	-	-	2.56	12.21	201.97	0.70	15.2	31.28
Ideal results						17.63	413.45	0.77	0.21	10.87

The system optimization of the second loop showed better results for some EPs such as EP3, EP4, and EP5. However, not so better results, almost close, for EP1 and EP2. Nevertheless, optimization methods gave a solution with a compromise and not satisfactory. For this reason, extracting the system of contradiction, which reflects the core problem of the system, is a need. To do so, we continue the process with the next steps.

Step 5: Extract the first GSC based on different varied APs

The goal of this step is to search for the first GSCs at which the entire set of EPs is satisfied, at different threshold values and based on one or many varied APs. As a result, by increasing the number of varied AP, the complexity of changing the model increases, but the model is closer to ideal solution, as shown in Table 43. Worth mentioning that all extracted contradictions at global and individual thresholds are detailed in appendix D.

Table 43: Table to indicate volume of the extracted GSC at different threshold values under different varied APs (within the 2nd design loop)

No. of varied AP Threshold (%)	1	2	3
0-0%	0	0	0
0-6%	0	1	2
0-25%	1	6	6

Step 6: Reduce the global threshold values for obtaining GSC (with the possibility of varying the included number of APs)

Similar to the first design loop, in this iterative process, the global binarization threshold was gradually decreased until contradictions emerged in the system. It is worth noting that the option to specify the number of action parameters included in the contradiction was exercised. As mentioned before, resolving contradictions with just one action parameter was preferred due to its perceived ease. In this particular iteration, the focus was on the extraction of a Generalized System of Contradictions (GSC) between experiments 5 and 8, as shown in Figure 75. A GSC was extracted based on changes in the strut thickness, ranging between 1.5 mm and 3 mm, while keeping the cell form and type of material as contextual factors. By following these steps, a refined set of experimental configurations was obtained, leading to a reduction in the global binarization threshold to 25%, compared to 38% in the first loop.

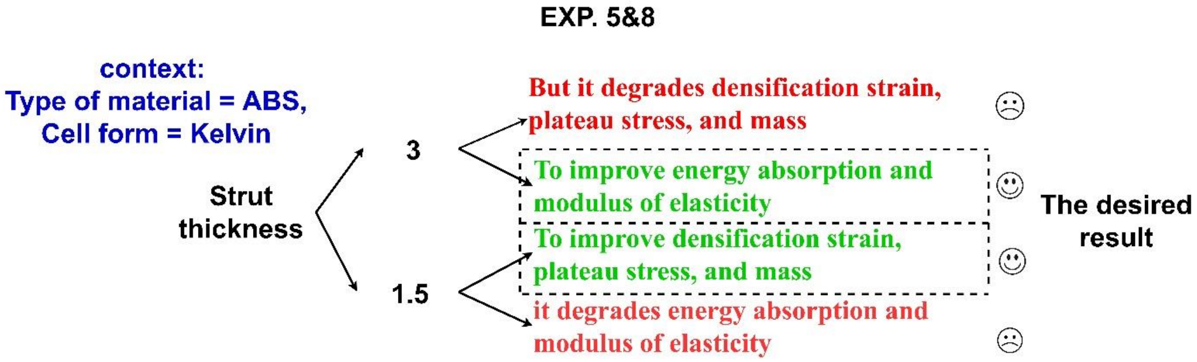


Figure 75: extracted GSC based on one varied AP (2^{nd} design loop)

Step 7: Propose solution concepts (SC) and fabricate them

By applying separation principles on the analyzed system, a solution concept based on applying separation in space was proposed. The solution concept is based on separating two strut thicknesses, and this concept is shown in Figure 76. This concept is providing large strut thickness of a size of 3 mm at the perimetric zone of the structure, except the corners, to provide a good energy absorption, rigidity. While maintaining small strut thickness of a size 1.5 mm at the corners of the structure (locations of stress concentration) to provide better densification strain, plateau stress and lower global mass.

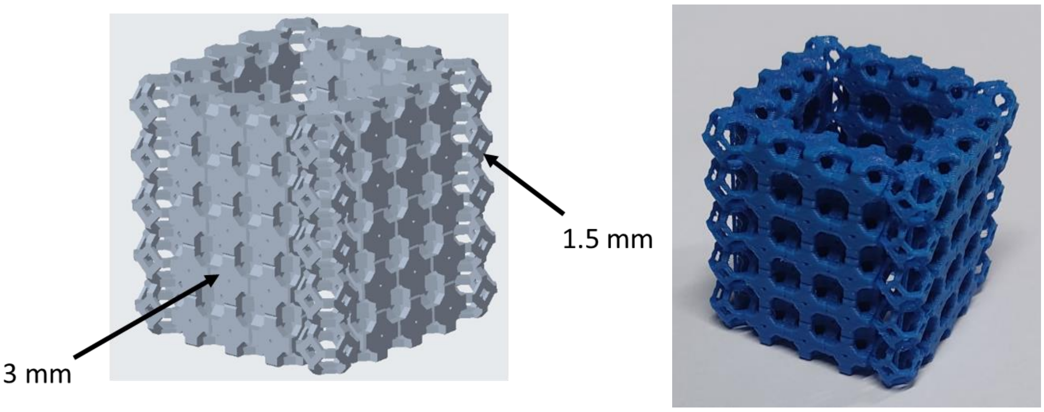


Figure 76: The proposed solution concept based on separating the strut thickness in space (2^{nd} design loop)

5.4 Discussion of results and feedback

The discussion of results will be divided in this section into two levels, one level is to discuss the comparison between the proposed method and an existing method such as Pareto-based approach. The second level is to discuss the results of the proposed method and provide a feedback discussion.

5.4.1 Comparing the proposed method with other existing method(s)

To make the reader aware of the difference between the developments made with the proposed method, and the existing method(s), stated in the chapter 5, it is necessary to make a comparison between the existing method(s) and the proposed one. This comparison is used to verify the applicability of our proposal, as well. The Table 44 shows a comparison between the results of the pareto-based method and our proposed method in terms of extracting and solving system of contradictions.

Table 44: A comparison between the proposed method based on the DoE and Pareto-based approach

Criteria	Pareto-based approach	Proposed method
Dependence on experimental data	This approach analyzes the available data e.g., experiments	This method analyzes the available data e.g., experiments
Applicability of TRIZ Separation Principles	Applied TRIZ-based methods to solve physical contradictions (PC). Solving complex PC is uncertain	Integrated SI units with separation principles to solve physical contradictions
Extraction of GSC	Only GSC on pareto frontier	GSC based on a binarization threshold value and a number of varied AP
The Feasibility of Solution Concepts (SC)	The proposed solution concepts are not tested	The feasibility of the proposed solution concepts is tested

5.4.2 Comparing the results of first and second design loops

The proposed method is composed of iterative inventive design steps, as mentioned before. In this chapter, two design loops were performed to examine two hypothesises, the first one is that the design could achieve the ideality better with solving a higher number of varied APs in the physical system of contradictions. The second hypothesis is that the developed system could close more to the ideality at each design loop. The resulting performance of the new system presented by solving two APs in the GPC gave better reults than the new system based on one AP. Second, as shown in Figure 77, an example from the case study on the resulting performance of two evaluation parameters, energy absorption and modulus of elasticity. The strength of the proposed meethod is guaranteeing approaching the ideal results after one or several loops. The figure shows the reformulation of design problems based on the design iterations and the number of varied action parameters inside the extracted physical contradictions.

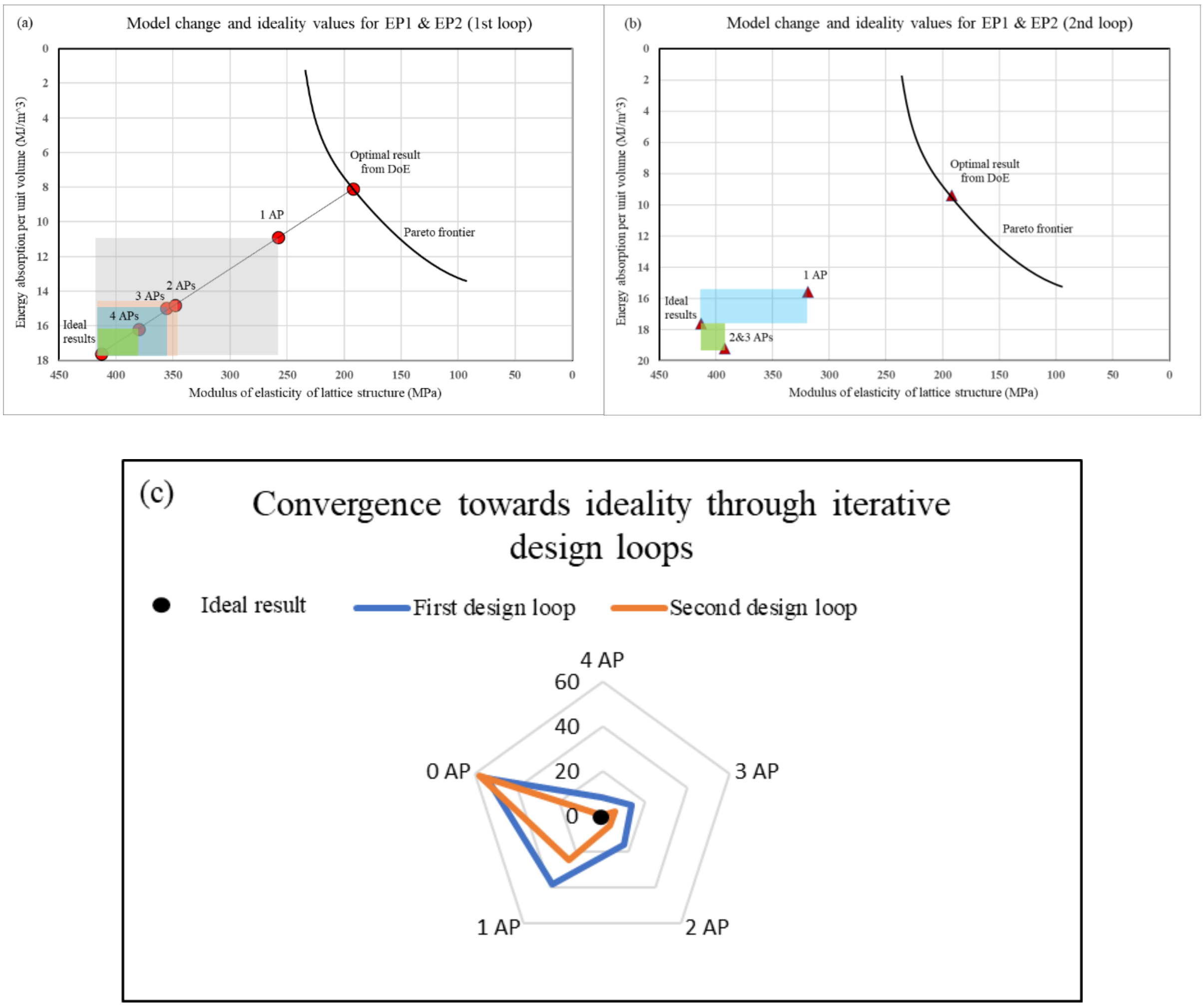


Figure 77: An example on the reformulation of problems to bring closer to ideality with iterative design loops, (a) the results of first contradictions from first loop, (b) the second loop, (c) a comparison chart between the two loops

Also, the same figure illustrates an example of potential solution location based on the number of parameters to resolve for EP1 and EP2. The value called 'optimal result' represents the solution out of DoE in the design space closest to the ideality, positioning on the Pareto frontier. It is important to note that to get closer to the solution, many action parameters must be included. Whereas, to facilitate resolution, it is preferable to minimize the number of action parameters included in the physical contradiction (PC).

5.4.3 Comparing the solution concepts out of first and second design loops

As a result of performing a couple of design loops, a set of resulting solutions and solution concepts were given. These solutions are a result of a multi-objective optimization process and an inventive model changing process based on TRIZ principles. However, in the Figure 78 we show a comparison between the resulting solutions out of changing the model between the two design iterations.

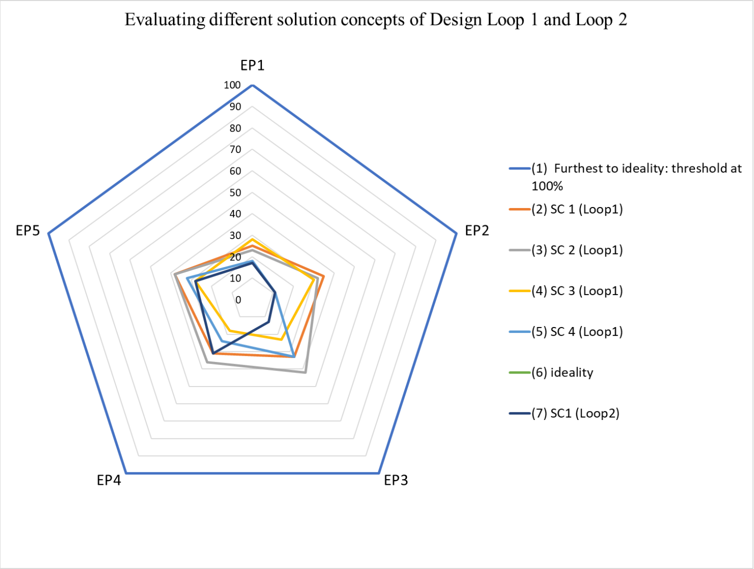


Figure 78: A comparison of multiple solutions and solution concepts out of two iterative design loops

In this figure, Figure 78, one can see that performing a second design iteration resulted in a higher performance of the designed system. Evaluation parameters 1,2,3,5 enhanced than the first design iteration. It is argued that with the continuous development of the same system by performing multiple iterations e.g., design loops, the system can achieve the ideality.

5.4.4 Method feedback and discussion

This feedback discussion of used method is demonstrated based on two main questions; first, what is the positive feedback observed after applying the proposed method? Second, what are the potential limitations that are determined as a result of the application of the proposed method?

Answering the first question could be resumed in the following bullet points:

- The proposed GTP helped in the prompt selection of design parameters, physical and performance. GTP helped avoid neglecting certain ones that may have a significant influence on the system's behavior.
- The analysis of output results from DoE helped in completing information on the GTP and CDB.
- The proposed method established rules for selecting binarization threshold values during the analysis of experimental results. It can lead to a simplification of the model change process by reducing the number of physical parameters considered in resolving contradictions, making problem-solving easier (or resulting in minor changes in the initial model, enabling short-term solutions). Moreover, it could help in prioritizing the extracted GSC.
- The use of the threshold also prompts users of the method to carefully consider the initial constraints' values in the system and observe the effect of a small variation in these constraints

on the final resolution. They can assess the impacts on the model's complexity, solution feasibility, expected performance, costs, etc.

- The method provides steps for the practical validation of feasibility, prototyping, and checking the applicability of the proposed inventive solution concept(s) (SC). Thanks to the proposed CDB and GTP in chapter 3.
- The proposed method used inventive methods and models to solve contradictions. Moreover, it enabled the integration between SI units of physical quantities and TRIZ separation principles to solve complex contradictions.
- The stated rules to determine threshold values made the extraction of contradictions very precise and exact to those whose solution can solve the whole design problem directly.
- The solved solution concepts (SC) were evaluated by using the concept of binarization threshold which helped in selecting the closest SC to ideality.

Answering the second question, in this research work, we could only solve the complex physical contradictions which are constituted of quantitative parameters, but not qualitative. Despite this, the integration of SI units and separation principles with the help of the GTP and CDB showed a strong potential to solve highly complex physical contradictions in the upcoming research work. However, this research opened the door for future research work to evolve this proposal in order to solve more complex contradictions.

5.4.5 Conclusion

This chapter presents a novel method to solve complex design problems by combining Design of Experiments (DOE), Generalized Table of Parameters (GTP), Contextual Database (CDB), and TRIZ-based inventive methods. This method was illustrated by solving one complex design problem in the mechanical field of lattice structures. The method demonstrated several strengths, including efficient parameter selection, getting benefits from threshold determination to highlight system conflicts, integration of SI units and TRIZ principles, and validation of solution concepts. It also highlighted the importance applying optimization methods to detect compromising solutions or try finding a final solution of the design problem. The proposed method is an iterative design method based on changing the model continuously until achieving the ideal results. Two loops were performed, approving the strength of getting approach to ideal results by the minimum change of the designed system. However, challenges were noted in handling qualitative parameters during solving highly complex physical contradictions e.g., with more than one varied AP. Despite this, the chapter emphasized the method's potential for addressing complex contradictions and the validation of proposed solution concepts. The resulting configurations of the DoE were analyzed by using regression model and main effect plots.

Therefore, the obtained information weas provided, as a loop, to the CDB and the linked GTP. Moreover, this information helped in understanding better the design system.

Chapter 6 Conclusions and Perspectives

This thesis embarked on a journey to develop inventive problem-solving methods within the scope of industrial product and material design. The contemporary industrial market, marked by rapid technological advancements, intensified competition, and soaring consumer expectations, necessitated a paradigm shift in the approaches to design and problem-solving. This research unfolded systematically, adhering to a structured methodology that commenced with the identification of research problems, traversed through a comprehensive exploration of inventive design approaches, posed insightful research questions, and culminated in the proposal of inventive solutions aimed at overcoming existing research gaps.

6.1 Reminder of research questions

In chapters 1 and 2, we introduced the background for our thesis and our motivations to contribute in developing the iterative design process which is based on the four phases: Analysis of initial situation-system modeling-optimization-invention. These developments are done within inventive problem-solving methods to better model the design system and ease revealing and resolving the inventive design problems in a broader general context. To organize our problems and present our contributions, Chapter 1 initialized the research work with an initial question, which was:

What approach to adopt for solving complex problems, based on the analysis of the initial situation according to the objectives to be achieved and the extraction, resolution of priority contradictions, without relying too heavily on experts and utilizing available data?

After, in chapter 2, because of the state-of-the-art, this question was refined to four research questions that locate our problematic of this thesis. Let us recall the four questions:

Q1: How can a systematic inventive design process be adapted to address problems in an expanded general context with various potential application fields?

Q2: Based on the built model, collected information and data, how to extract the most prioritized problem to be solved?

Q3: How can experiments be used to gain deeper insights into system behavior to develop the system towards ideality?

Q4: How can the model change process, particularly in resolving generalized contradictions, be simplified, and made more feasible within the inventive design problem-solving process?

6.2 Contributions

The contributions of this research are profound to make a significant impact and that have the potential to develop the inventive design methods:

- Contextual database (CDB) and Generalized Table of Parameters (GTP): The development of a contextual database linked to a generalized table of parameters, meticulously constructed from diverse data sources, has emerged as a pivotal tool serving the inventive design problem-solving process. This table stands as a resource of domain-specific knowledge, offering a structured repository of design parameters and insights essential for comprehending the design system. Moreover, the developed GTP significantly reduces the reliance on domain experts and make the use of inventive design methods easier for non-experts.
- Prioritized problem extraction: the research has elucidated a systematic approach to extract and prioritize critical design problems from the GTP, leveraging the importance of collected information and data. These problems provide a well-defined model for more precise design problem resolution. The prioritized problems are proposing holistic problem model which includes the entire set of performance parameters. This can lead to specific solution concepts for specific design problems and reducing the used means to achieve these solution concepts i.e., by using GTP.
- "Binarization threshold": This research introduces a technique that can control modifications in the designed models, by controlling the reformation of the design problem. This technique of threshold can help in deciding the number of action parameters linked to evaluation parameters which helps to reduce the number of action parameters involved in resolving contradictions. This not only simplifies problem-solving but can also lead to minor model changes, enabling short-term solutions. This represents a limitation of the recent study, and one perspective is to consider long-term solutions by potentially increasing the complexity of the implemented changes in the model. Furthermore, the utilization of the threshold encourages users to carefully evaluate the initial constraints in the system and consider the effects of even slight variations on the final resolution, including factors such as model complexity, solution feasibility, expected performance, and costs.
- Solution Concept (SC) feasibility validation: an indispensable component of this research is providing the capability of testing the feasibility of proposed solutions. This critical validation step serves as a litmus test, determining whether the proposed designs are not just theoretically sound but also practically executable in the real-world context.

6.3 Limitations

However, no research is without its limitations:

- Difficulty of handling qualitative parameters: while our proposed methods introduced an incorporation between the SI units' approach with quantitative parameters within the generalized system of contradictions (GSC). This incorporation helped in reformulating complex physical contradictions to be simplified for resolution. However, our proposal may still face challenges in handling the qualitative parameters effectively within the generalized system of contradictions.
- Process mentality: in chapter 3, the GTP and its linked CDB were presented to be integrated within the inventive design process. Despite the benefits of these contributions, filling the GTP and collecting all the data manually may consume a lot of time and effort.
- The optimal application of the proposed concept of threshold, in chapter 5, and its impact on various aspects of problem-solving, such as feasibility, expected performances, and costs, needs to be further explored. Moreover, one perspective is to explore long-term solutions by potentially increasing the complexity of the implemented changes in the model.

6.4 Further Research perspectives

Considering these findings and limitations, this research opens doors to several promising avenues for future exploration and innovation:

- Solving complex GSC: investigating techniques for applying the SI units approach, see section 5.2, with the qualitative parameters within the generalized system of contradictions (GSC), will significantly expand the scope of solving more complex contradictions including both quantitative and qualitative parameters. Even though the way was used to resolve the complex GSC by using the SI units was just the first step and it opens the door to develop this way more in the future research work.
- Process automation: the future work of this study holds profound promise, marked by the strategic integration of automation and artificial intelligence (AI) to reshape the inventive design process. The perspectives center on three key dimensions: automating the filling of the Generalized Table of Parameters (GTP), collecting information for the Contextual Database (CDB), and leveraging AI for seamless exploitation of the GTP within the inventive design process, as illustrated in Figure 79.

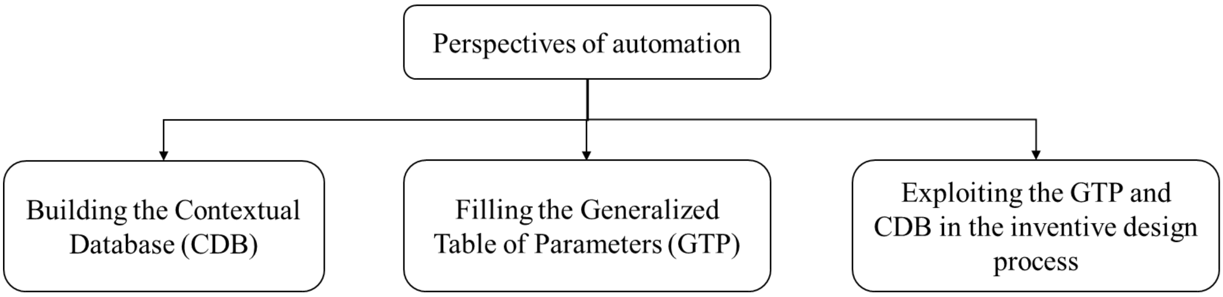


Figure 79: Perspectives on automation

1. Automated GTP Population:

   - Efficient Data Extraction: The integration of AI and automation aims to revolutionize the labor-intensive task of populating the GTP. Automation algorithms will systematically extract relevant information from the vast repository in the Contextual Database (CDB), streamlining the process and significantly reducing the time required for manual data entry.

   - Dynamic Relationship Mapping: AI-driven algorithms will dynamically map relationships between each pair of parameters, navigating through constitutive laws, graphs, and equations in the CDB. This ensures that the GTP reflects the nuanced interdependencies within the design system, promoting accuracy and comprehensiveness.

   - Adaptive Learning: Machine learning capabilities embedded in the automation process will enable continuous improvement. The system will adapt and refine its understanding of relationships over time, ensuring that the GTP remains a dynamic and evolving resource, capable of accommodating new insights and changes in the design landscape.

2. Information Collection for CDB:

   - AI-Enhanced Data Collection: Automation will extend to the collection of information for the Contextual Database. AI algorithms will scour scientific articles, literature reviews, and other repositories to extract relevant data. Natural Language Processing (NLP) will be employed to derive valuable insights from unstructured text, enriching the CDB with a wealth of domain-specific knowledge.

    - Continuous Enrichment: The automation process will not be static. It will continuously enrich the CDB by updating it with new information, studies, and research results in the relevant domain. This ensures that the database remains current, reflective of the latest advancements, and adaptable to emerging challenges.

  3. AI-Driven GTP Exploitation:

    - Streamlined Design Process: The ultimate goal is to automate the exploitation of the GTP within the inventive design process. AI will play a central role in extracting contradictions, analyzing data, identifying inventive solutions, and guiding decision-making. Designers can leverage AI to navigate the extensive information in the GTP efficiently, allowing for a more focused and strategic approach to problem-solving.
    - Judging and evaluating outcomes: AI will contribute to evaluating the feasibility of proposed solutions, considering factors such as performance, costs, and expected outcomes. This critical validation step ensures that proposed designs are not just theoretically sound but also practically executable in real-world industrial contexts.

- Evaluating the proposed solution concepts (SC): as it was concluded in chapter 5, there were more than one solution concept at the end, proposed to solve the design problem. Based on the developed methods at CSIP, or outside, it becomes possible to integrate one or more of solution-evaluating methods, such as, the solution concept modeling and evaluation based on function-structure and behavior [118].
- Physical mechanical testing: the research work in this PhD proposes promising approaches to systematize the design process, including prototyping the solution concept using additive manufacturing technology. Testing these fabricated solution concepts and validating the results, especially those that align with the specifications of industrial applications, would be interesting and valuable in making these potential solutions feasible, applicable, and thoroughly tested. For example, the specific case study of energy absorber, in this PhD, proposed certain solution concepts as outputs. One can conduct static tests such as mechanical uniaxial compression tests, uniaxial tension tests, flexure test, as illustrated in Figure 80. Conducting such test gives more credibility of the proposed solutions.

Figure 80: Mechanical testing machines (tensile, compression, flexure) at INSA Strasbourg, on the left-hand side, Zwick Roell® Z005 (maximum 5 kN), on the right-hand side, Zwick Roell® Z050 (maximum 50 kN)

In summary, this research marks a significant step forward in how we solve problems and design products and materials in industries. The ideas and solutions presented here open exciting possibilities for future innovations in industry. By carefully studying inventive problem-solving methods, this research equips us with the skills and information we need to tackle industrial challenges more efficiently, giving us hope for a better future in design and finding solutions.

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Appendices

Appendix A: VBA script to automate creating and hyperlinking files of Contextual Database (CDB) to the Generalized Table of Parameters (GTP)

```
Sub CreateWordFiles()
    Dim cell As Range
    Dim row As Integer
    Dim col As Integer
    Dim folderPath As String
    Dim fileName As String
    Dim wordApp As Object
    Dim wordDoc As Object
    Dim sentence As String

    ' Set the folder path to the same folder as the Excel file
    folderPath = ThisWorkbook.Path & "\"

    ' Loop through each cell in the table
    For Each cell In Range("F34:AZ36")

        ' Get the row and column numbers
        row = cell.row - 6
        col = cell.Column - 4

        ' Generate the file name as the letter from the first column then (-) then the number from the first row'
        fileName = Cells(row + 6, 1) & "-" & Cells(1, col + 4) & ".doc"

        ' Create a new Word application and document
        Set wordApp = CreateObject("Word.Application")
        Set wordDoc = wordApp.Documents.Add

        ' Set the orientation of the page to landscape layout
        wordDoc.PageSetup.Orientation = 1 'wdOrientLandscape = 1

        ' Add a header with the file name
        wordApp.ActiveWindow.View.Type = 3 'wdPrintView = 3
        wordApp.ActiveWindow.ActivePane.View.SeekView = 0 'wdSeekMainDocument = 0
        wordApp.Selection.Paragraphs.Alignment = 0 'wdAlignParagraphCenter = 0
        wordApp.ActiveWindow.ActivePane.View.SeekView = 9 'wdSeekCurrentPageHeader = 9
        wordApp.Selection.HeaderFooter.Range.Text = fileName
        wordApp.Selection.Font.Name = "Times New Roman"
        wordApp.Selection.Font.Size = 12

        ' Add a footer with the date and page number
        wordApp.ActiveWindow.ActivePane.View.SeekView = 10 'wdSeekCurrentPageFooter = 10
        Set footer = wordApp.Selection.HeaderFooter
```

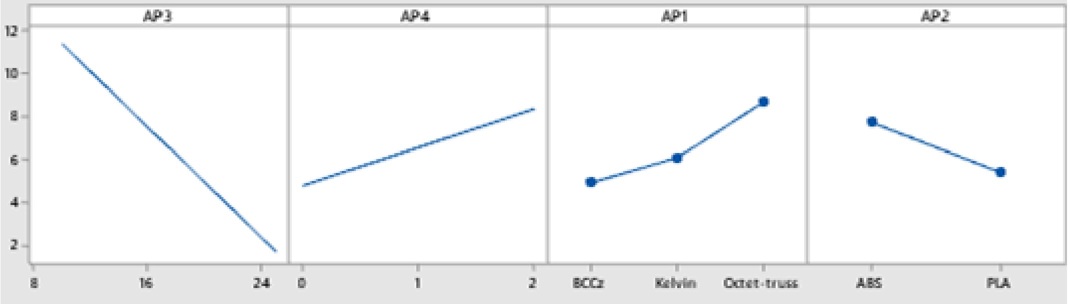
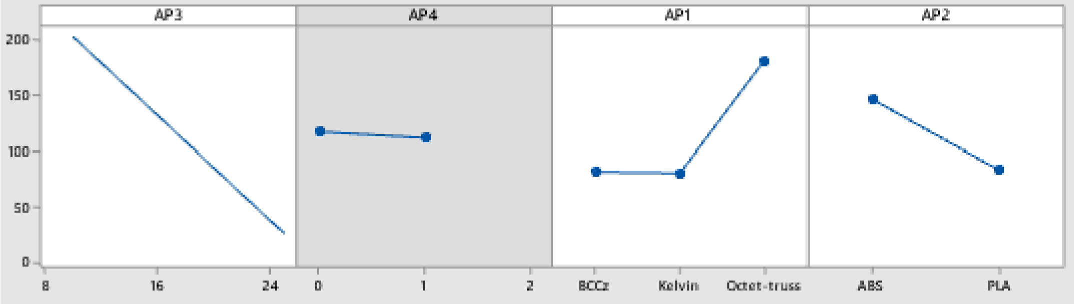
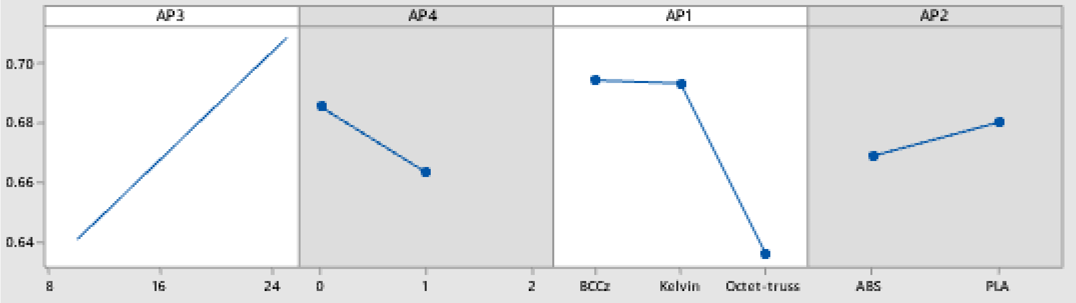
```
        footer.Range.Text = Format(Date, "Long Date")
        footer.Range.Font.Name = "Times New Roman"
        footer.Range.Font.Size = 12
        footer.Range.ParagraphFormat.Alignment = 0 'wdAlignParagraphLeft = 0

        ' Add the table on the first page
        wordDoc.Content.Paragraphs.Add
        Set myTable = wordDoc.Tables.Add(wordDoc.Range, 12, 1)
        myTable.Borders.Enable = True
        myTable.cell(1, 1).Range.Text = "The information in this file concerns the influence between " &
Cells(row + 6, 5) & " and " & Cells(7, col + 4)
        myTable.cell(2, 1).Range.Text = ""
        myTable.cell(3, 1).Range.Text = "Scientific article/book"
        myTable.cell(5, 1).Range.Text = "Experts' opinions"
        myTable.cell(7, 1).Range.Text = "CAD/FEM software"
        myTable.cell(9, 1).Range.Text = "Conflict(s)"
        myTable.cell(11, 1).Range.Text = "Remarks/References"
        For i = 1 To 13
            For j = 1 To 1
                myTable.cell(i, j).Range.Font.Name = "Times New Roman"
                myTable.cell(i, j).Range.Font.Size = 16
            Next j
        Next i

        wordDoc.SaveAs folderPath & fileName
        wordDoc.Close

        ' Add a hyperlink to the cell
        cell.Parent.Hyperlinks.Add Anchor:=cell, Address:=folderPath & fileName

        Set wordDoc = Nothing
        Set wordApp = Nothing

    Next cell
End Sub
```

Appendix B: Specific table out of the Generalized Table of Parameters (GTP)

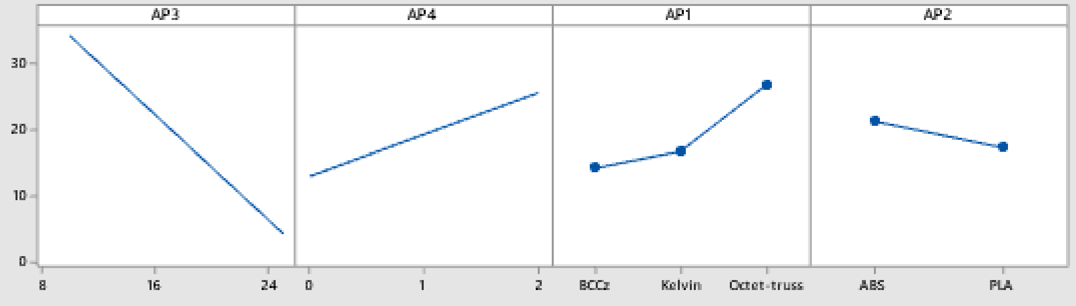
Physical Parameters		Evaluation Parameters (EP)					
	Optimization direction	Maximize	Minimize	Maximize	Maximize	Minimize	Contradictions
		Energy absorption per unit volume	Plateau stress	Densification Strain	Modulus of elasticity of lattice structure	Mass	
PhP1	Relative density of lattice structure	(high)/(3)	(low)/(3)	(low)/(3)	(high)/(3)	(low)/(3)	YES
PhP2	Global dimensions	(low)/(1)	(high)/(1)	(low)/(1)	(high)/(1)	(low)/(3)	YES
PhP3	Shape of structure	(Cone with blunt tip)/(3)	(Sphere)/(1)	(Sphere)/(1)	(Cube)/(3)	(Square pyramid)/(2)	YES
PhP4	Number of used materials	(high)/(3)	(low)/(3)	(low)/(3)	(low)/(3)	(high)/(2)	YES
PhP5	Gradience	(high)/(2)	(low)/(2)	(high)/(1)	(low)/(1)	(high)/(3)	YES
PhP6	Periodicity	(other)/(2)	(low)/(2)	(high)/(2)	(high)/(3)	(high)/(1)	YES
PhP7	Wall thickness	(high)/(2)	(low)/(3)	(low)/(2)	(high)/(3)	(low)/(3)	YES
PhP8	External wall thickness	(high)/(1)	(low)/(1)	(low)/(1)	(high)/(1)	(low)/(3)	YES
PhP9	Strut length	(low)/(2)	(high)/(2)	(low)/(2)	(high)/(2)	(low)/(2)	YES
PhP10	Cell form	(Octet-truss)/(3)	(BCC)/(3)	(Graded BCCz)/(3)	(Graded BCCz)/(3)	(BCC)/(1)	YES
PhP11	Cell size	(low)/(3)	(high)/(3)	(high)/(3)	(low)/(3)	(high)/(3)	YES
PhP12	Strut thickness	(high)/(2)	(low)/(3)	(low)/(1)	(high)/(3)	(low)/(3)	YES
PhP13	Young's modulus of base material	(high)/(2)	(low)/(2)	(low)/(1)	(high)/(3)	(0)/(0)	YES
PhP14	Density of base material	(high)/(3)	(low)/(2)	(high)/(2)	(high)/(2)	(low)/(3)	YES

PhP15	Poisson's ratio of base material	(high)/(2)	(high)/(2)	(high)/(2)	(low)/(3)	(low)/(1)	YES
PhP16	Hardness of base material	(low)/(2)	(low)/(1)	(low)/(1)	(high)/(3)	(0)/(0)	YES
PhP17	Compressive stress	(high)/(2)	(low)/(2)	(low)/(1)	(0)/(0)	(0)/(0)	YES
PhP18	Angle of test orientation	(Z-axis)/(1)	(Z-axis)/(1)	(Z-axis)/(1)	(Z-axis)/(2)	(0)/(0)	YES
PhP19	Displacement	(high)/(1)	(low)/(2)	(high)/(3)	(0)/(0)	(0)/(0)	YES
PhP20	wall section	(high)/(1)	(low)/(3)	(low)/(2)	(high)/(2)	(low)/(3)	YES
PhP21	Open or closed	(Closed cell)/(2)	(Closed cell)/(3)	(Open cell)/(1)	(Closed cell)/(3)	(Open cell)/(3)	YES
PhP22	interconnection	(high)/(2)	(low)/(2)	(low)/(1)	(high)/(3)	(low)/(2)	YES
PhP23	Strut angle	(high)/(2)	(low)/(2)	(low)/(2)	(other)/(3)	(other)/(1)	YES
PhP24	Arrangement direction of cells	(Z-axis)/(2)	(X-axis)/(1)	(X-axis)/(2)	(Z-axis)/(2)	(X-axis)/(1)	YES
PhP25	Distance of variation of gradience	(low)/(2)	(high)/(2)	(high)/(1)	(low)/(1)	(high)/(3)	YES
PhP26	Loss modulus of base material	(low)/(1)	(low)/(0)	(high)/(1)	(low)/(1)	(0)/(0)	YES
PhP27	Storage modulus of base material	(low)/(1)	(low)/(2)	(low)/(1)	(high)/(3)	(0)/(0)	YES
PhP28	Strut section	(high)/(2)	(low)/(3)	(low)/(1)	(high)/(3)	(low)/(3)	YES
PhP29	Strain rate	(high)/(3)	(low)/(3)	(high)/(2)	(high)/(3)	(0)/(0)	YES
PhP30	Ambient temperature	(low)/(3)	(high)/(3)	(low)/(2)	(low)/(3)	(high)/(1)	YES
PhP31	Strut shape	(circle)/(1)	(square)/(2)	(square)/(2)	(circle)/(3)	(Square)/(3)	YES
PhP32	Type of base material	(ABS)/(3)	(PLA)/(3)	(PLA)/(3)	(ABS)/(3)	(ABS)/(3)	YES

Appendix C: Detailed analysis results of Design of Experiments (DoE) for energy absorber case study

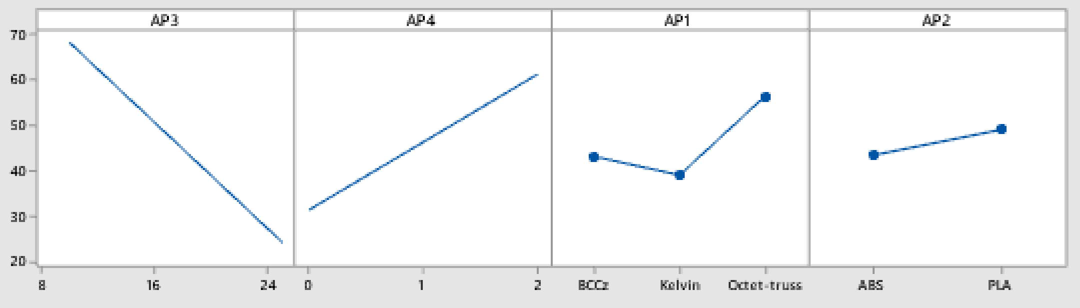
<table>
<tr><th></th><th>AP3</th><th>AP4</th><th>AP1</th><th>AP2</th></tr>
<tr><td rowspan="2">EP1</td><td colspan="4">
</td></tr>
<tr><td colspan="4">
<table>
<tr><th>AP1</th><th>AP2</th><th>Equation model of EP1</th><th>R^2 (%)</th></tr>
<tr><td>BCCz</td><td>ABS</td><td>EP1 = 15.88 - 0.6111 AP3 + 0.906 AP4</td><td rowspan="6">96.75</td></tr>
<tr><td>Kelvin</td><td>ABS</td><td>EP1 = 20.90 - 0.8210 AP3 + 0.722 AP4</td></tr>
<tr><td>Octet-truss</td><td>ABS</td><td>EP1 = 21.75 - 0.8931 AP3 + 3.738 AP4</td></tr>
<tr><td>BCCz</td><td>PLA</td><td>EP1 = 8.91 - 0.3468 AP3 + 0.906 AP4</td></tr>
<tr><td>Kelvin</td><td>PLA</td><td>EP1 = 13.93 - 0.5566 AP3 + 0.722 AP4</td></tr>
<tr><td>Octet-truss</td><td>PLA</td><td>EP1 = 14.78 - 0.6287 AP3 + 3.738 AP4</td></tr>
</table>
</td></tr>
<tr><td rowspan="2">EP2</td><td colspan="4">
</td></tr>
<tr><td colspan="4">
<table>
<tr><th>AP1</th><th>AP2</th><th>Equation model of EP2</th><th>R^2 (%)</th></tr>
<tr><td>BCCz</td><td>ABS</td><td>EP2 = 310.0 - 11.26 AP3</td><td rowspan="6">91.27</td></tr>
<tr><td>Kelvin</td><td>ABS</td><td>EP2 = 338.6 - 12.95 AP3</td></tr>
<tr><td>Octet-truss</td><td>ABS</td><td>EP2 = 590.2 - 21.56 AP3</td></tr>
<tr><td>BCCz</td><td>PLA</td><td>EP2 = 122.3 - 4.18 AP3</td></tr>
<tr><td>Kelvin</td><td>PLA</td><td>EP2 = 150.9 - 5.86 AP3</td></tr>
<tr><td>Octet-truss</td><td>PLA</td><td>EP2 = 402.5 - 14.48 AP3</td></tr>
</table>
</td></tr>
<tr><td rowspan="2">EP3</td><td colspan="4">
</td></tr>
<tr><td colspan="4">
<table>
<tr><th>AP1</th><th>Equation model of EP3</th><th>R^2 (%)</th></tr>
<tr><td>BCCz</td><td>EP3 = 0.5773 + 0.00667 AP3</td><td rowspan="3">60.29</td></tr>
<tr><td>Kelvin</td><td>EP3 = 0.6767 + 0.00093 AP3</td></tr>
<tr><td>Octet-truss</td><td>EP3 = 0.5333 + 0.00587 AP3</td></tr>
</table>
</td></tr>
</table>

EP4



AP1	AP2	Equation model of EP4	R² (%)
BCCz	ABS	EP2 = 31.45 - 1.153 AP3 + 11.51 AP4 - 0.380 AP3*AP4	97.67
Kelvin	ABS	EP2 = 47.58 - 1.833 AP3 + 9.82 AP4 - 0.380 AP3*AP4	
Octet-truss	ABS	EP2 = 61.71 - 2.502 AP3 + 17.43 AP4 - 0.380 AP3*AP4	
BCCz	PLA	EP2 = 19.30 - 0.686 AP3 + 11.51 AP4 - 0.380 AP3*AP4	
Kelvin	PLA	EP2 = 35.44 - 1.366 AP3 + 9.82 AP4 - 0.380 AP3*AP4	
Octet-truss	PLA	EP2 = 49.56 - 2.035 AP3 + 17.43 AP4 - 0.380 AP3*AP4	

EP5

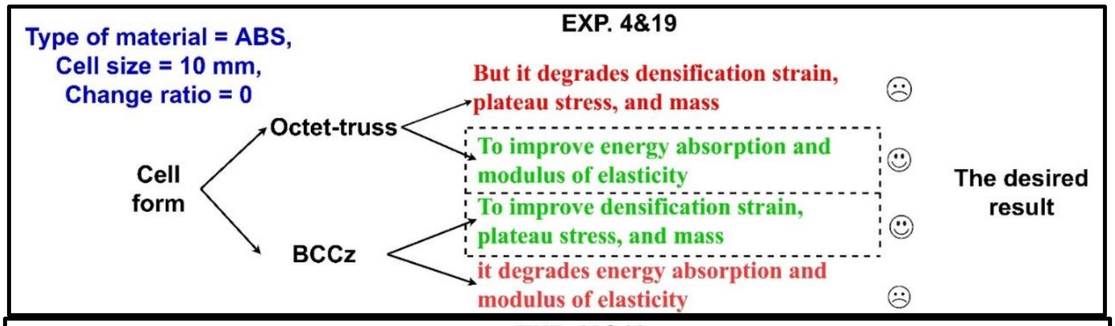
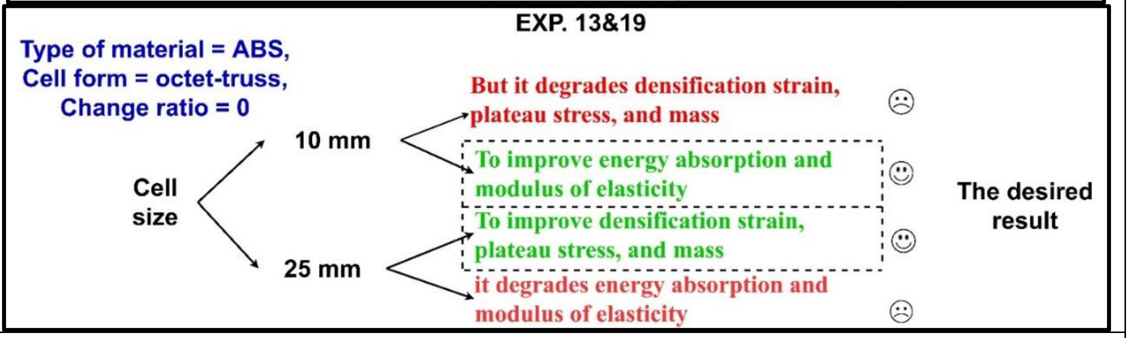
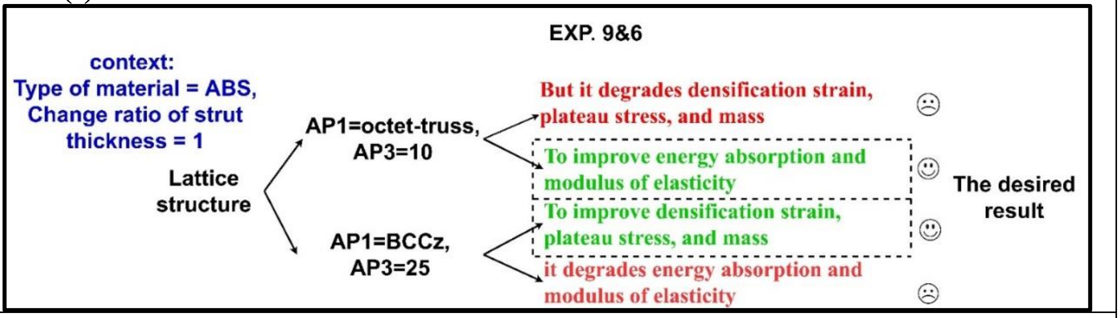


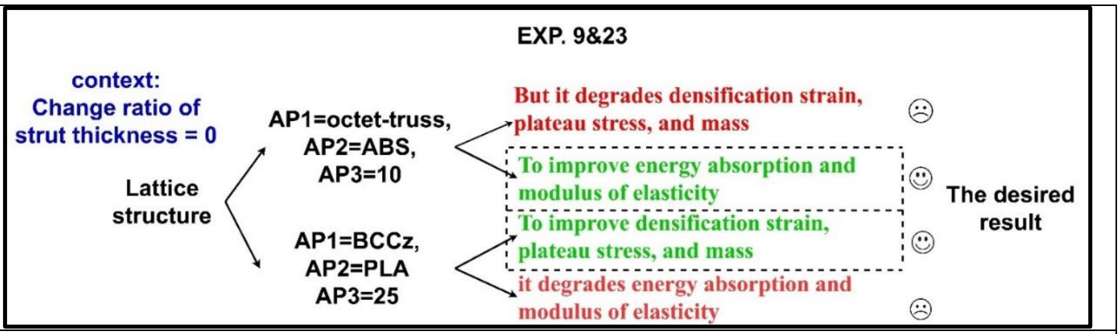
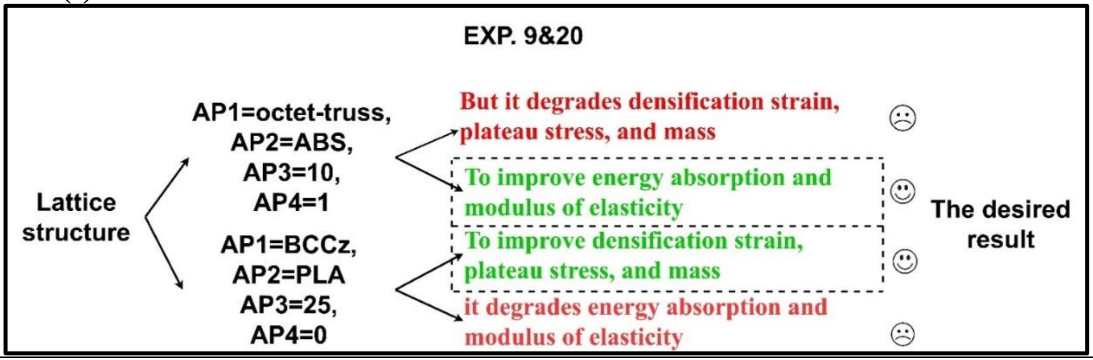
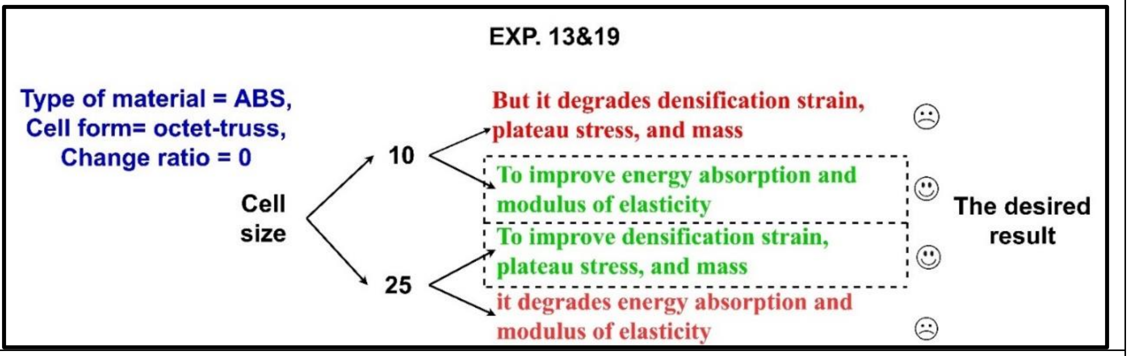
AP1	AP2	Equation model of EP5	R² (%)
BCCz	ABS	EP2 = 66.40 - 2.339 AP3 + 25.54 AP4 - 0.608 AP3*AP4	97.01
Kelvin	ABS	EP2 = 50.96 - 1.691 AP3 + 25.54 AP4 - 0.608 AP3*AP4	
Octet-truss	ABS	EP2 = 89.91 - 2.919 AP3 + 25.54 AP4 - 0.608 AP3*AP4	
BCCz	PLA	EP2 = 72.06 - 2.339 AP3 + 25.54 AP4 - 0.608 AP3*AP4	
Kelvin	PLA	EP2 = 56.62 - 1.691 AP3 + 25.54 AP4 - 0.608 AP3*AP4	
Octet-truss	PLA	EP2 = 95.57 - 2.919 AP3 + 25.54 AP4 - 0.608 AP3*AP4	

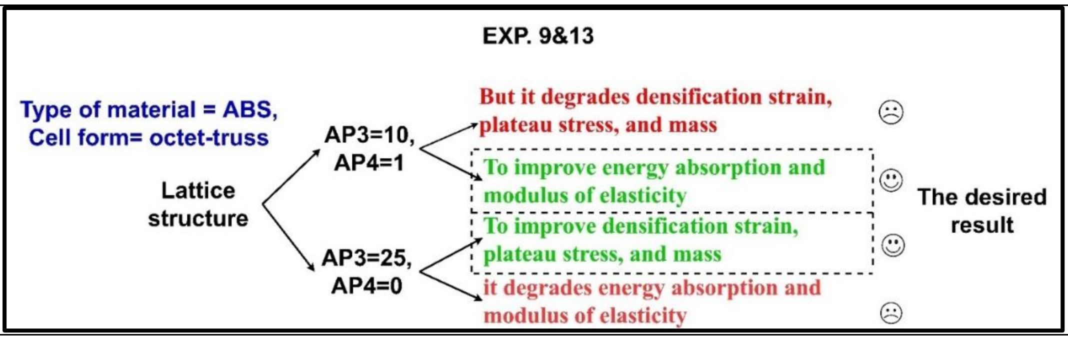
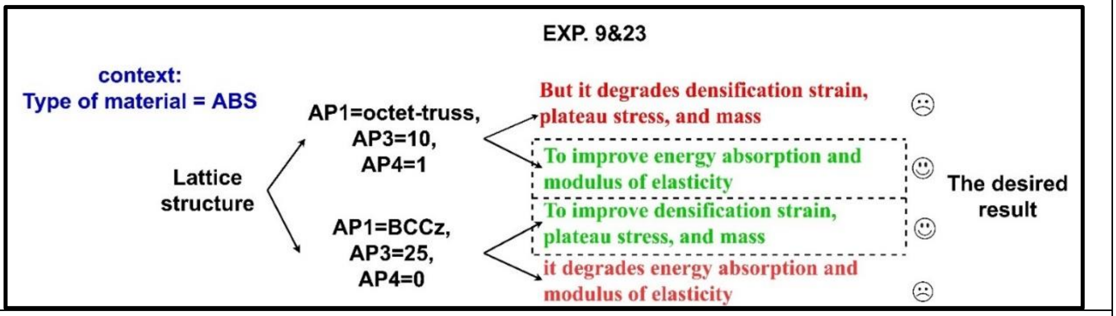
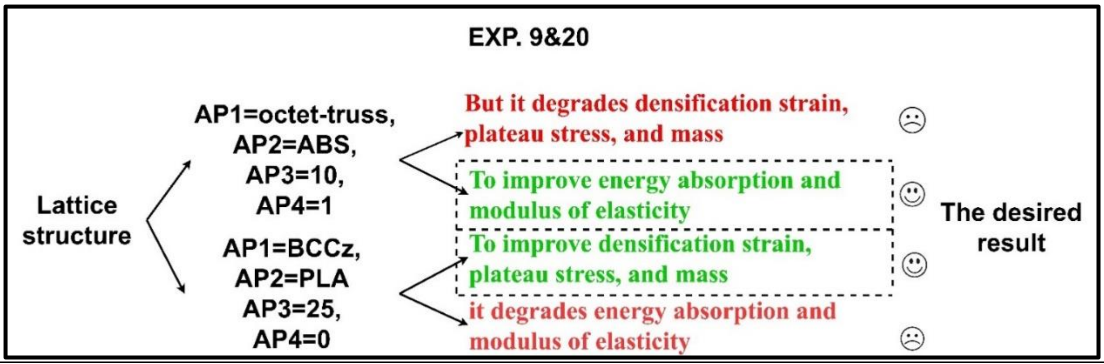
Appendix D: The extracted Generalized System of Contradictions (GSCs) at global and individual threshold values (for 1st and 2nd design loops)

The GSCs interest us are the contradictions appear at specific binarization threshold values. Hence, the next table will illustrate a conclusion of the extracted GSCs at different threshold values under different varied APs (from one to four), as indicated in Table 45.

Table 45 : The first generalized systems of contradictions found at different threshold values and under the change of different APs (1st design loop)

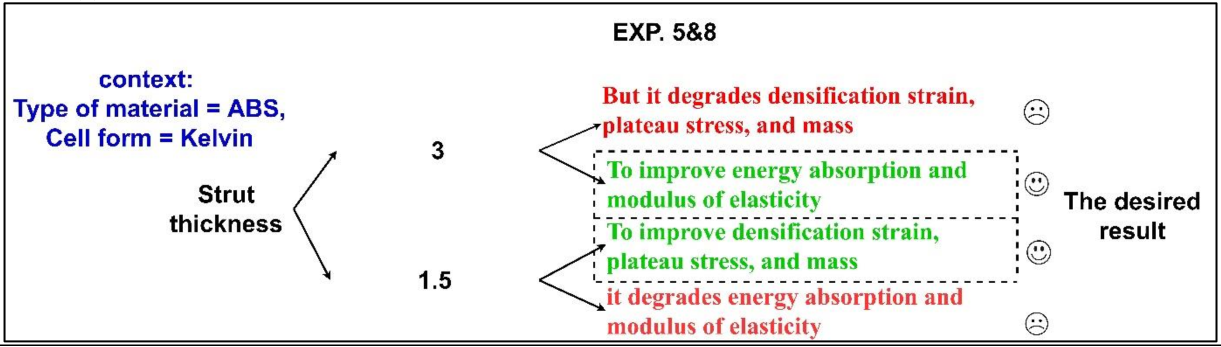
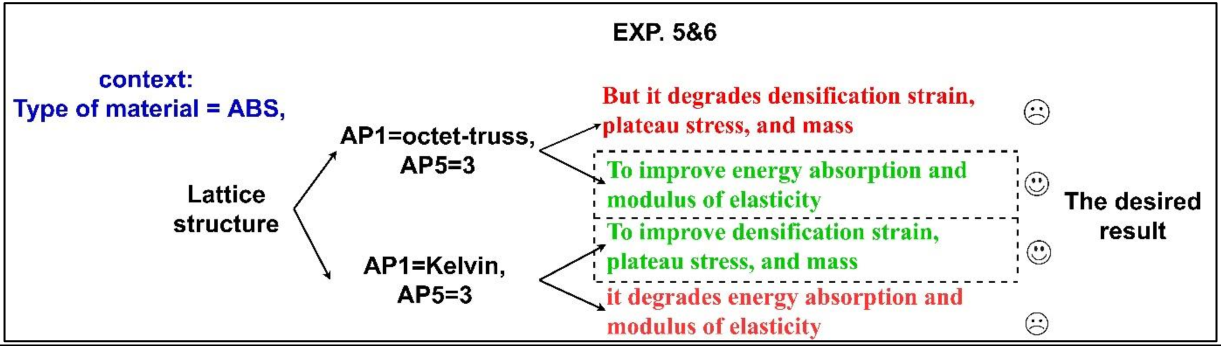
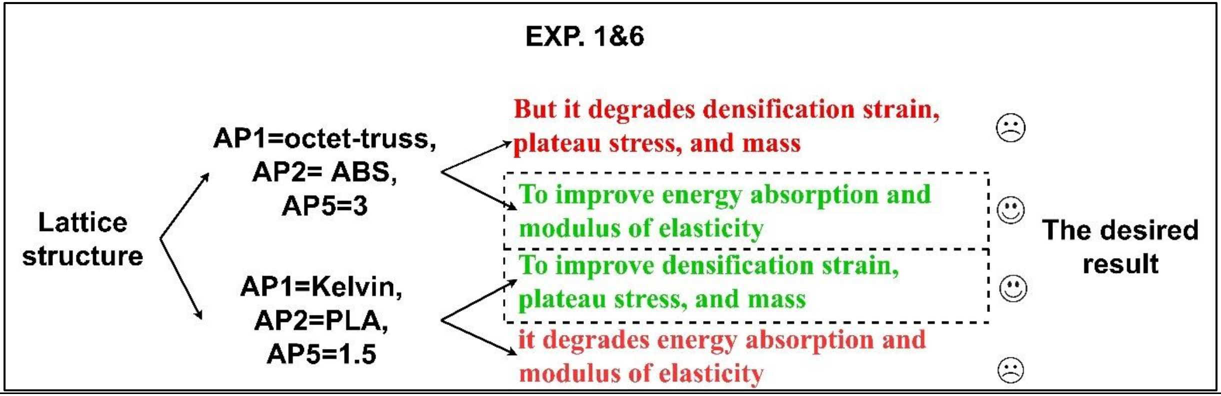
No. of varied APs	First appeared contradiction(s)
1	Type of Threshold: Global Value(s) of Threshold: EP1=EP2=EP3=EP4=EP5= 0%-38%  
2	Type of Threshold: Global Value(s) of Threshold: EP1=EP2=EP3=EP4=EP5= 0%-16% 
3	Type of Threshold: Global Value(s) of Threshold: EP1=EP2=EP3=EP4=EP5= 0%-14%

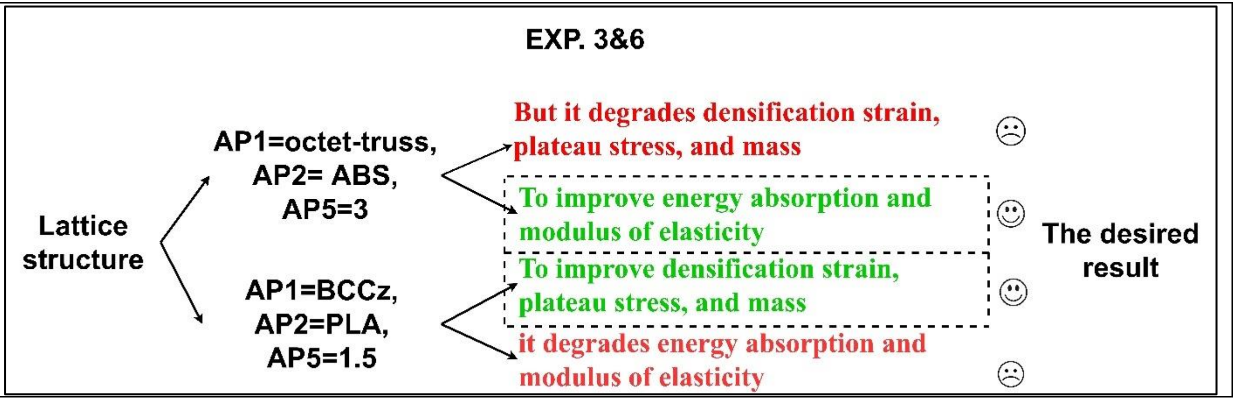
	
4	Type of Threshold: Global Value(s) of Threshold: EP1=EP2=EP3=EP4=EP5= 0%-8% 
1	Type of Threshold: Individual Value(s) of Threshold: EP1= 0%-41% EP2= 0%-32% EP3= 0%-38% EP4= 0%-28% EP5= 0%-40% 
2	Type of Threshold: Individual Value(s) of Threshold: EP1= 0%-36% EP2= 0%-28% EP3= 0%-33% EP4= 0%-25% EP5= 0%-32%

	
3	Type of Threshold: Individual Value(s) of Threshold: EP1= 0%-0% EP2= 0%-0% EP3= 0%-0.42% EP4= 0%-0.018% EP5= 0%-0.02% 
4	Type of Threshold: Individual Value(s) of Threshold: EP1= 0%-0% EP2= 0%-0% EP3= 0%-0.087% EP4= 0%-0.02% EP5= 0%-0.02% 

Concerning the second design loop, the GSCs interest us are the first conflicts appear at specific threshold values. Hence, the next table will illustrate a conclusion of the extracted GSCs at different threshold values under different varied APs (from one to four), as indicated in Table 46.

Table 46 : The first generalized systems of contradictions found at different threshold values and under the change of different APs (2nd design loop)

No. of varied APs	First appeared contradiction(s)
1	Type of Threshold: Global Value(s) of Threshold: EP1=EP2=EP3=EP4=EP5= 0%-25% 
2	Type of Threshold: Global Value(s) of Threshold: EP1=EP2=EP3=EP4=EP5= 0%-6% 
3	Type of Threshold: Global Value(s) of Threshold: EP1=EP2=EP3=EP4=EP5= 0%-6% 

	 EXP. 3&6 Lattice structure AP1=octet-truss, AP2= ABS, AP5=3 AP1=BCCz, AP2=PLA, AP5=1.5 But it degrades densification strain, plateau stress, and mass To improve energy absorption and modulus of elasticity To improve densification strain, plateau stress, and mass it degrades energy absorption and modulus of elasticity The desired result

Appendix E: Journals and conferences contributions

- Published journal articles

Mohamed ABDELLATIF, Hicham CHIBANE, Sébastien DUBOIS, Roland DE GUIO, Thierry ROLAND. " Method to Build a Generalized Table of Parameters linked to a Contextual Database: Lattice Structure as a Case Study." (Accepted under publication for the journal FME transactions, Volume 51, No 4)

- Conferences

Mohamed ABDELLATIF, Hicham CHIBANE, Sébastien DUBOIS, and Roland DE GUIO. "Integrating Design of Experiments (DoE) with Contextual Database (CDB) to Solve Inventive Problems. Application on Lattice structures", Accepted for Congrès des Jeunes Chercheurs en Mécanique – MECA-J, 2023 (28-30 August 2023)

Marwa Ben Moallem, Remy Houssin, Amadou Coulibaly, Mohamed Haykel Ammar, Diala Dhouib and **Mohamed ABDELLATIF**. "Incorporating TRIZ Methodology into Semi-Structured Interviews for Innovative Insights", Accepted for World Conference TRIZ Future 2023 - 12.-14. September 2023 – Germany

Mohamed ABDELLATIF, Hicham CHIBANE, Sébastien DUBOIS, and Roland DE GUIO. "Contribution to cross-fertilization of optimization and invention for solving complex problems. Application on Lattice structures", journée de mécanique, ICube, Strasbourg, 2022

- Submitted journal articles

Hanifi Masih, Hicham Chibane, Remy Houssin, Denis Cavallucci, and **Mohamed ABDELLATIF**. "Prioritizing the initial problem choice in the inventive design process: Proposal of an FMEA-AHP-based method." (Under a submission for the International Journal on Interactive Design and Manufacturing (IJIDeM))

Résumé en français

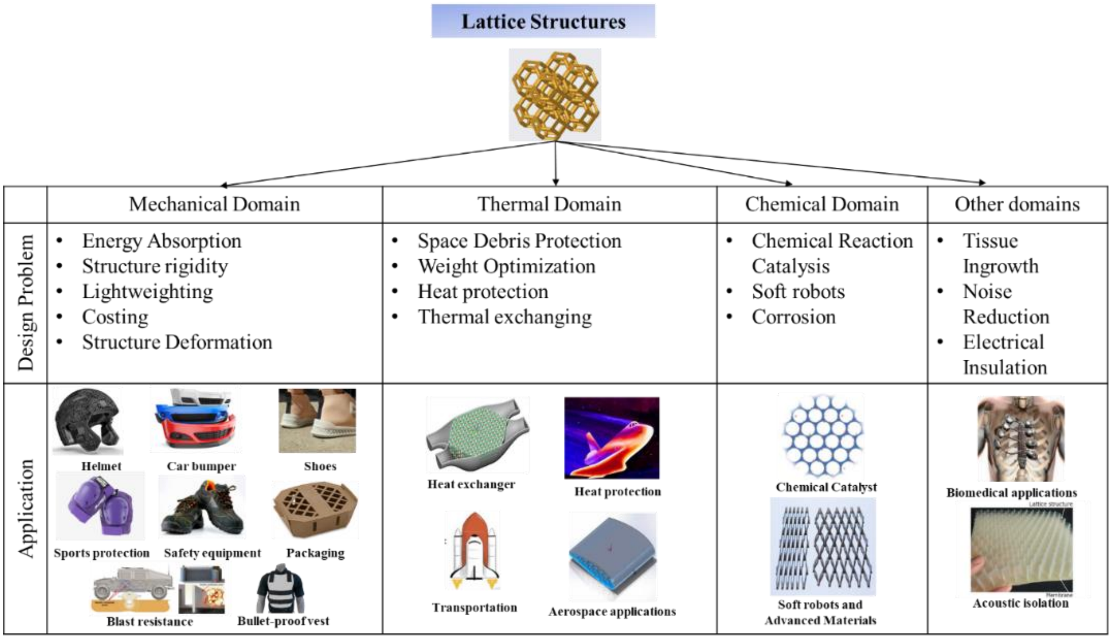
Contributions aux méthodes de conception inventive de systèmes à base de structures lattice

1. Introduction et contexte

Les recherches présentées dans cette thèse se déroulent au sein du laboratoire ICube (Laboratoire des sciences de l'ingénieur, de l'informatique et de l'imagerie), plus précisément au sein de l'équipe CSIP (Conception, Système d'Information et Processus Inventifs). L'équipe CSIP se consacre à la formalisation de l'activité d'invention à travers l'application de méthodes basées sur TRIZ dans la conception de produits/systèmes, en intégrant les perspectives des sciences de l'ingénieur et de l'information. Le financement de ce projet provient de l'école doctorale ED269 Mathématiques, Sciences de l'Information et de l'Ingénieur (MSII).

Au fil des décennies, le monde industriel connaît une évolution caractérisée par des avancées technologiques rapides, une concurrence accrue et des attentes croissantes des consommateurs. Cette évolution souligne la nécessité de disposer de méthodes de conception de produits efficaces pour relever les défis de plus en plus complexes auxquels sont confrontées les entreprises industrielles. Il est donc crucial de disposer de méthodes efficaces pour analyser, comprendre et résoudre systématiquement ces problèmes afin de garantir la création de produits répondant aux besoins et aux exigences de l'industrie. Ces méthodes permettent de gagner du temps en identifiant rapidement les problèmes, en trouvant des solutions appropriées et en évitant des erreurs de conception coûteuses.

Dans cette thèse, nous explorons l'utilisation de méthodes de conception inventive pour résoudre une famille de problèmes de conception liés à des systèmes basés sur des structures lattice. Pour illustrer le problème pratique de cette recherche, prenons un exemple. Supposons que nous voulions produire une semelle de chaussure de sport avec une caractéristique telle que l'absorption de chocs ou le refroidissement, un casque de vélo avec une caractéristique telle que l'absorption de chocs et la rigidité, et un isolant acoustique avec une caractéristique telle que la réflexion des ondes sonores à partir de structures lattice. Les propriétés attendues des structures lattice ne sont pas les mêmes pour chacun de ces objets. La semelle est censée absorber l'énergie et assurer le refroidissement thermique ; le casque est censé absorber l'énergie et assurer la rigidité ; et l'isolant est censé absorber ou réfléchir les ondes sonores (voir d'autres exemples à l’illustration 1). Ces trois exemples partagent le même objectif de trouver des moyens de réaliser ces propriétés à l'aide de systèmes de structures lattice, mais les problèmes liés à la recherche de ces solutions peuvent être très différents. Le processus de résolution peut exploiter des ressources communes aux trois problèmes. L'une de nos questions est de savoir comment capitaliser les connaissances et les mettre à la disposition des concepteurs de la manière la plus opérationnelle possible.



	Mechanical Domain	Thermal Domain	Chemical Domain	Other domains
Design Problem	• Energy Absorption • Structure rigidity • Lightweighting • Costing • Structure Deformation	• Space Debris Protection • Weight Optimization • Heat protection • Thermal exchanging	• Chemical Reaction Catalysis • Soft robots • Corrosion	• Tissue Ingrowth • Noise Reduction • Electrical Insulation
Application	Helmet Car bumper Shoes Sports protection Safety equipment Packaging Blast resistance Bullet-proof vest	Heat exchanger Heat protection Transportation Aerospace applications	Chemical Catalyst Soft robots and Advanced Materials	Biomedical applications Acoustic isolation

Illustration 1: Différents problèmes relevant de différents domaines liés à un système de structure lattice

Il est évident que la résolution de problèmes est importante. Les méthodes de résolution de problèmes (MRP) peuvent être classées en deux catégories : les méthodes routinières et les méthodes inventives. Les méthodes de résolution de problèmes routinières se concentrent principalement sur l'analyse des causes profondes d'un problème et sur l'application de solutions connues et standardisées, tandis que les méthodes de résolution de problèmes inventives encouragent l'invention en utilisant des principes et des modèles pour générer des idées nouvelles et originales. Il est important de noter que ces catégories ne s'excluent pas mutuellement et peuvent être combinées selon les besoins. Parfois, une approche routinière peut être utilisée pour résoudre une partie d'un problème, tandis qu'une approche inventive peut être appliquée pour traiter une autre partie plus complexe ou stimuler la créativité. Dans cette thèse, la conception est abordée sous l'angle des méthodes inventives de résolution des problèmes et des améliorations possibles de ces méthodes. Le défi consiste à proposer des solutions pour des problèmes complexes interconnectés pouvant relever de différents domaines. Un autre défi est de proposer des solutions génériques pouvant être adaptées en fonction de l'étude de cas traitée.

La MRP inventive vise à stimuler la créativité en utilisant des principes, des modèles et des techniques spécifiques pour résoudre des problèmes de conception. Une famille bien connue de méthodes largement utilisées dans la communauté scientifique et industrielle provient de la TRIZ (Théorie de la résolution des problèmes d'invention). Il s'agit d'un ensemble de méthodes organisées pour trouver des solutions créatives et inventives aux problèmes de conception. La TRIZ encourage la pensée créative, l'analyse approfondie des contradictions (conflits) et l'utilisation des principes de solutions existantes comme source d'inspiration pour résoudre les problèmes. Dans le cadre de l'amélioration et de la systématisation de la conception inventive, plusieurs développements ont été réalisés au laboratoire ICube ces dernières années. Les approches les plus avancées [1]-[3] intègrent les étapes suivantes : Analyse de la situation initiale, modélisation du système, optimisation, extraction des contradictions et, enfin, résolution du problème.

Analyse de la situation initiale (AIS) : Cette première étape consiste à analyser la situation initiale en détail et à comprendre clairement le problème ou le défi de la conception. Elle inclut l'identification des objectifs, des contraintes, des exigences et des aspects critiques liés au problème.

Modélisation du système : Une fois la situation initiale analysée, l'étape suivante consiste à modéliser le système de manière structurée en spécifiant ses paramètres et leurs relations en vue de l'application de méthodes d'optimisation ou de conception inventive. Cela peut impliquer la création de diagrammes, de graphiques ou de représentations visuelles pour comprendre les composants, les interactions et les dépendances du système ou du processus en question.

Optimisation : Après avoir modélisé le problème, l'étape suivante consiste à vérifier si une solution standard peut être trouvée. Une solution est considérée comme standard si elle se situe dans le domaine défini par l'ensemble des paramètres modélisant le système, sans remettre en cause les relations entre ces paramètres ni ajouter un nouveau paramètre ou une nouvelle relation. Les approches d'optimisation explorent l'espace des solutions défini par ces relations. Si aucune solution standard satisfaisante n'est trouvée, ou si de meilleures solutions sont recherchées, une approche inventive de la résolution du problème est nécessaire, en identifiant d'abord les contradictions qui doivent être résolues pour atteindre les objectifs de conception.

Extraction des contradictions : Au cours du processus actuel d'optimisation, des contradictions d'objectifs peuvent apparaître, c'est-à-dire des situations dans lesquelles l'amélioration d'un aspect entraîne la détérioration d'un autre aspect. L'extraction des contradictions consiste à identifier ces objectifs contradictoires et leurs causes, qui peuvent également être exprimées sous la forme de valeurs contradictoires des paramètres de conception du système. Ces contradictions constituent le problème inventif à résoudre.

Résolution du problème : Une fois les contradictions identifiées, diverses méthodes et outils peuvent être utilisés pour résoudre le problème, tels que l'application de principes et de modèles inventifs de résolution de problèmes, l'utilisation de principes de séparation ou l'exploration de solutions existantes dans d'autres domaines ayant traité des contradictions généralisées similaires.

Toutes ces étapes sont intégrées dans le processus de conception illustré à l’illustration 2, où les rectangles noirs représentent les principales phases de la méthode et les cases bleues les activités de conception prévues, les moyens pour les activités et les résultats de chaque phase.

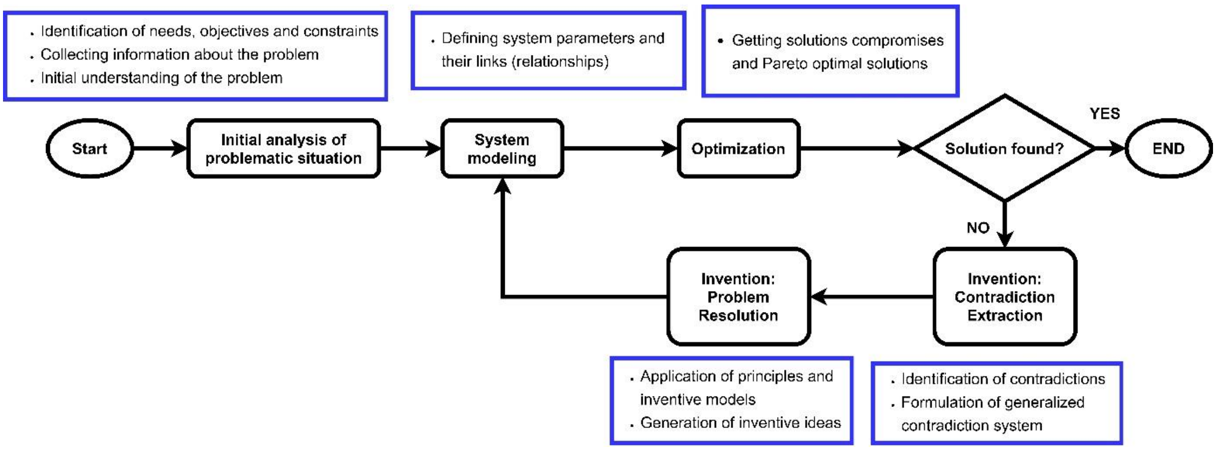


Illustration 2: Le processus de conception itérative.

2. Problème(s) initial(aux)

Chaque étape de la (méta) méthode décrite dans l'illustration 2 est réalisée à l'aide d'outils et de méthodes spécifiques qui permettent ou facilitent leur mise en œuvre. Les outils disponibles sont divers ; le choix des outils dépend des conditions préalables de l'utilisateur et, dans une certaine mesure, du problème traité. Dans cette thèse, l'approche mentionnée ci-dessus est mise en œuvre sur des problèmes liés à la conception de produits ou de matériaux basés sur des structures lattice, en utilisant largement les outils de simulation, d'optimisation et d'identification des contradictions à partir des données disponibles.

Dans ce contexte, l'une des phases considérées comme insuffisamment développées est l'analyse initiale de la situation. Il s'agit peut-être de la phase la moins formalisée du processus de résolution des problèmes, reposant sur la collecte d'informations auprès d'experts. Cette collecte d'informations peut révéler des incohérences entre les opinions des experts et peut se heurter à des difficultés liées à la disponibilité des experts. L'objectif de cette thèse est donc de répondre à la question suivante :

« Comment aborder la résolution de problèmes complexes en analysant la situation initiale par rapport aux objectifs à atteindre, en identifiant et résolvant les contradictions prioritaires, tout en minimisant la dépendance à l'égard des experts et en utilisant les données disponibles ? »

3. Méthodologie de Recherche

Après avoir mis en évidence les problèmes initiaux de la recherche, la méthodologie de recherche suivie pour mener à bien ce travail de recherche se compose de cinq étapes :

1. Explorer des approches et méthodes existantes dans le domaine de la résolution des problèmes de conception afin de comprendre comment ces problèmes initiaux ont été traités par d'autres travaux de recherche et quelles sont les limites de ces contributions.

2. Préciser les questions de recherche auxquelles le processus de recherche doit répondre entièrement ou partiellement.
3. Proposer des approches et des méthodes pour combler les lacunes de la recherche constatées. Cette étape était censée être accomplie en exploitant les ressources disponibles telles que les bases de données scientifiques, les commentaires des experts, les approches expérimentales, qualitatives et numériques.
4. Illustrer les points forts et les limites des méthodes proposées lors de la troisième étape.
5. Proposer et développer un nouveau produit de structures lattice.

Étant donné que la structure lattice joue un rôle essentiel dans cette thèse en tant que ressource pour illustrer la ou les méthodes proposées, il est important de présenter clairement différents aspects et faits concernant les problèmes de la structure lattice, les définitions, les matériaux utilisés et les travaux de recherche connexes. Ces aspects sont abordés dans la section suivante.

4. La conception de Structure lattice

Les structures lattice ont trouvé des applications diverses, couvrant des domaines tels que l'aérospatiale, l'automobile, la biomécanique, etc. Leurs propriétés prometteuses, notamment l'absorption d'énergie, des rapports poids/résistance élevés et des capacités de gestion thermique, en font des candidats privilégiés pour des applications variées. La recherche développée dans ce mémoire se concentre sur la fabrication d'absorbeurs d'énergie mécaniques basés sur des lattices, abordant les défis liés à l'absorption d'énergie, aux propriétés mécaniques et à l'optimisation.

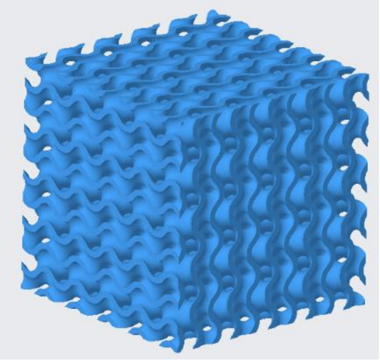


Illustration 3: Structure lattice (le type de cellule est Gyroid)

4.1. Fabrication additive et structures lattices

Les structures lattices sont largement produites grâce à la technologie de fabrication additive. Dans ce contexte, le processus de fabrication additive joue un rôle crucial, illustrant comment les structures sont conçues couche par couche à l'aide d'un logiciel de CAO et imprimées par un processus informatisé. Les avantages de la fabrication additive, tels que l'efficacité énergétique, la flexibilité de la conception et la personnalisation, sont mis en avant. Le choix des matériaux polymères pour la fabrication additive est également abordé, mettant l'accent sur leur adéquation aux applications envisagées.

4.2. Classification des structures lattice et optimisation

L'étude examine différents types de structures lattice, classées en fonction de leur géométrie, telles que les structures basées sur des éléments de renfort, sur des squelettes, sur des surfaces et sur des coques. Ces structures s'appuient respectivement sur les surfaces minimales triplement périodiques, également appelées Triply Periodic Minimal Surface (TPMS) en anglais. L'optimisation et la conception inventive des structures lattice sont explorées, mettant en lumière les contributions intégrant les méthodes TRIZ, l'apprentissage automatique et l'optimisation multi-objectifs pour améliorer la résistance aux chocs, l'absorption d'énergie et les propriétés mécaniques.

4.3. Conclusions et contributions de la recherche

En conclusion, la recherche vise à systématiser le processus de conception inventive dans un contexte large, proposant une méthode applicable à de multiples problèmes dans le même domaine. L'étude de cas sur le comportement mécanique des structures lattice souligne son intérêt méthodologique et sa demande industrielle. L'approche originale de l'étude se concentre sur la résolution de problèmes centraux complexes à l'aide de méthodes basées sur TRIZ, se distinguant ainsi des travaux antérieurs qui ont pu négliger certaines contradictions et limitations. Dans l'ensemble, la thèse contribue à faire progresser la compréhension et l'application des structures lattices dans la résolution de problèmes d'ingénierie à multiples facettes.

5. Structure de la thèse et des résultats

Cette thèse est structurée en six chapitres :

Chapitre 1 "Introduction Générale": Ce chapitre introduit le contexte global dans lequel cette recherche est réalisée, en soulignant que l'objectif global de cette recherche est de systématiser les processus de conception inventive dans un cadre étendu. L'étude de cas choisie, "comportement mécanique des structures en lattice", sert d'illustration pratique de l'application de cette méthode. Le chapitre justifie ce choix, évoquant à la fois l'intérêt méthodologique et la demande industrielle pressante pour les structures en lattice, mettant en avant leur potentiel pour résoudre divers problèmes. Dans le contexte plus large de la résolution inventive de problèmes, le chapitre souligne l'importance de traiter des problèmes interconnectés dans des domaines divers. Il introduit la classification des Méthodes de Résolution de Problèmes (PSM), plaidant en faveur de l'adoption des PSM inventives, en particulier TRIZ, pour naviguer à travers des problèmes complexes et interconnectés. La méthode proposée, intégrant l'Analyse de la Situation Initiale, la Modélisation du Système, l'Optimisation, l'Extraction des Contradictions et la Résolution des Problèmes, offre une approche complète et itérative de la conception. Le segment introductif pose le cadre de la thèse en définissant le contexte de la recherche, exposant les défis liés à la conception de structures en lattice et introduisant l'approche inventive de résolution de problèmes ancrée dans les principes de TRIZ.

Chapitre 2 "État de l'art des méthodes existantes de résolution de problèmes et de conception" : Ce chapitre examine les méthodes traditionnelles et inventives de conception de produits et de résolution de problèmes présentes dans la littérature scientifique. Il met l'accent sur les caractéristiques de chaque approche, leurs avantages et leurs limites. Cette revue de la littérature permet de situer la contribution de la thèse dans le domaine de la conception inventive. Le chapitre souligne également le problème de recherche présenté au chapitre 1, centré sur le développement d'outils et de méthodologies visant à améliorer les pratiques existantes en matière de conception inventive. Les objectifs principaux comprennent l'évaluation des méthodes existantes de résolution des problèmes de conception, l'évaluation de leur efficacité dans la modélisation des paramètres du système de conception, et l'examen minutieux de la manière dont ces méthodes prennent en compte les relations et les influences complexes entre les paramètres de conception.

En partant du processus de la boucle de conception illustré dans l’illustration 2, les méthodes recherchées sont étudiées pour comprendre dans quelle mesure elles répondent à la question initiale, posée dans la section 1.1. Les méthodes présentées sont discutées à la lumière de la question initiale et l'état de l'art est réalisé sur la base de la question : Quelle approche adopter pour résoudre des problèmes complexes, sur la base de l'analyse de la situation initiale en fonction des objectifs à atteindre et de l'extraction, de la résolution des contradictions prioritaires, sans trop s'appuyer sur des experts et en utilisant les données disponibles ?

Malgré les approches et les méthodes existantes dans la résolution de problèmes de conception inventive itérative, l'état de l'art révèle que le processus de conception inventive itérative (boucle de conception) souffre encore de certaines limitations et de certains inconvénients à travers les différentes étapes. Cette synthèse permet d'affiner la question initiale et de formuler un ensemble de problèmes de recherche à traiter dans le cadre de cette thèse. Les problèmes de recherche de cette thèse peuvent être résumés en quatre problèmes principaux :

Q1 : Comment un processus systématique de conception inventive a-t-il pu être adapté pour résoudre des problèmes dans un contexte général élargi avec divers domaines d'application potentiels ?

Q2 : Sur la base du modèle construit, des informations et des données collectées, comment extraire le problème le plus prioritaire à résoudre ?

Q3 : Comment les expériences ont-elles pu être utilisées pour mieux comprendre le comportement du système afin de le faire évoluer vers l'idéalité ?

Q4 : Comment simplifier le processus de changement de modèle, en particulier pour résoudre les contradictions généralisées, et le rendre plus réalisable dans le cadre du processus de résolution des problèmes de conception inventive ?

Le traitement de ces problèmes de recherche, en tout ou en partie, est détaillé dans les chapitres suivants. Les travaux futurs ou les problèmes traités partiellement sont expliqués dans le dernier chapitre.

Chapitre 3 "Tableau généralisé des paramètres (TGP)" : Ce chapitre détaille la méthode proposée pour créer le (TGP), comme le montre le tableau I. Il explique comment le tableau des paramètres est obtenu en rassemblant diverses informations pertinentes sur le problème de conception. Les différentes étapes de la création du TGP, y compris la collecte d'informations auprès d'experts et l'inclusion d'une bibliographie spécifique au domaine, sont décrites en détail. Le tableau généralisé propose de regrouper les données essentielles relatives au système, y compris les variables physiques, qualitatives, quantitatives et de performance. Cela permet de comprendre les interrelations entre les paramètres et d'améliorer la modélisation du système.

Tableau I: Un tableau indicatif avec un exemple pour illustrer la topologie du tableau généralisé des paramètres (TGP)

Index	→						1	14.94	15	15.1	15.2
↓	Parameter type	→					PhP	PhP	PrP	PrP	PrP
	↓	Source of parameter	→				1,2	2	1,2,3	1,2,3	1,2,3
		↓	Parameter unit	→			No unit	No unit	Joule/mm^3	N/mm^2	No unit
			↓	Parameter family	→		Structure	Cell	Energy	Energy	Energy
				↓	Parameter category	→	Quantitative	Qualitative	Quantitative	Quantitative	Quantitative
					↓	Parameter name	Relative density of lattice structure	Strut shape	Energy absorption per unit volume	Plateau stress	Densification Strain
A	PhP	1,2	No unit	Structure	Quantitative	Relative density of lattice structure		other	1	1	-1
B	PhP	1,3	Millimeter (mm)	Structure	Quantitative	Global dimensions	-1	0	other	other	other
C	PhP	1	No unit	Structure	Qualitative	Shape of structure	0	0	other	X	X

Valeur	Signification

1	(augmenter) lorsqu'un paramètre de la ligne augmente, alors un paramètre de la colonne augmente également
-1	(diminuer) lorsqu'un paramètre de la ligne augmente, alors un paramètre de la colonne diminue
0	(Aucune influence) aucune influence d'un paramètre de la ligne sur un paramètre de la colonne
X	(Aucune information) aucune information rescencée sur la relation entre les deux paramètres
other	Cela signifie un ou plusieurs scénarios : 1. Il y a des informations supplémentaires dans un autre fichier, liées à la cellule contenant (autre). 2. La cellule relie un paramètre qualitatif à un autre paramètre qualitatif ou à un paramètre quantitatif.

Source	Explanation
1	Le paramètre est extrait de S1, qui se compose uniquement de revues de la littérature.
2	Le paramètre est extrait de S2, qui se compose uniquement des opinions d'experts.
3	Le paramètre est extrait de S3, qui provient de l'analyse des logiciels CAD/FEM uniquement.
1,2	Le paramètre est extrait à la fois de S1 et de S2, qui sont des revues de la littérature et des opinions d'experts.
1,3	Le paramètre est extrait à la fois de S1 et de S3, qui sont des revues de la littérature et l'analyse des logiciels CAD/FEM.
2,3	Le paramètre est extrait à la fois de S2 et de S3, qui sont des opinions d'experts et l'analyse des logiciels CAD/FEM.
1,2,3	Le paramètre est extrait de S1, S2 et S3, qui sont des revues de la littérature, des opinions d'experts et l'analyse des logiciels CAD/FEM.
▨	L'intersection entre le paramètre dans une ligne et lui-même dans une colonne.

La base de données contextuelle (BDC) relie les cellules TGP aux informations complémentaires, ce qui rationalise l'extraction des contradictions pour trouver des solutions inventives, comme illustré dans l'illustration 4. L'automatisation par le biais de scripts dans le langage Visual Basic pour les applications (VBA) simplifie ce processus, offrant une ressource complète pour une résolution efficace des problèmes. Cette approche favorise le partage des connaissances et la collaboration, et peut être adaptée à différents domaines, bien que l'accent soit mis ici sur le domaine mécanique.

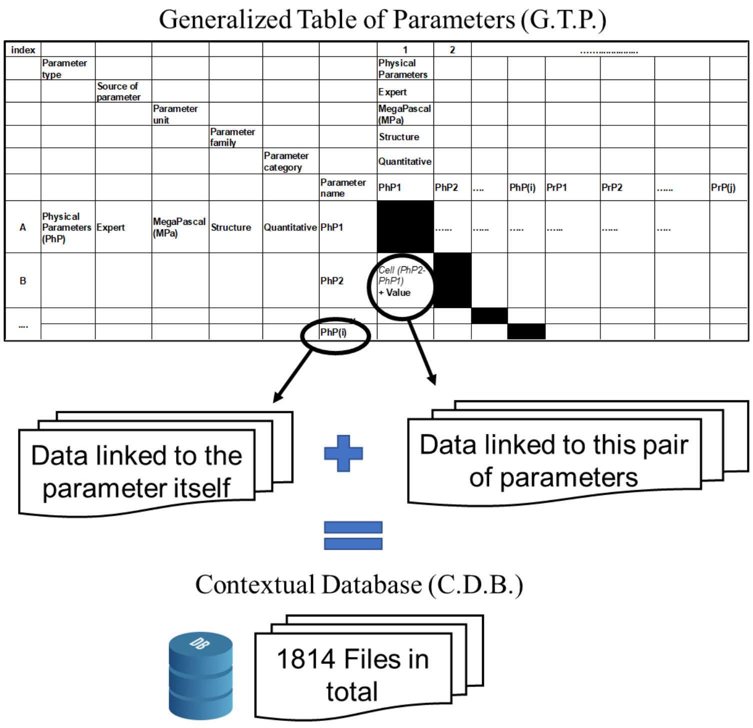


Illustration 4: Le lien entre les fichiers de la BDC et la table TGP

Chapitre 4 "Exploitation du TGP (identification des contradictions)" : S'appuyant sur les résultats du chapitre 3, ce chapitre se concentre sur l'utilisation du TGP dans le processus de résolution de problèmes inventifs. Il explique comment le TGP facilite l'analyse de la situation initiale et la modélisation du système en fournissant un accès rapide et structuré à diverses connaissances. Il explore le modèle du système de contradictions (SoC) dans le cadre de TRIZ. Le chapitre présente une méthode permettant d'extraire et de hiérarchiser non seulement les contradictions classiques de TRIZ, mais aussi les systèmes généralisés de contradictions en utilisant le TGP et la base de données.

Une étude de cas est traitée pour illustrer les forces et les limites de la méthode proposée. Cette étude de cas porte sur la fabrication d'un absorbeur d'énergie dont l'élément central est une structure en lattice. Cette structure doit être très résistante aux chocs, rigide et légère. L'application de la méthode permet d'extraire un SCG prioritaire à résoudre, comme le montre l'illustration 5.

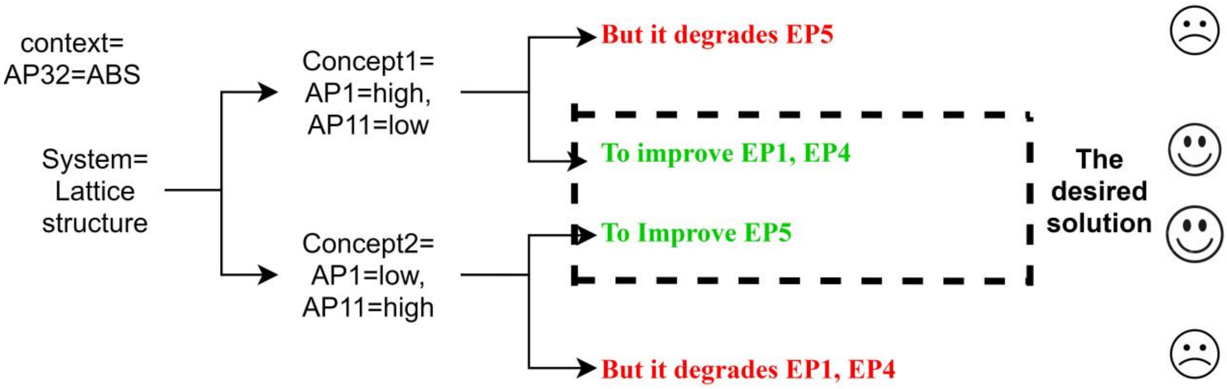


Illustration 5: Le système de contradictions généralisé(SCG)

Ce SCG était vrai dans le contexte d'un matériau de type ABS, indiquant que le système de structures en lattice devait être composé de deux concepts. Le premier concept consistait à avoir des structures en lattice avec une densité relative élevée et une taille de cellule faible pour satisfaire à l'absorption d'énergie et au module d'élasticité. La même structure devait avoir une densité relative faible et une taille de cellule élevée pour fournir une structure légère.

Malgré le potentiel de la méthode proposée, des développements ont été suggérés pour présenter des solutions spécifiques aux problèmes des systèmes techniques dans un contexte particulier en appliquant l'approche expérimentale (basée sur le Plan d'Expériences PdE).

Chapitre 5 "L'invention par les plans d'expérience" : Ce chapitre présente une méthode de conception basée sur le plan d’expériences (PdE) pour résoudre les problèmes de conception lorsque les sources traditionnelles et les avis d'experts sont insuffisants. Ces expériences peuvent être réalisées soit par expérimentation physique, soit en utilisant des modèles et des simulations numériques. Au départ, un plan d'expériences a été planifié en tenant compte des paramètres du système et des mesures de performance souhaitées. Néanmoins, cette étape a encore utilisé le TGP (Tableau Généralisé des Paramètres) (voir chapitre 4) pour mieux sélectionner les paramètres du plan et éviter de négliger certains d'entre eux qui peuvent avoir une influence significative sur le comportement du système.

Inversement, une fois mise en œuvre, cette méthode a également été utilisée pour remplir les cellules vides du TGP, car elle permet de clarifier les relations entre les paramètres du système. La méthode basée sur les plans d'expériences (PdE) vise à définir un ensemble d'expériences à mener en faisant varier les niveaux de paramètres afin de collecter des données sur le comportement du système. Sur la base des résultats obtenus, la modélisation a permis de comprendre les relations entre les paramètres et les performances et d'identifier les contradictions potentielles.

Les contradictions d’objectifs, également appelées "contradictions techniques", peuvent survenir en raison de la nécessité de faire des compromis entre différentes performances recherchées. C'est pourquoi une optimisation multi-objectifs est entreprise pour trouver des solutions se situant sur le front de Pareto, c'est-à-dire des solutions qui représentent les meilleurs compromis entre des objectifs. L'optimisation multi-objectifs cherche à trouver un ensemble de solutions optimales au sens de Pareto plutôt qu'une solution optimale unique, car les objectifs peuvent être contradictoires et ne peuvent pas être optimisés simultanément.

Nous suggérons d'introduire un seuil, également appelé "seuil de binarisation", pour extraire les conflits du système. Ce seuil représente une variation des valeurs des contraintes d'optimisation. Il peut conduire à une simplification du processus d'ajustement du modèle en réduisant le nombre de paramètres physiques pris en compte dans la résolution des contradictions, facilitant ainsi la résolution des problèmes (ou entraînant des changements mineurs dans le modèle initial, permettant des solutions à court terme). L'utilisation du seuil incite également les utilisateurs de la méthode à examiner attentivement les valeurs des contraintes initiales dans le système et à observer l'effet d'une petite variation de ces contraintes sur la résolution finale. Ils peuvent évaluer les impacts sur la complexité du modèle, la faisabilité de la solution, la performance attendue, les coûts, etc.

Ainsi, en assistant les nombreuses étapes de résolution de problèmes suggérées dans cette nouvelle approche, la conception d'expériences peut jouer un rôle essentiel dans le processus de conception inventive. Afin de faciliter la compréhension de cette méthode, la discussion s'appuie progressivement sur un exemple concret utilisant des structures en lattice. Ce chapitre vise à développer une méthodologie basée sur le PdE qui vise à définir un ensemble d'expériences à mener en faisant varier les niveaux de paramètres afin de collecter des données sur le comportement du système. Sur la base des résultats obtenus, la modélisation permet de comprendre les relations entre les paramètres et les performances et d'identifier les contradictions potentielles.

Un exemple spécifique d'application de cette méthode pour résoudre des problèmes de conception liés au comportement mécanique de structures lattice est présenté, afin d'illustrer l'applicabilité de la méthode proposée. Cette méthode est composée de 16 étapes séquentielles qui seront expliquées en détail dans ce chapitre. D'autre part, le PdE réalisé sera analysé à l'aide de plusieurs méthodes telles que le modèle de régression, la méthode des surfaces de réponses (MSR) et l'analyse de la variance (ANOVA). Cette analyse permettra de compléter les informations relatives à la modélisation de la situation problématique dans le tableau généralisé des paramètres (TGP) et de mieux comprendre la situation problématique, ce qui permettra de surmonter certaines limites de la méthode proposée au chapitre 4.

Le logiciel PTC CREO® sera utilisé pour construire des modèles CAO de structures lattices en vue de réaliser des expériences par simulation numérique. Ensuite, le logiciel ABAQUS® sera employé pour effectuer des simulations numériques non linéaires dans le cadre de la partie expérimentale. Le logiciel Minitab® sera utilisé pour deux choses : la première est d'effectuer l'analyse des résultats obtenus par PdE, la seconde est d'appliquer l'algorithme du gradient réduit (RGA) pour une optimisation multi-objectifs. L'algorithme NSGA-II (Non-dominated Sorting Genetic Algorithm) sera également exploité, en utilisant le paquetage Pymoo® basé sur Python. NSGA-II est utilisé pour fournir un ensemble de solutions représentées par le front de Pareto afin de visualiser le compromis entre ces objectifs dans le contexte de l'optimisation d'un système.

À la fin de la méthode proposée, un ensemble de contradictions sera choisi pour être résolu en utilisant des méthodes inventives basées sur TRIZ, c'est-à-dire ici les principes de séparation basés sur TRIZ. Les nouveaux modèles modifiés et les concepts de solution proposés seront testés à l'aide d'une approche numérique, à savoir le logiciel d'éléments finis ABAQUS®. Les nouveaux modèles seront évalués afin d'examiner leurs performances et donc de savoir si les objectifs de conception sont atteints ou non. La séquence de l'approche proposée est illustrée dans l’illustration 6.

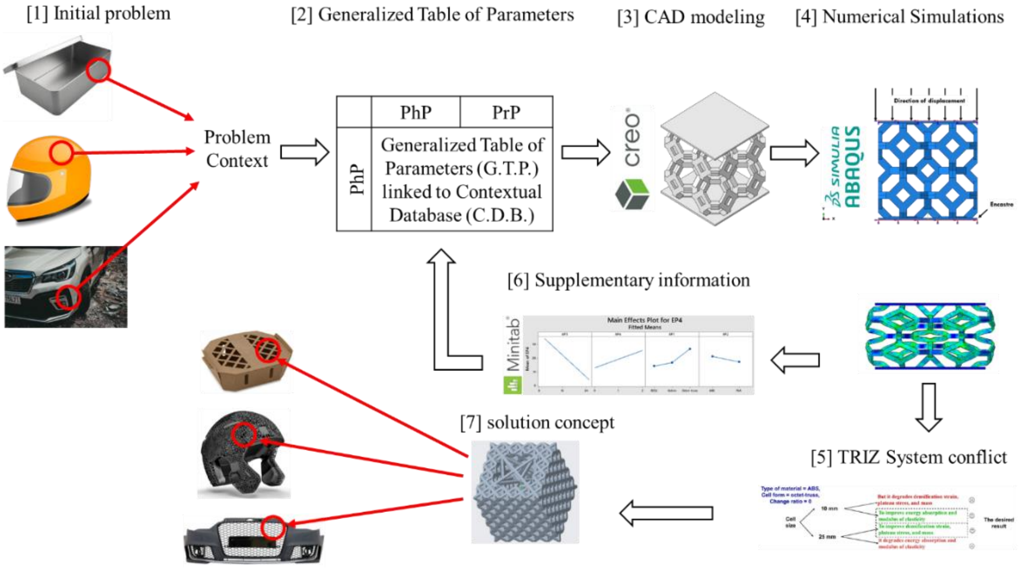


Illustration 6: An illustration of the proposed method to evolve from an existing system to a new developed system

Ce chapitre présente une méthode systématique, illustrée par l'étude du comportement mécanique des structures en lattice. Il démontre comment l'expérimentation, physique ou numérique, aide à comprendre les relations entre les paramètres et les performances, à déceler les contradictions potentielles et à optimiser les solutions. L'incorporation d'un seuil rationalise le processus d'ajustement du modèle et encourage une évaluation réfléchie des contraintes.

La méthode a démontré plusieurs points forts, notamment la sélection efficace des paramètres, les avantages de la détermination des seuils pour mettre en évidence les conflits entre les systèmes, l'intégration des unités SI et des principes TRIZ, et la validation des concepts de solution. Elle a également mis en évidence l'importance de l'application de méthodes d'optimisation pour détecter les solutions de compromis ou essayer de trouver une solution finale au problème de conception.

La méthode proposée est une méthode de conception itérative basée sur la modification continue du modèle jusqu'à l'obtention des résultats idéaux. Deux boucles ont été réalisées, approuvant la force de l'approche des résultats idéaux par la modification minimale du système conçu. Toutefois, des difficultés ont été constatées dans le traitement des paramètres qualitatifs lors de la résolution de contradictions physiques comportant des concepts de plus d’un paramètre. Malgré cela, le chapitre a mis l'accent sur le potentiel de la méthode pour résoudre des contradictions complexes et la validation des concepts de solution proposés. Les configurations de PdE qui en résultent ont été analysées à l'aide d'un modèle de régression et de diagrammes des effets principaux.

6. Comparaison des résultats des première et deuxième boucle de conception

La méthode proposée est composée de boucles itératives de conception inventive, comme indiqué précédemment, où chaque itération rapproche le système obtenu d’un système répondant à tous les objectifs (idéalité). Dans ce chapitre, deux boucles de conception ont été réalisées pour examiner deux hypothèses concernant la relation entre ces boucles et la contradiction choisie à chaque itération. La première hypothèse était fondée sur la croyance que la conception pourrait mieux atteindre l'idéalité en abordant la contradiction physique qui est constituée d'un plus grand nombre de paramètres d'action. Cette hypothèse teste l'idéalité du système et le nombre de paramètres d'action inclus dans la contradiction physique résolue. La seconde hypothèse était que le système développé pourrait se rapprocher davantage de l'idéalité à chaque boucle de conception si l’on se met dans la situation de la première hypothèse à chaque itération. La performance résultante du nouveau système, présentée en résolvant deux paramètres d'ajustement dans le GPC, a donné de meilleurs résultats que le nouveau système basé sur un seul paramètre d'ajustement. La contradiction basée sur deux paramètres quantitatifs a été résolue en les remplaçant par un seul paramètre quantitatif équivalent identifié à travers la Table Généralisée des Paramètres (GTP) et validé mathématiquement à l'aide des formules de la base de données contextuelle (CDB). L'illustration 7 est un exemple tiré de l'étude de cas sur la performance résultante de deux paramètres d'évaluation, l'absorption d'énergie et le module d'élasticité. Cette illustration montre la force de la méthode proposée réside dans sa capacité à garantir l'approche des résultats idéaux au fur et à mesure de la réalisation des boucles de conception. La figure montre la reformulation des problèmes de conception en fonction des itérations de conception et du nombre de paramètres d'action variés et liés aux contradictions physiques extraites.

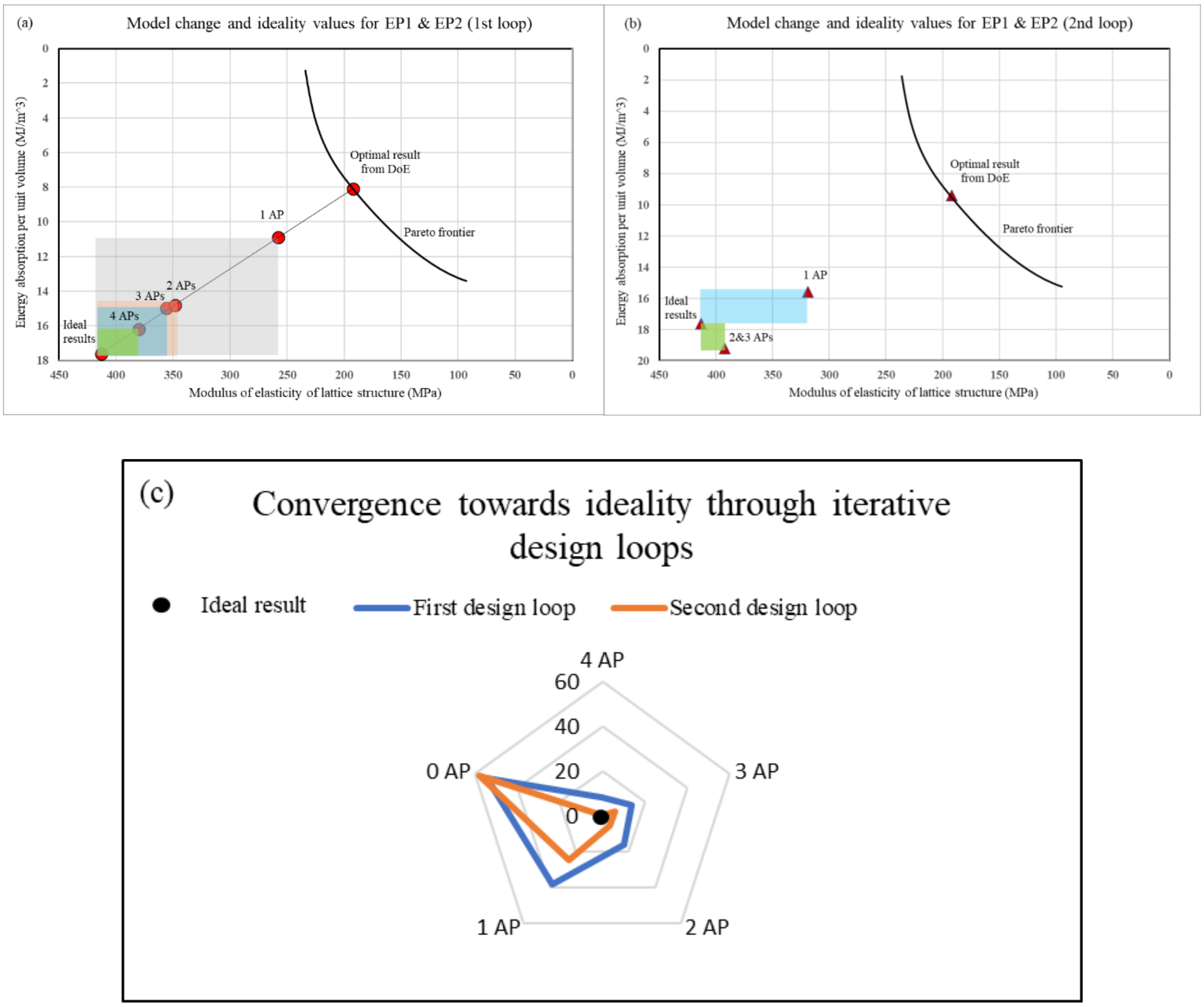


Illustration 7: Un exemple sur la reformulation des problèmes pour rapprocher l'idéalité avec des boucles de conception itératives, (a) les résultats des premières contradictions de la première boucle, (b) la deuxième boucle, (c) un tableau de comparaison entre les deux boucles

La même figure illustre également un exemple d'emplacement de solution potentielle en fonction du nombre de paramètres à résoudre pour EP1 et EP2. La valeur appelée "résultat optimal" représente la solution de PdE dans l'espace de conception la plus proche de l'idéalité, se positionnant sur la frontière de Pareto. Il est important de noter que pour se rapprocher de la solution, de nombreux paramètres d'action doivent être inclus. Pour faciliter la résolution, il est préférable de minimiser le nombre de paramètres d'action inclus dans la contradiction physique (CP).

7. Comparaison des concepts de solutions issus de la première et de la deuxième boucle de conception

L'exécution de plusieurs boucles de conception a donné lieu à un ensemble de solutions et de concepts de solutions. Ces solutions sont le résultat d'un processus d'optimisation multi-objectifs et d'un processus inventif de changement de modèle basé sur les principes TRIZ. Toutefois, l'illustration 8 montre une comparaison entre les solutions résultant du changement de modèle entre les deux itérations de conception.

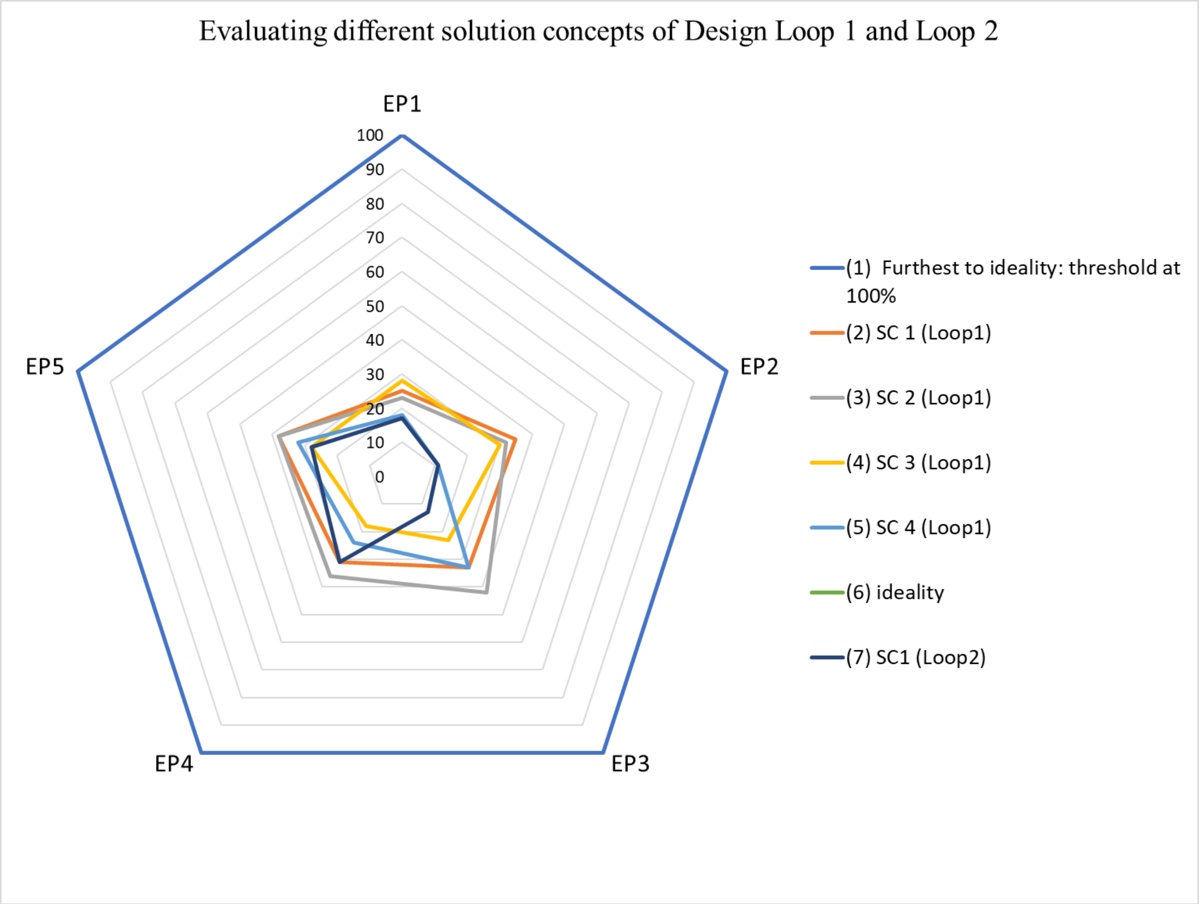


Illustration 8: Comparaison de plusieurs solutions et concepts de solutions issus de deux boucles de conception itératives (the ideality is the centeral point in the center of the graph)

Dans cette illustration, la figure 8, on peut voir que l'exécution d'une deuxième itération de conception a permis d'améliorer les performances du système conçu. Les paramètres d'évaluation 1, 2, 3, 5 ont été améliorés par rapport à la première itération de conception. On pourrait suggérer qu'avec le développement continu du même système en effectuant de multiples itérations, par exemple des boucles de conception, le système pourrait potentiellement tendre vers l'idéalité.

Chapitre 6 "Conclusion et perspectives" : Cette recherche s'est déroulée de manière systématique, en adhérant à une méthodologie structurée qui a commencé par l'identification des problèmes de recherche, a traversé une exploration complète des approches de conception inventive, a posé des questions de recherche et a abouti à la proposition de solutions inventives visant à combler les lacunes existantes en matière de recherche. Dans les paragraphes et sous-sections suivants, nous mettons en évidence les principales contributions, les limitations et les perspectives futures de ce travail de recherche.

8. Contributions

Les contributions de cette recherche sont susceptibles de développer les méthodes de conception inventive:

- Base de données contextuelle (BDC) et Tableau Généralisé des Paramètres (TGP) : Le développement d'une base de données contextuelle liée à un tableau généralisé de paramètres, méticuleusement construit à partir de diverses sources de données, est apparu comme un outil au service du processus de résolution des problèmes de conception inventive. Ce tableau constituait une ressource de connaissances spécifiques au domaine, offrant un référentiel structuré de paramètres de conception et d'idées essentielles à la compréhension du système de conception. En outre, le TGP développé réduisait considérablement la dépendance à l'égard des experts du domaine et facilitait l'utilisation des méthodes de conception inventive pour les non-experts.
- Extraction de problèmes prioritaires : La recherche a permis de proposer une approche systématique pour extraire et hiérarchiser les problèmes de conception critiques du TGP, en tirant parti de l'importance des informations et des données collectées. Ces problèmes ont fourni un modèle bien défini pour une résolution plus précise des problèmes de conception. Les problèmes ont été classés par ordre de priorité, proposant ainsi un modèle de problème holistique qui incluait l'ensemble des paramètres de performance. Cela pouvait conduire à des concepts de solutions spécifiques pour des problèmes de conception spécifiques et à la réduction des moyens utilisés pour atteindre ces concepts de solutions, c'est-à-dire en utilisant le TGP.

- "Seuil de binarisation" : Cette recherche introduit une technique qui peut contrôler les modifications dans les modèles conçus en maîtrisant la reformulation du problème de conception. Cette technique du seuil peut aider à décider du nombre de paramètres d'action liés aux paramètres d'évaluation, ce qui contribue à réduire le nombre de paramètres d'action impliqués dans la résolution des contradictions. Cela simplifiait non seulement la résolution des problèmes, mais pouvait également conduire à des modifications mineures du modèle, permettant ainsi de trouver des solutions à court terme. Cela représente une limitation de l'étude récente, et l'une des perspectives consiste à envisager des solutions à long terme en augmentant éventuellement la complexité des modifications apportées au modèle. En outre, l'utilisation du seuil encourageait les utilisateurs à évaluer soigneusement les contraintes initiales du système et à prendre en compte les effets des variations, même légères, sur la résolution finale, y compris des facteurs tels que la complexité du modèle, la faisabilité de la solution, les performances attendues et les coûts.

9. Limites

Cependant, aucune recherche n'est exempte de limites :

- Difficulté de traiter les paramètres qualitatifs : Alors que les méthodes que nous proposions introduisaient une incorporation entre l'approche des unités SI et les paramètres quantitatifs au sein du système de contradictions généralisé (SCG), cette incorporation a permis de reformuler des contradictions physiques complexes afin de les simplifier en vue de leur résolution. Cependant, notre proposition pouvait encore rencontrer des difficultés pour traiter efficacement les paramètres qualitatifs dans le cadre du système généralisé de contradictions.
- Processus manuel : Au chapitre 3, le TGP et la BDC qui lui étaient liés ont été présentés pour être intégrés dans le processus de conception inventive. Malgré les avantages de ces contributions, le remplissage du TGP et la collecte manuelle de toutes les données pouvaient prendre beaucoup de temps et d'efforts.
- L'application du concept de seuil ‘Threshold’ : proposé au chapitre 5, pour connaître son impact sur divers aspects de la résolution de problèmes, tels que la faisabilité, les performances attendues et les coûts, devrait faire l'objet d'un examen plus approfondi. En outre, l'une des perspectives consiste à envisager des solutions à long terme en augmentant éventuellement la complexité des modifications apportées au modèle.

10. Perspectives de recherche

Compte tenu de ces résultats et de ces limites, cette recherche ouvre la voie à plusieurs pistes prometteuses pour l'exploration et l'innovation future:

- Résolution des SCG complexe : Étudier les techniques d'application de l'approche des unités du Système International (SI), voir la section 5.2, avec les paramètres quantitatifs au sein du Système de Contradictions Généralisé (SCG), aurait élargi considérablement le champ de résolution de contradictions plus complexes comprenant à la fois des paramètres quantitatifs et qualitatifs. Même si la méthode utilisée pour résoudre le SCG complexe en utilisant les unités SI n'était qu'une première étape, elle aurait ouvert la voie à un développement plus poussé de cette méthode dans les futurs travaux de recherche.

- Automatisation du processus : Les perspectives de ce travail sont prometteuses, caractérisées par l'intégration stratégique de l'automatisation et de l'intelligence artificielle (IA) en vue de redéfinir le processus de conception inventive. Les perspectives s'articuleront autour de trois dimensions clés : l'automatisation du remplissage du tableau généralisé des paramètres (TGP), la collecte d'informations pour la base de données contextuelle (BDC) et l'exploitation de l'IA pour une exploitation transparente du TGP dans le cadre du processus de conception inventive, comme le montrait l'illustration 9.

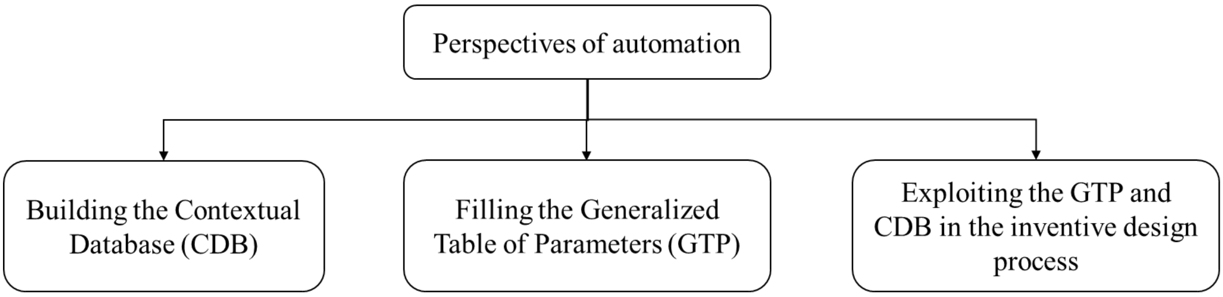


Illustration 9: Perspectives sur l'automatisation

1. Population automatisée de TGP:

   - Extraction efficace des données : L'intégration de l'IA et de l'automatisation vise à révolutionner la tâche laborieuse que représentait l'alimentation du TGP. Les algorithmes d'automatisation extrairont systématiquement les informations pertinentes du vaste référentiel de la base de données contextuelle (BDC), rationalisant ainsi le processus et réduisant de manière significative le temps nécessaire à la saisie manuelle des données.
   - Cartographie dynamique des relations : Les algorithmes pilotés par l'IA établiront dynamiquement les relations entre chaque paire de paramètres, en naviguant à travers les lois constitutives, les graphiques et les équations de la BDC. Cela garantira que le TGP reflète les interdépendances nuancées au sein du système de conception, favorisant la précision et l'exhaustivité.
   - Apprentissage adaptatif : Les capacités d'apprentissage automatique intégrées au processus d'automatisation permettront une amélioration continue. Le système s'adaptera et affinera sa compréhension des relations au fil du temps, garantissant que le TGP reste une ressource dynamique et évolutive, capable d'intégrer de nouvelles idées et des changements dans le paysage de la conception.

2. Collecte d'informations pour le BDC:

   - Collecte de données améliorée par l'IA : L'automatisation s'étendra à la collecte d'informations pour la base de données contextuelle. Des algorithmes d'IA parcoureront les articles scientifiques, les revues de littérature et d'autres référentiels pour en extraire

les données pertinentes. Le traitement du langage naturel (NLP) sera utilisé pour obtenir des informations précieuses à partir de textes non structurés, enrichissant ainsi la BDC d'une multitude de connaissances spécifiques à un domaine.
    - Enrichissement continu : Le processus d'automatisation ne sera pas statique. Il enrichira continuellement la BDC en la mettant à jour avec de nouvelles informations, études et résultats de recherche dans le domaine concerné. Cela garantit que la base de données reste à jour, reflète les dernières avancées et s'adapte aux nouveaux défis.

3. Exploitation du TGP pilotée par l'IA:

    - Processus de conception rationalisé : L'objectif ultime est d'automatiser l'exploitation du TGP dans le cadre du processus de conception inventive. L'IA jouera un rôle central dans l'extraction des contradictions, l'analyse des données, l'identification de solutions inventives et l'orientation de la prise de décision. Les concepteurs pourront s'appuyer sur l'IA pour naviguer efficacement dans les nombreuses informations contenues dans le TGP, permettant une approche plus ciblée et plus stratégique de la résolution des problèmes.
    - Juger et évaluer les résultats : L'IA contribuera à l'évaluation de la faisabilité des solutions proposées, en tenant compte de facteurs tels que les performances, les coûts et les résultats escomptés. Cette étape critique de validation permettra de s'assurer que les conceptions proposées ne sont pas seulement valables sur le plan théorique, mais qu'elles peuvent également être mises en œuvre dans des contextes industriels réels.

- Évaluation des concepts de solution proposés (SC) : comme conclu dans le chapitre 5, plusieurs concepts de solution ont été proposés pour résoudre le problème de conception. En se basant sur les méthodes développées au CSIP ou ailleurs, il devient possible d'intégrer une ou plusieurs méthodes d'évaluation des solutions, telles que la modélisation et l'évaluation des concepts de solutions basées sur la fonction-structure et le comportement.
- Essais mécaniques physiques : les travaux de recherche menés dans le cadre de ce doctorat proposent des approches prometteuses pour systématiser le processus de conception, y compris le prototypage du concept de solution à l'aide de la technologie de fabrication additive. Tester ces concepts de solutions fabriquées et valider les résultats, en particulier ceux qui s'alignent sur les spécifications des applications industrielles, serait intéressant et précieux pour rendre ces solutions potentielles réalisables, applicables et testées de manière approfondie. Par exemple, l'étude de cas spécifique de l'absorbeur d'énergie dans cette thèse a proposé certains concepts de solutions comme résultats. On peut effectuer des tests statiques tels que des tests de compression

mécanique uniaxiale, des tests de tension uniaxiale, des tests de flexion, comme le montre l'illustration 10. La réalisation de ces tests donne plus de crédibilité aux solutions proposées.

Illustration 10: Machines d'essais mécaniques (traction, compression, flexion) à l'INSA de Strasbourg, à gauche, Zwick Roell® Z005 (maximum 5 kN), à droite, Zwick Roell® Z050 (maximum 50 kN)

En résumé, cette recherche représente une avancée significative dans la façon dont les problèmes sont résolus et dont les produits ainsi que les matériaux peuvent être conçus. Les idées et les solutions présentées ouvrent des perspectives passionnantes pour les innovations futures dans le secteur. En examinant de près les méthodes inventives de résolution des problèmes, cette recherche dote les professionnels du domaine des compétences et des informations nécessaires pour relever de manière plus efficace les défis industriels. Elle offre ainsi la possibilité d'un avenir meilleur dans le domaine de la conception et de la recherche de solutions.

Mohamed ABDELLATIF

Contributions aux méthodes de conception inventive de systèmes à base de structures lattice

Résumé

Cette recherche vise à progresser dans la résolution inventive des problèmes en design industriel, en se concentrant sur les structures lattice. Dans un paysage industriel dynamique, elle aborde systématiquement des problèmes identifiés, mettant l'accent sur une méthode offrant la capacité de résoudre divers problèmes dans un contexte général élargi. Le défi réside dans la masse d'informations à étudier. La thèse propose deux approches : une base de données contextuelle liée avec une table de paramètres généralisée, ainsi que l'utilisation de plans d'expérience pour révéler des relations entre les paramètres et les mesures de performance. Ces approches réduisent la dépendance aux experts et améliorent le processus de conception inventive. L'étude se concentre sur le comportement mécanique des structures lattice, exploitant des solutions pour diverses catégories. Bien que l'application soit limitée au domaine mécanique, la méthode offre un potentiel d'extension à d'autres domaines. Cette recherche marque une avancée significative, offrant des possibilités innovantes en réponse à une demande industrielle substantielle pour les structures lattice.

Mots clés : Résolution de problèmes, conception, structures lattice, TRIZ

Abstract

This research aims to advance inventive problem-solving in industrial design, focusing on lattice structures. In a dynamic industrial landscape, it systematically addresses identified problems, emphasizing a method capable of solving various issues within an expanded general context. The challenge lies in the vast amount of information to be studied. The thesis proposes two approaches: a Contextual Database linked to Generalized Table of Parameters, and the use of Design of Experiments to reveal relationships between parameters and system performance measures. These approaches reduce reliance on experts and enhance the inventive design process. The study focuses on the mechanical behavior of lattice structures, leveraging solutions for various categories. Although the application is confined to the mechanical field, the method offers potential extension to other domains. This research signifies a significant advance, providing innovative possibilities in response to substantial industrial demand for lattice structures.

Keywords: Problem solving, Design, Lattice Structure, TRIZ