Programmatic Design Methods in Architecture
(GA+TRIZ Solution Search Method)

by

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DEDICATION

To my beloved one. Arman, who has been accompanying me throughout this journey.
To my mother, Zohreh, who always has been a role model for me.
To my father, Nariman, who missed me but has been patient to let me follow my dreams.
To my daughter, Naahid, to whom I wish a bright future.

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ABSTRACT

When an architectural design problem is stated, it may take several iterations to evaluate the design alternatives, modify the problem statement and the corresponding solutions and make the final decision. The recursive essence of an architectural design procedure and the designer's tendency to explore further possibilities increases the use of iterative programming search methods to find suitable solutions. Although there have been successful accomplishments in parametric modeling and evolutionary form exploration methods, the prior step of *problem structuring* has been developed less. We can still solve the wrong problem correctly. Thus, the step of problem structuring has significant effect on the final design outcome.

A common challenge in the application of computational design methodology is to discern the parameters that influence the project outcome. Sometimes the solution may be found around a design parameter that is not included in the parametric model and form exploration procedure. This challenge is more likely when contradictory design objectives exist in a project. Then, the designer may favor one design criterion over the others, or compromise (trade-off) and choose a solution among a group of suitable ones. In such cases, the corresponding Pareto front may be studied to find the best trade-off solutions between two or more performative design objectives. A third approach can be the attempt to eliminate the contradiction innovatively. Accordingly, the designer may apply data mining techniques or clustering and classification algorithms to achieve higher-level information or implicit search goals to make a final decision. In this dissertation, I intend to introduce a design search method that a designer unspecialized in the field of data mining can understand and employ in both the formulation of a design problem and in the exploration of generated solutions.

The main goal of this dissertation is to introduce a method which provides better *problem structuring* and *decision making*. This computational search method is expected to provide the benefits of the application of a genetic algorithm (GA) and the Theory of Inventive Problem Solving (TRIZ) at the same time. The TRIZ Inventive Principles and the associated Matrix of Contradiction are combined with a Non-Destructive Dynamic Population Genetic Algorithm

(NDDP GA) used in the ParaGen method, initially developed by Peter von Buelow, to develop the GA+TRIZ method. The GA+TRIZ method helps the designer build a better parametric model where pertinent variables, not all possible ones but those which will more probably be dominant, are included. Furthermore, following the map of the GA+TRIZ design method can provide higher-level information which is useful in making better decisions when conflicting design objectives exist.

To examine the suitability and benefits of the application of the GA+TRIZ search method, four design case studies are carried out using the GA+TRIZ map of work. The cases are chosen from design explorations previously solved using only the ParaGen method. In each design case, the design process and the outcome of the explorations are compared with the corresponding results from in the previous trials with the ParaGen-only procedure. The following four metrics are used to evaluate the application of the GA+TRIZ method:

- Diversity and particularity of solutions
- Performative cost
- Time efficiency
- The amount of data provided for decision making

The outcome of this research is the description of the GA+TRIZ search method along with examples of its application and all the required codes, scripts, and components.

Chapter 1: Introduction

1.1. Research background

When an architectural design problem is stated, it may take several iterations to evaluate the design alternatives, modify the problem statement and the corresponding solutions and make the final decision. The recursive essence of an architectural design procedure and the designer's tendency to explore further possibilities increases the use of iterative programming search methods to find suitable solutions. ParaGen, originally introduced by Peter von Buelow and still under development at the University of Michigan Hydra Lab, is a multi-objective evolutionary (MOE) exploration method intended for early design phases of architectural problems. Comparing to similar MOE methods, the significant characteristic of the ParaGen is its capacity to provide suitable interaction between the designer and the computational form generator. It allows considering qualitative and quantitative design objectives at the same time within the design process. Further details about this method have been described in several published papers and conference presentations [1, 2, 3, 4, 5, 6].

As a member of the doctoral research group in the field of Building Technology (BT) at the Taubman College of Architecture and Urban Planning of the University of Michigan, I have been engaged with a range of form exploration projects using ParaGen. The projects include the form exploration of a two-lane truss bridge [7], a lattice tapered tower similar to the Shukhov Water Tower [8], a shading screen with a middle-eastern geometrical pattern [9], a timber folded plate dome [10], and a one-bedroom house unit [11]. In all of these projects, the configuration of the initial concept was described parametrically, and a genetic algorithm was used to generate possible solutions. Then, the design objectives and constraints were considered as the fitness functions operating on the form generator or as some filters is being applied to the database. In all of the studied cases, the ParaGen framework helped to explore further possible design alternatives and relatively accelerate the process of generation, evaluation, and selection of suitable design solutions. Though there have been occasions where contradictory benefits were demanded, and a trade-off between two or more parameters was necessary. Also, it has happened that after the accomplishment of the exploration process we noticed the necessity of including a certain variable in the parametric model which has been disregarded.

For example, in the case of designing the one-bedroom house unit, once, solutions with wide windows and less energy demand were being searched. Although looking at the Pareto front to pick the most desirable solution was helpful, it came to mind that it would have been better to initially consider the building material or specification of the windows as a design variable, Then, it might be possible to eliminate the effect of the undesirable thermal performance of the large windows. In this case, we had to either create another parametric model, re-run all the simulations and re-do the form exploration process, or remain restricted with the generated solutions of the current parametric model. Once again, the issue was raised that what would be the set of suitable solutions if the design objectives address both the greater floor area and less energy demand? How may we think outside the box to make a trade-off between the two objectives?

We have experienced other similar situations where we were not satisfied with the provided information about the consequences of a set of input data. Consider the creation of the lightest truss bridge while the greater height of the trusses is preferred. The analysis indicates that these two design objectives are incompatible when other design parameters such as the structural material, truss patterns, and the specification of elements are the same. Furthermore, in the case of designing a timber folded plate dome, lower Annual Sunlight Exposure but higher spatial Daylight Autonomy seemed conflicting. Also, searching for the design alternatives of the dome with lower reverberation time (RT60) but greater depth of folds highlighted the contradictory design objectives, and it was not straightforward to determine the final solution. Making a decision becomes more difficult where more contradictory objectives exist at the same time. Consequently, the following questions were raised:

- Is the parametric model used within the search process suitable and does it include the pertinent variables? How can we be comfortable that a design problem is well-structured and that the parametric model is suitable for such a problem?
- How may the designer be provided with some hints about the variables that may be good to study and include in the parametric model?

- In the case of contradictions among objectives, how can the designer make a more innovative decision besides using the Pareto front?

The form exploration using the ParaGen method and the discussed experiences instigate further studies on design, problem structuring, decision making, and creative problem-solving. In the following sequel, the research problem is stated, and the expected outcome of this study is explained.

1.2. Statement of the problem

Although there have been successful accomplishments in parametric modeling and evolutionary form exploration methods, the prior step of *problem structuring* has been developed less. “A wrong problem can be proposed and solved correctly” [12]. This statement elucidates the significant effect of problem structuring on the final design outcome. “A problem clearly defined is already half solved” [13]. The main challenges in a conceptual design procedure relate to the ambiguous information, undefined problem requirements and conflicts among the design parameters and lack of general problem-solving methods [14].

Accordingly, an early challenge of a design task is to discern the parameters that influence the project outcome. Sometimes the solution may be found around a design parameter that is not included in the parametric model and form exploration procedure. One may bring the argument that the more design parameters are included through a search process, the better the solutions will be. However, defining a gigantic parametric model and running more diverse simulations require more time and will be prohibitive.

The explained challenge is more likely when contradictory design objectives exist in a project. In such case, the designer may give privilege to only one design criterion over the others, or compromise (trade-off) and choose a solution among a group of suitable ones. A third approach can be the attempt to eliminate the contradiction innovatively. The designer may use data mining techniques or apply clustering and classification algorithms or separate the solutions by search space distance. In the literature of the field of design, such techniques are addressed as the application of *higher-level information* or as sometimes has been called *implicit search goals* [15, 16, 17]. These techniques remind us that Pareto fronts describe only the performative functions we included in the corresponding plot. However, we can use other information to make the final decision. The Theory of Inventive Problem Solving (TRIZ) is known to provide the designer such high-level information.

1.3. Purpose of the study

The main goal of this research is to introduce a method which provides better *problem structuring* and *decision making*. This computational search method is expected to provide the benefits of the application of a genetic algorithm and the Theory of Inventive Problem Solving (TRIZ) at the same time. Accordingly, the method is called GA+TRIZ. Although this hybrid method can be employed in many fields of knowledge, it aims particularly to support the conceptual phase of design in the architecture domain. On the one hand, the GA+TRIZ method is to help the designer to build a better parametric model where pertinent variables, not all possible ones but those which will more probably be dominant, are included. On the other hand, following the map of the GA+TRIZ design method can provide some higher-level information to make a better decision when conflicting design objectives exist.

The outcome of this research will be the description of the GA+TRIZ search method along with examples of its application and all the required codes, scripts, and components. Besides, the attempt is made to investigate the extent to which the Theory of Inventive Problem Solving can be applied in architectural design. There are several TRIZ tools whose contribution to the field of architecture can be studied in more detail. The focus of this dissertation is on the application of the 40 inventive principles and the matrix of contradiction during the conceptual phase of design. The contribution of other TRIZ tools may be investigated in future works.

1.4. Research Hypotheses

The GA+TRIZ method is based on the ParaGen framework and the TRIZ matrix of contradiction. ParaGen, on its own, can expand the designer's perspective and provide a series of suitable solutions using an evolutionary design approach. The implementation of a Non-Destructive Dynamic Population Genetic Algorithm (NDDP GA) in ParaGen method allows investigation of unexpected solutions and justification of design process dynamically regarding any change in the design context or the designer's preferences. On the other hand, application of TRIZ in the field of design can draw the designer's attention in a completely different direction when she seems being blocked with a limited set of possible solutions. In fact, what is expected from the coupling of ParaGen and TRIZ, can be stated as the four following features:

1. Either expanding the search space for a broader diversity among solutions or focusing on particular details of similar solutions
2. Increasing the efficiency of the search process in terms of required time
3. Providing further information on the very early steps of the design process in order to improve the problem structuring
4. Enhancing the interaction between the designer and the computational form generator

To examine the suitability and benefits of the application of the GA+TRIZ search method, four design cases are carried out using the GA+TRIZ map of work. The cases are chosen from design explorations the author has previously accomplished using only the ParaGen method. In each design case, the design process and the outcome of the explorations are compared with the corresponding ones in the previous experience with the ParaGen-only map of work. Four metrics, including *diversity and similarity of solutions*, *performative cost*, *time efficiency*, and amount of *data provided for decision making,* are determined to evaluate the application of the GA+TRIZ method. The definitions of these four metrics are described in detail in Chapter 3.

1.5. The dissertation framework

This dissertation includes four chapters. The first chapter describes the main problem statement of this study, the first sparks of its formation and the hypotheses examined through this investigation. The second chapter contains a critical review of the literature relevant to the development of the GA+TRIZ exploration method. In each subsection of Chapter 2, the attempt is made to address the relation between what is concluded from the literature and the new exploration method proposed in Chapter 3. The third chapter begins by introducing the research methodology and follows with outlining the GA+TRIZ method. Then, the chapter continues with the description of the four main design cases where more details of the application of the GA+TRIZ method are explained. Meanwhile, the potentials and probable challenges of applying the proposed new method are discussed. Chapter 4 includes a conclusion on the application of the GA+TRIZ method along with the outline of the relevant future work.

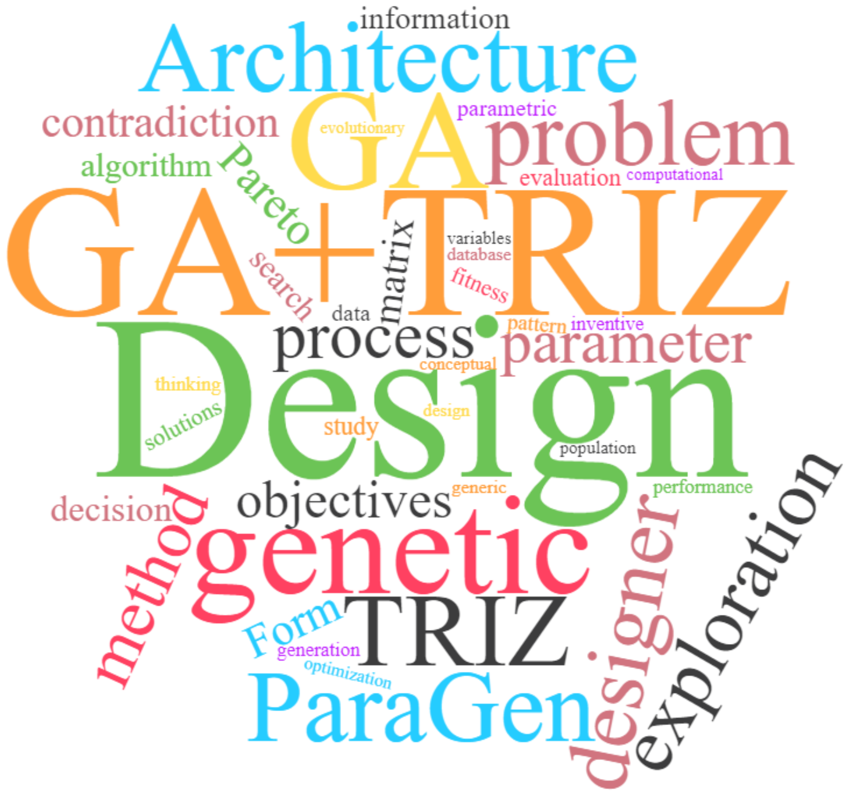


Figure 1: The word cloud of the most used keywords in this dissertation

Chapter 2: Review of the Literature

Design has a wide range of definitions in different disciplines. Architects, engineers, graphists, urban planners, and interior designers are involved with elements and contexts that make their design activity apparently different. In addition, there are some definitions of design, such as "to initiate change in man-made things" [18], that are too general and abstract to help us understand design clearly. However, it is possible to find a spectrum in which all of these definitions fall. Designers consciously direct their thought toward a/some specified goal(s) to solve a real-world problem. Within this process, a designer employs, on one hand, her imagination and intuition seeking diverse alternatives and, on the other hand, brings rationality and logic to evaluate all of her alternative solutions. Accordingly, a designer is involved with both divergent and convergent productive thinking through a design process. In this study, efforts have been made to improve designers' thinking skills. Hence, at the beginning, it is appropriate to re-state some design related keywords that are the basic foundation of the proposed GA+TRIZ design method. First, consider that a designer is expected to *solve* a real-world *problem*.

2.1. Design problem

One of the characteristics of a design problem, unlike a mathematics problem, is that the problem is not apparent and should be defined. A client may request a residential complex built in reinforced concrete. Then, through meeting sessions, the designer may recognize that the main reason for client's emphasis on reinforced concrete construction is that she is concerned with sound transmission among residential units. Thus, the design problem can be shifted to provide an appropriate sound insulation while thinking of using other materials such as timber plates to create a building with a lower carbon footprint. In addition, determining the design objectives and their relative priorities is a subjective decision, and the designer and client may be uncertain about them. In fact, a design problem may not be uncovered and explicitly stated within a separate preliminary phase and it needs to be updated dynamically. In other words, defining a problem and finding solutions are not linearly related but they become clearer together almost simultaneously. The following section describes how similar to several design methods, the proposed GA+TRIZ method is based on a dynamic exploration process.

2.2. Problem-solving

In literature, problem-solving is described as a goal-directed activity [18, 6]. A designer should consciously direct her thought toward a specified goal to find solutions to a real-world problem. Consider that the definition of this real-world problem may vary in different contexts or phases. Therefore, the designer needs to think *productively* and *creatively*. Productive thinking, originally introduced by Wetheimer (1959), focuses on the end goal and the necessity of willful control of thought toward the specified end [18]. Creative thinking addresses the ability to perceive the problem in several different contexts and shifts attention from one thing to another to generate a variety of perspectives [18]. It seems suitable to describe productive and creative thinking a bit further in order to make the basic principles of the GA+TRIZ method clearer.

Bartlett explains that productive thinking may occur in either a *closed system*, where there are a limited number of items to be involved, or an *adventurous* circumstance. In the latter situation, successful problem solving may depend on elements that are not normally related but can be brought together in a new way [19]. The GA+TRIZ method introduced and developed in this dissertation stimulates adventurous thinking through a problem-solving activity.

There is a consensus that creative thinking is not just a skill or talent, but it is also related to context. Many psychologists introduce the following five stages of creative thinking that highlight the relation between problem and context [18]:

1. Recognition of the problem (first insight)
2. Conscious effort to solve the problem (preparation)
3. Thinking with no conscious effort (incubation)
4. The sudden emergence of the idea (illumination)
5. Verification of the solution(s)

Among the theorists discussing aspects of creative thinking, Guilford represents such pondering as a balance of divergent and convergent thinking toward solving a problem [20]. Imagination, intuitive or artistic thoughts are sorts of divergent thinking that allow a designer’s mind to wander in different directions and generate a variety of perspectives and see the problem from diverse aspects. On the other hand, reasoning, rational or logical thinking is considered to be purposive and convergent toward a certain conclusion. Consequently, a designer is expected to proceed through a combination of divergent and convergent thinking to define and solve a problem.

2.3. Design process

As discussed, design does not take place in a moment. The designer progresses through a process which is usually described as a series of steps. Similar to design definition, there are several descriptions of the design process that represent where to begin and how to proceed. Some of these descriptions are general and some others are specific. The American Institute of Architects (AIA) divides the design process into five phases [21]:

1. Schematic design
2. Design development
3. Construction documents
4. Bidding and negotiation
5. Construction contract administration

These five phases are proposed to provide the legal framework of certain design services that should be acknowledged by both clients and designers. AIA's classification of design phases indicates the expected outcome, in terms of reports, sketches, and drawings, and the level of details. However, to improve the design outcome designers, in particular, the novices should learn not only what to produce but also how to work. Therefore, in this dissertation, *design process* indicates a series of actions to uncover a problem as well as to find solutions.

Markus and Maver present a map of the design process shown in Figure 2 [18]. Accordingly, in each phase, the designer is expected to analyze the problem, synthesize and solve the problem, appraise the solutions, and make a decision. Makus and Maver believe that synthesis and appraisal take place through an iterative process. However, Lawson emphasizes that there might be additional backward movement from decision making or appraisal to problem analysis (see Figure 3) [18]. Schon, Goel, Pirollis, Lloyd, and Scott have accomplished separate studies and concluded that problem structuring re-occurs periodically in the design process, particularly in architects' studies [22] [23] [24]. Thus, design can be described as a co-evolution of the problem statement and its solution [25].

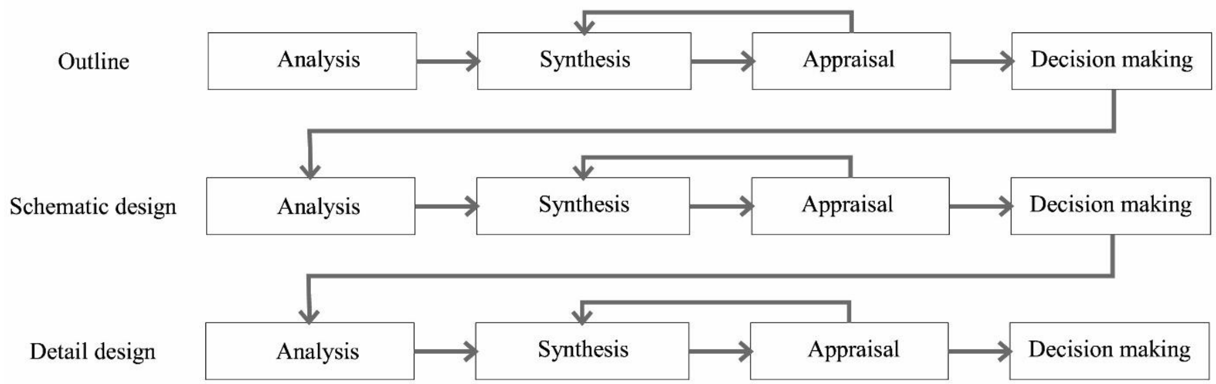


Figure 2: Markus and Maver's map of the design process

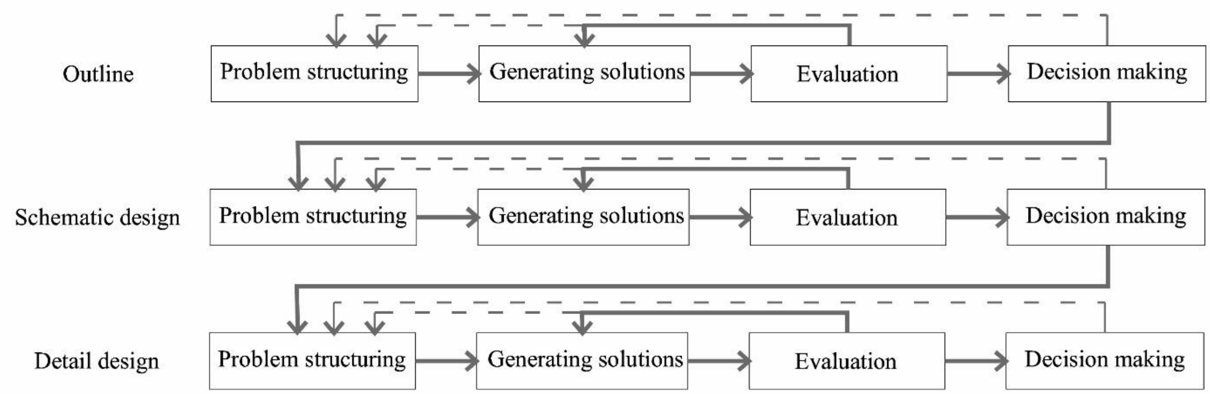


Figure 3: Lawson's map of the design process

Studies have revealed the designers' tendency to use only one or a limited number of design ideas despite the recurring problem structuring [26] [27]. There were many cases where goals and constraints have been changed, but the designer appears to apply patches rather than rejecting the principal conceptual solution and developing a new better one. Ball et al. call this phenomenon *fixation* on initial concepts [27]. Lawson's map of the design process, similar to that of Markus and Maver, does not illustrate the actions required for avoiding such unreasonable restriction of the solution exploration. However, Lawson asserts that it is vital to develop design strategies that allow searching a wide range of solutions. He claims that many designers may get locked into a small circle that includes only a part of the whole problem. In his viewpoint, designers often waste their time by navigating around some particular issues which in retrospect are seen unimportant or even of their own making. Lawson suggests developing different maps of the design process to work along *parallel lines of thought* [18]. Such maps of work should contain multiple divergent and convergent steps [14] [28] [29].

Liu et al. presented three major divergent-convergent approaches within a design process [30]. The first design approach includes multiple levels of divergence and then multiple levels of convergence (see Figure 4). In this approach, multiple levels of solution generation and evaluation allow managing the complexity of the design problem. However, having a series of divergences without convergences yields a too large of a solution space to explore. Also, the similar solution may be generated, and unnecessary exploration may occur. The second approach contains multiple pairs of divergences and convergences (see Figure 5). This approach does not have the former issue, but solutions at each level may be harder for the designer to understand. The third approach includes two sections. In the first section, multiple divergent-convergent steps allow for a gradual increase in the number of solutions but reducing the complexity of the problem. In the second section, multiple levels of divergences and convergences reduce the number of concepts without compromising the richness of the space (see Figure 6).

Fricke [31] believes that in addition to fixation on initial concepts, excessive expansion of the search space is also a weak design strategy. Spending time on organizing and managing the set of solutions rather than the careful evaluation and modification of the alternatives is inappropriate. Therefore, a balance of divergence and convergence in solution exploration is advised. Accordingly, Eastman, Agabani, and some other researchers suggest both *evolutionary* and *revolutionary* modifications of early solutions [32] [33] [18]. These two strategies will be discussed in the following to show how a *genetic algorithm* and the *Theory of Inventive Problem Solving (TRIZ)* can contribute to the architectural design field. But earlier, it is suitable to review a few points about the conceptual design phase.

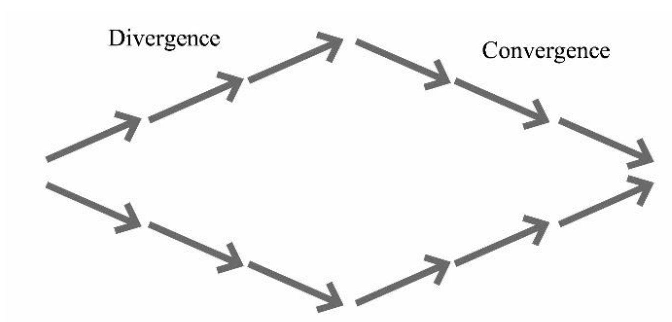


Figure 4: A design approach that contains multiple levels of divergences followed by multiple levels of convergences

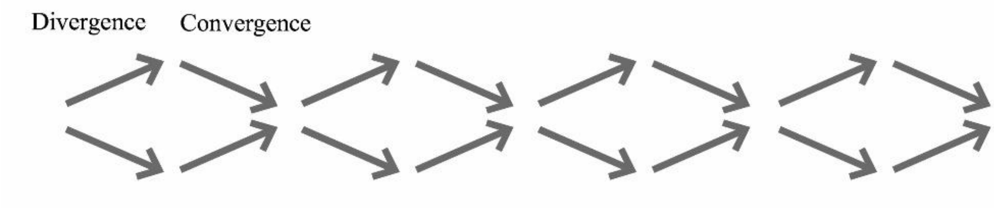


Figure 5: A design approach where each level of divergence is followed by a level of convergence

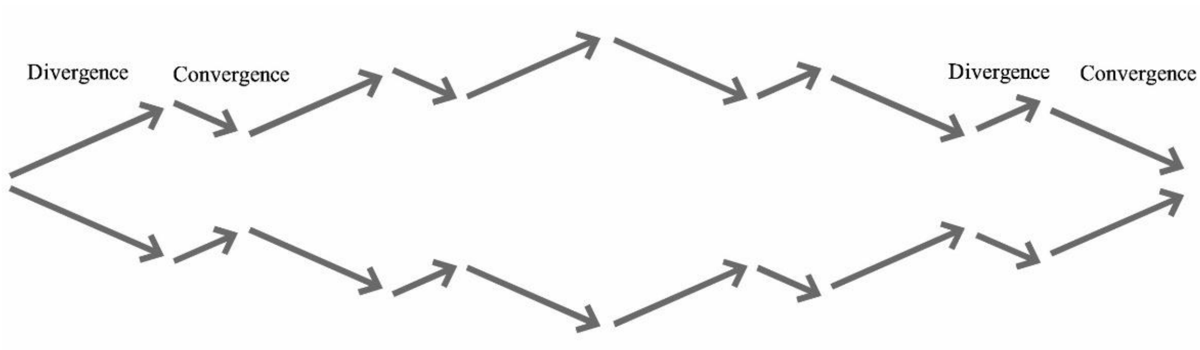


Figure 6: A design approach with multiple divergences and convergences in two different rates

2.4. Conceptual design phase

The focus of this study is on the schematic design phase. In the conceptual design phase, the problem is studied in a fairly rough way, and requirements and objectives are defined and synthesized into design alternatives [34] [18]. In the field of science and technology, conceptual design means an iterative process of gathering information, generating and representing solutions, transformation, and manipulation of them, and finally, communicating about the various domains of the design task [35].

Several studies have highlighted the importance of the conceptual design phase [36] [37]. Paulson's curve demonstrates the relationship between the cumulative cost of a project and the level of influence on determining and controlling costs through a design process (see Figure 7) [38]. At the early stage, the design team is making major decisions such as the structural and mechanical systems and building configuration. At this stage, the decisions have by far the greatest influence on the determination of the cumulative cost of the project while actual expenditure is relatively small. Wang also believes 75% of the product life-cycle cost is determined during the preliminary phase of design [36] [37].

In the recent decade, Computer Aided Conceptual Design approach has come into play to facilitate the implementation of the convergence and divergence process and prevent designers from investing in poor design alternatives. In the traditional approach, decision making relies more on the designer's insight rather than a numeric evaluation of the building performance. According to Paulson's curve, when such evaluation is postponed to the phase of developing design or a limited range of performances are roughly evaluated, the project will have a greater cumulative cost. Above all, because of the limitation of time and cognitive abilities, or the influence of a primary design direction, a relatively narrow range of solutions are studied in the traditional approach. In contrast, the computer-aided design approach allows the numeric evaluation of building performance and enlarges diversity and the number of design alternatives. In addition, interdisciplinary collaboration is facilitated through the design process.

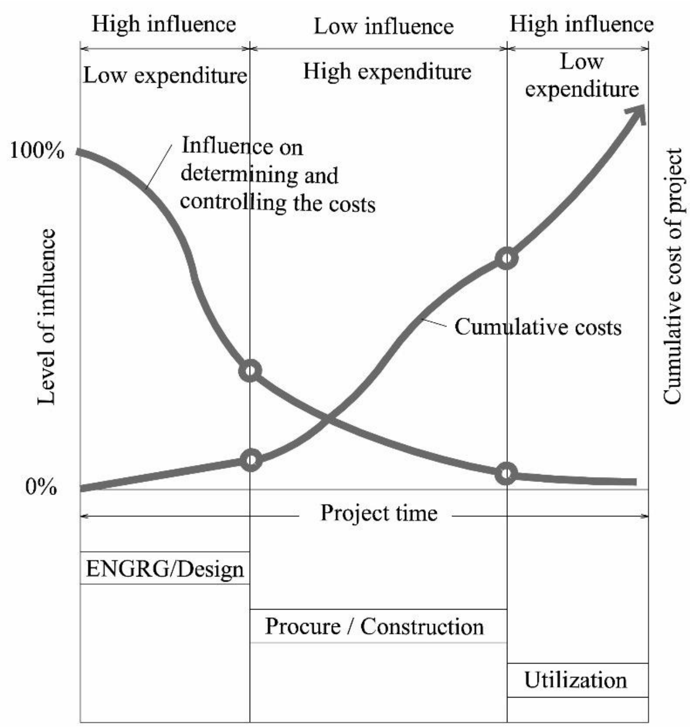


Figure 7: Level of influence on project costs *[38]*

There are various computational tools that can provide a suitable path to the exploration of possible solutions leading to a decision. Parametric modeling, based on the consistent structure of dependencies within a problem, allows for the generation of a variety of solutions relatively quickly. Automation of design cycles assists the designer to explore the population of solutions, evaluate their performance and store the result of the assessment conveniently. Evolutionary form exploration methods, mainly using a genetic algorithm, allow searching the solution space for unexpected alternatives while using a *fitness function* to guide the generation of solutions [37]. In the following, the contributions of evolutionary form exploration methods in conceptual design are discussed.

2.5. Evolutionary form exploration methods

Selecting a method to generate and evaluate solutions depends on the design problem. Sometimes the solution space is relatively small, and a mathematical description of the building shape and numerical analysis of a specific performance yield the suitable solutions. When there are multiple design objectives and a population of solutions should be explored for a series of suitable ones, application of an evolutionary algorithm will be beneficial.

Application of evolutionary algorithms can be traced back to the early 1950s when they were used by several biologists [16]. In 2006, at the World Congress on Computational Intelligence, evolutionary multi-objective optimization (EMO) was recognized as one of the three fastest growing research fields among all computational intelligence topics [16].

In an evolutionary algorithm, a nature-inspired mechanism is employed to evaluate a population of feasible solutions and evolve the candidate solution(s) toward better and better individuals. The better the quality of a candidate solution, the higher the probability that its genetic characteristics will be passed on the new generation of solutions [39] [17]. An evolutionary algorithm may be deterministic or stochastic. The former has one starting point and tends to quickly converge the exploration scope to usually a single best solution [17]. However, in the latter, there can be many starting points and random operations enlarge the search space. A genetic algorithm, simulated annealing, and particle swarm optimization inspired by birds' flocking or fish schooling are the examples of stochastic evolutionary algorithms.

There is also a popular approach to use a combination of evolutionary algorithms. The typical procedure is to employ a global search algorithm to obtain a series of suitable solutions and then use another algorithm as a local optimizer to refine the result and choose the most desirable one. Further information about the examples of such hybrid algorithms can be found in [40, 41]. The scope of this dissertation includes the application of a genetic algorithm to accomplish the form exploration in the conceptual design phase.

2.5.1. Genetic Algorithms

During the 1960s and 1970s genetic algorithms were developed at the University of Michigan under the direction of John Holland [42] [43]. Gradually, variations of genetic algorithms have been introduced. In a genetic algorithm, the variables of the parametric model are analogous to genes on chromosomes. In all GAs, common steps are population initialization, evaluation, selection, recombination and mutation, replacement, and iteration [44]. A random population of feasible solutions is initiated to be evaluated and explored for the more fit individuals. The evaluation of solutions may be measured regarding objective functions with mathematical or computational models. It is also possible that the designer directly evaluates the solutions considering subjective functions. Then, a fitness function, derived from the design objectives and constraints, is employed to select the more fit individuals [39]. Selection may be carried out using procedures such as roulette-wheel selection, stochastic universal selection, ranking selection, or tournament selection [39]. It is also possible to select the best individual directly as a parent to breed the next generation. This direct selection accelerates the convergence of the applied genetic algorithm. However, the diversity of the population may be reduced.

Mechanisms such as *recombination* and *mutation* are employed to generate solutions and transmit the characteristics of a pair of solutions to the new offspring [16]. The mechanism of recombination combines characteristics of two parents to breed a new possibly better child. In contrast, mutation, locally but randomly, operates on a single parent and changes one or more characteristics. Then, the breeding population is changed in each cycle of exploration. The application of a fitness function can be used in a way to guarantee that the selected good solutions are never lost in the GA operation unless a better solution is found. This concept is known as *elitism*.

The productive use of a genetic algorithm implies topological thinking [45]. Defining the parametric model of the solutions, the designer should emphasize proportions and relations among the components and not on the lengths and areas. As mentioned, there are variations of genetic algorithms with different ways of population selection and ranking methods. The algorithm applied in the GA+TRIZ hybrid method is based on a Non-Destructive Dynamic Population GA (NDDP-GA), used in ParaGen developed by Peter von Buelow.

In this GA, the chromosomes (parametric values) are bred to create the geometric body of the new solutions. Initially, a pool of random solutions is generated and stored in a database. Then, a population of parents is dynamically selected from this pool (the database) based on the fitness function to breed new children. The crossover operator swaps genetic characteristics between the parents to produce the newborn child and occasionally a mutation operator changes the value of a gene to a new random value. Based on the Half Uniform Crossover method (HUX), the newborn child (solution) may inherit some exact characteristics of parent 1, or exactly that of parent 2 or a combination of the two [46]. Figure 8 demonstrates the HUX principles. The characteristics of parents 1 and 2 are described in terms of geometric shapes [47]. The performance of the new solution is evaluated using various simulation software. Then, both performance and geometric values are uploaded to the database. Images are also included and linked to the solution.

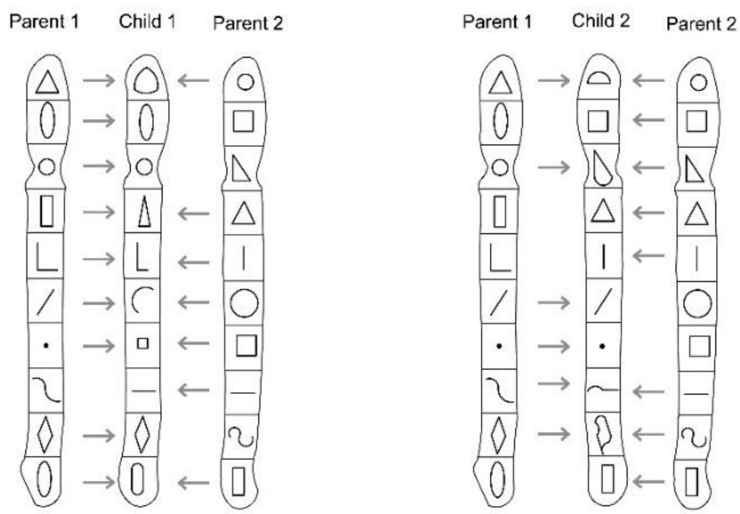


Figure 8: A schematic demonstration of the Half Uniform Crossover (HUX) *[47]*

In a traditional GA approach, any defective or poor performing solution is usually removed (killed off) from the breeding population. However, in the NDDP GA all solutions, both well-performing and poorly performing solutions are stored in the database. Therefore, if the design criteria are changed, the solutions previously known as defective and poor may also come into play. Therefore, through the process of defining and solving the design problem, the NDDP GA not only allows the required adjustment regarding the context but also is informative for the designer to learn what makes a good solution [2].

2.5.2. Form exploration versus optimization

Form exploration and optimization have several similarities and differences. The first step of both form exploration and optimization is the formulation of the problem. This step requires relative mathematical knowledge and familiarity with simulation programs. Formulation of a problem involves:

- Determining the number, nature, and type of the design variables as being dependent or independent, continues or discrete
- Defining the number and nature of performative objectives as being single-objective or multi-objective, uni-modal or multi-modal
- Identifying the constraints and their natures
- Setting the problem domains.

The second step in both approaches is running the search process and monitoring the implementation of applied algorithms and automated tasks. There are a wide variety of algorithms to be employed, and their appropriateness depends on the context of the problem. Most commonly used algorithms are [41]:

- The family of direct search algorithms that can find a local minimum point such as exhaustive search, Hooke–Jeeves algorithms, coordinate search algorithm, mesh adaptive search algorithm, generating set search algorithm, simplex algorithms
- Integer programming family that solves problems which consist of integers or mixed integer variables such as Branch and Bound methods, exact algorithm, simulated annealing, Tabu search, hill climbing method, CONLIN method
- The family of stochastic population-based algorithms which allows several performative evaluations and provides series of suitable solutions instead of one global optimum solution such as genetic algorithm, genetic programming, evolutionary programming, differential evolution, cultural algorithm, particle swarm optimization (PSO), ant colony algorithm, bee colony algorithm, intelligent water drop
- Other types such as Harmony search algorithm, firefly algorithm, invasive weed optimization algorithm

Meanwhile, some errors may arise in case of an infeasible combination of variables or output reading. These errors can be prevented or reduced by correcting the acceptable intervals of variable values and considering enough simulation time.

In the third step, the designer should control the termination criteria of the form exploration or optimization process. The termination criteria may depend on the maximum number of generations, reaching an acceptable performative value and a specified threshold, or time restrictions.

The fourth step, post-processing, is to study the generated solutions using diagrams, charts, tables, or plots and make a decision. If the optimization or exploration has merely a single objective (that rarely happens in reality) the optimum point can be easily found in the database or on the relevant plots. However, multi-objective optimization or exploration has two main goals. First, to find a set of solutions that is non-dominant and lies on the Pareto front; Second, to provide enough diversity of solutions to obtain the entire range of Pareto set [16]. In the end, the designer should make a non-technical, qualitative and experience-driven decision and select the most desirable solution. The Pareto front and the concept of trade-off are discussed in more details in the following section.

Form exploration differs optimization in several aspects [17]. First, the purpose of the optimization is to minimize the objective functions and find high-performing solutions. However, form exploration aims to expose designers to a wider diversity of solutions and allow adjustment of the design goals during the exploration process. As Mendez also asserts, the distinction between form exploration and optimization does not really rely on the applied algorithm but on the purpose and the moment it is used within the design process [17].

Second, any error during the optimization process may falsify the final result [41]. However, in form exploration, a failure in generation or evaluation of a solution does not impact the whole process. Simply a defective solution may be generated and stored in the database just as many other suitable solutions. Since there is not such a narrow convergence to select only one single best solution, the defective solution will normally be disregarded and excluded from the population of suitable solutions.

Third, in an optimization, almost all of the design objectives are quantitative. However, usually there are some subjective, qualitative goals that are important to consider in a practical design process. Also, the combination of two or more quantitative goals and the relative trade-off can be a subjective problem [48]. Form exploration allows incorporation of the designer input and addressing the subjective design goals.

2.5.3. The Pareto front and the concept of trade-off

A set of non-dominated solutions is called the Pareto front or a trade-off set. In a Pareto set, there is not any other feasible solution that improves one objective without sacrificing at least another one. This concept of exchanging loss in one aspect and gaining additional benefits in another aspect is known as trade-off [49]. There are two types of trade-offs:

1- Objective trade-off: Changing one objective in relation to the change in another one when moving from a feasible solution to another.
2- Subjective trade-off: Measuring how much the designer may accept the sacrifice of some objective function to improve another objective to a certain quantity.

Depending on the design objectives, a Pareto front may have any shape. If the objectives are not in contradiction, the Pareto front yields a single solution. However, contradictory objectives lie on a curve or line. A convex curve represents a low contrast, a line indicates a constant contrast, and a concave form emphasizes a high contrast [17] (see Figure 9). A Pareto front may be a combination of shapes. Considering all the design objectives, we cannot assume any individual on this curve to be better than others.

Although a Pareto front represents a series of suitable solutions, we still need to make a final decision and choose a single solution out of the front. This is why sometimes employing only a Pareto front is regarded as inappropriate in making the final decision. Some researchers suggest the weighting method though it requires prior knowledge and does not provide information for compromise between the objectives [50]. Data mining techniques, application of clustering and classification algorithms, or separation of solutions by search space distance are also recommended. Deb suggests employing *higher-level information*, what Mendez calls *implicit search goals*. Both Deb and Mendez point out that Pareto fronts describe only the performative functions and we may need to use other information to make the final decision [15, 16, 17]. Such information may not have been considered in the design problem because it seemed apparently irrelevant or expensive to be used in the search process. In Chapter 3, it is explained how the GA+TRIZ method introduces additional information to define the design problem better.

In addition, another way of refining the generated solutions and choose the most desirable one is by sorting them regarding their shapes to provide the most diversity or considering aesthetic issues.

In this case, the designer's interaction with the exploration process becomes important. In the following, interactive multi-objective search methods are discussed.

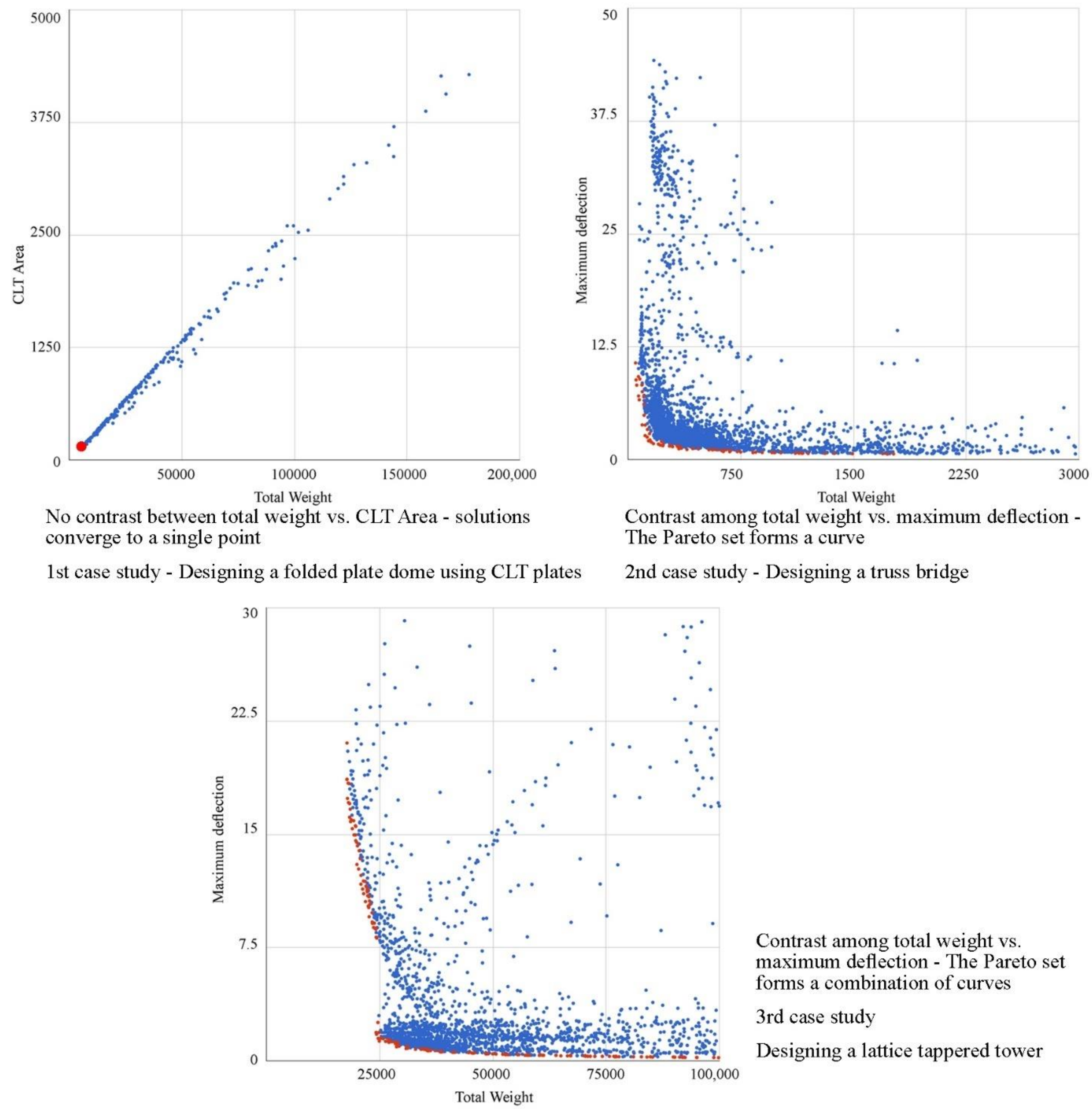


Figure 9: A variety of Pareto front shapes

2.5.4. The interactive multi-objective search method

In form exploration, there are some subjective goals, such as desired appearance, that cannot be parameterized. Also, the suitability of the solutions regarding some subjective preferences cannot be measured or numerically evaluated. A designer may find a certain percentage of perforation on a shell aesthetically pleasing, but another person may not. Hence, it is an advantage for an exploration method to allow appropriate interaction opportunity for the decision maker (DM), who might be the designer, the user or the client. Evolutionary form exploration methods allow human interaction to four different extents (see Figure 10) [49]:

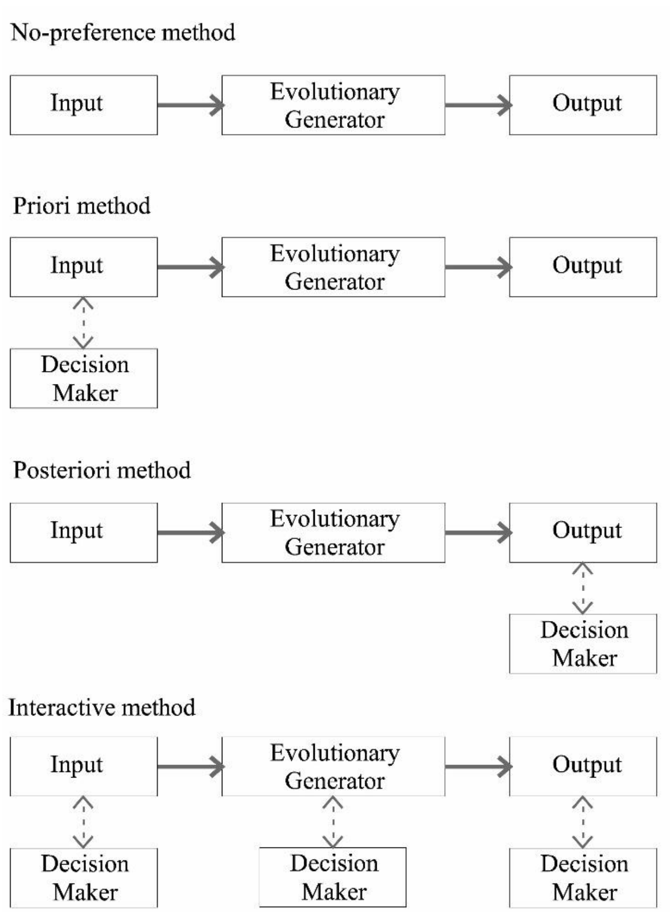


Figure 10: The four types of interaction between the decision maker and the computational form exploration programs

1. No-preference methods (without involving the DM): Instead of asking the DM for preference information, some assumptions of reasonable compromise are made
2. Priori methods: The DM first articulates the preference information, and then the optimization process takes place. This method is a straightforward approach, and the DM does not have to invest much time in the solution process. However, the DM may not have any expectation of possibilities, the diversity or quality of solutions
3. Posteriori methods: First the Pareto optimal solutions are generated and, then, the DM is asked to select the most preferred one. This method may be helpful since it provides the DM an overview of solutions. However, analyzing a large amount of information and

selecting the best one may be difficult for DM. Also, as long as the DM does not provide the preference information, there will be no clear boundary to stop the optimization process. The process may be stopped too early, or it may last too long which is usually expensive and difficult.

Sometimes the weighting method is suggested to assist the DM in this regard. The DM is asked to specify the most satisfactory weights at the beginning. But the problem is that sometimes these weights do not produce expected solutions at all because the DM does not necessarily know if the weights may work correctly.

4. Continuous interactive methods: The DM progressively specifies and adjusts her preferences after each iteration. Also, the DM can learn about the interdependencies of the design parameters in the problem and obtain an almost realistic expectation of final solutions.

Interactive methods are different from one another considering the style of interaction, the form in which information is given to the DM, and technical elements. The technical elements refer to the mathematical convergence of the method, the type of applied scalarizing function, the type of obtained final solutions, and the way that problems are handled. Traditionally, there are five occasions that the designer can interact with an evolutionary solution generator [49]:

1. Initializing the design objectives, constraints and criteria at the beginning of the form exploration process
2. Selecting the population of desirable solutions to generate further solutions
3. Generating the Pareto optimal solution(s) and determining the *mutation rate* and the *generation size*. See further examples in [48]
4. Adjusting the preference information as the exploration progresses and the design problem becomes clearer
5. Determining the best solution and terminating the exploration process

A large variety of interactive optimization methods exists. It is good to choose the one which is user-friendly enough, and the algorithm is flexible for further modifications due to the DM's intent [49]. Usually, the DM wants to feel in control of the process and understand it. Therefore, some techniques such as visualization are developed to help.

A proverb says that *a picture is worth a thousand words*. Visualization, that is, the transformation of symbolic data into geometric information helps the DM to form a mental picture of the symbolic data and assess the information more conveniently. Visualization techniques help the designer to assess the objective trade-off between any two feasible points and, also, to specify the most preferred solution directly in the Pareto frontier. Any visualization technique, employed throughout a multi-objective decision-making task, needs to be simple enough to be immediately understood and remain in the designer's mind. In addition, it is preferred to have the potential to depict all relevant information.

The GA+TRIZ method is to enhance the interaction between the designer and a GA-based computer-aided design tool. In the following section, the framework of ParaGen that is one of the foundations of the GA+TRIZ method is introduced, and its contributions to the design field are discussed.

2.5.5. ParaGen method

ParaGen, originally developed by Peter von Buelow, combines a Non-Destructive Dynamic Population Genetic Algorithm (NDDP-GA) and a SQL database to provide directed exploration of a solution space [5]. The ParaGen form exploration method starts by generating an initial population of solutions and continues with iterative cycles of systematic form generation. Each cycle includes selection of a population of parents regarding certain criteria, a half-uniform crossover (HUX) [51] to breed parents from the population, evaluation of solutions via the objective function, ranking and uploading the result in the database (see Figure 11). Determination of the criteria can be done through a SQL query or by Pareto sets [3] [52].

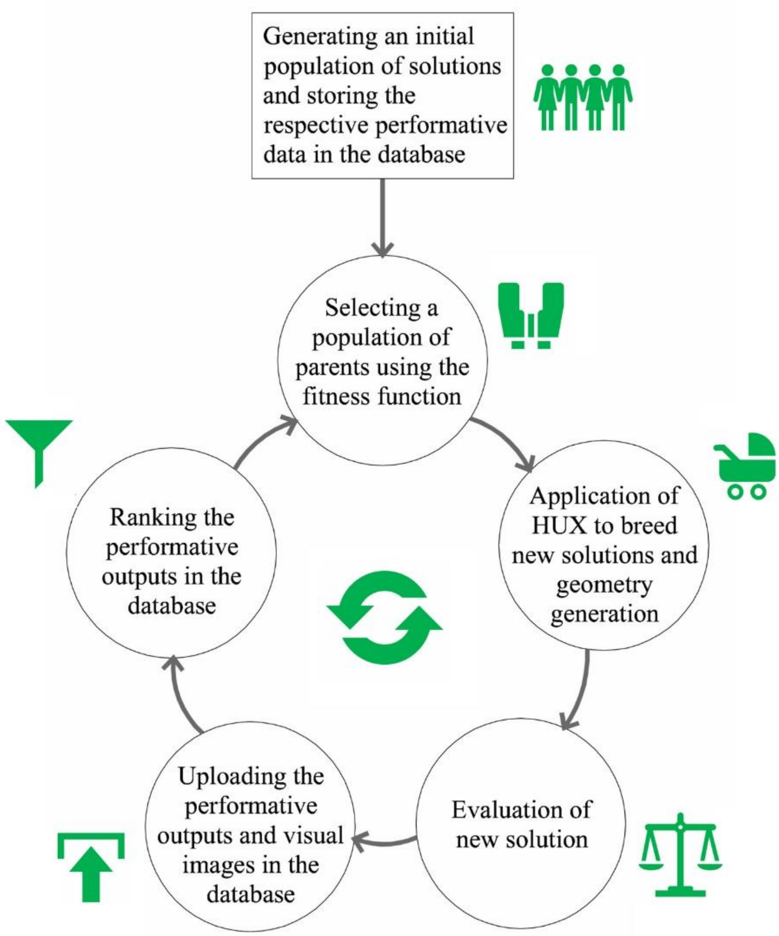


Figure 11: A cycle of the ParaGen form exploration process

Using the ParaGen method, a designer takes the steps of problem structuring, solution generation, evaluation, and decision making as described in the following:

1. Problem structuring and preparatory set up:

    1.1. Creating the parametric model and determining the variables, their acceptable intervals, constant parameters, and their values using, for example, the Grasshopper feature in Rhino or Formian software

    1.2. Setting up the database on the server for storing the input data and output results

    1.3. Setting up the simulation models in, for example STAAD Pro. or Rhino plugins

    1.4. Scripting the macros to link the spreadsheets with the analytical and graphical software

    1.5. Designing the automation model and writing the AutoHotKey (AHK) script to link the steps of form generation, analysis, evaluation, and data storage and create an entire closed cycle
    1.6. Running a few cycles to debug the automation process, and doing the required modifications
2. Initial population generation, primary evaluation, and adjustments:
    2.1. Running around 100 cycles with random input variables
    2.2. Evaluating the generated solutions regarding the relevant design objectives - SQL inquiry, the graphs displaying Pareto sets, and images of the solutions can be used to make a decision
3. Systematical solution generation and evaluation until satisfaction and termination of exploration:
    3.1. Setting the fitness function regarding the design objectives and the designer's preference
    3.2. Generating a series of solutions based on the fitness function
    3.3. Evaluating the generated solutions and taking steps 3.1. and 3.2. until being satisfied
4. Making the final decision

The ParaGen steps are also comparable to Lawson's design process. The four main ParaGen steps can fit into the four phases of problem structuring, solution generation, evaluation, and decision making with some back and forth movements. Figure 12 demonstrates the parallelism of the ParaGen form exploration method and Lawson's design process and Guildford's concept of convergence and divergence.

In addition, similar to other evolutionary exploration methods, there are multiple divergences and convergences within the ParaGen iterative steps. The divergent-convergent pattern is similar to the one illustrated in Figure 6. First, there is a divergent phase to generate random solutions. Then, when the fitness function is set and adjusted throughout the iterative process of form exploration, there can be several divergences and convergences until the exploration is terminated.

The ParaGen method provides interaction in three ways. First, ParaGen generates a searchable database of solutions which can be explored interactively for different and multiple combinations of objectives. This allows the designer to specify or adjust a preference, and (re)define the fitness function at the beginning of each set of the iterations.

Second, the ParaGen web interface allows the user to filter and sort the solutions based on any combination of geometry or performative parameters [1]. Similar to utilizing a telescope to observe one or some specific stars, the ParaGen web filters can be applied to focus on a well-performing set of solutions. Thus, the designer can inspect this manageable quantity of filtered solutions and make selections for further breeding if it is required.

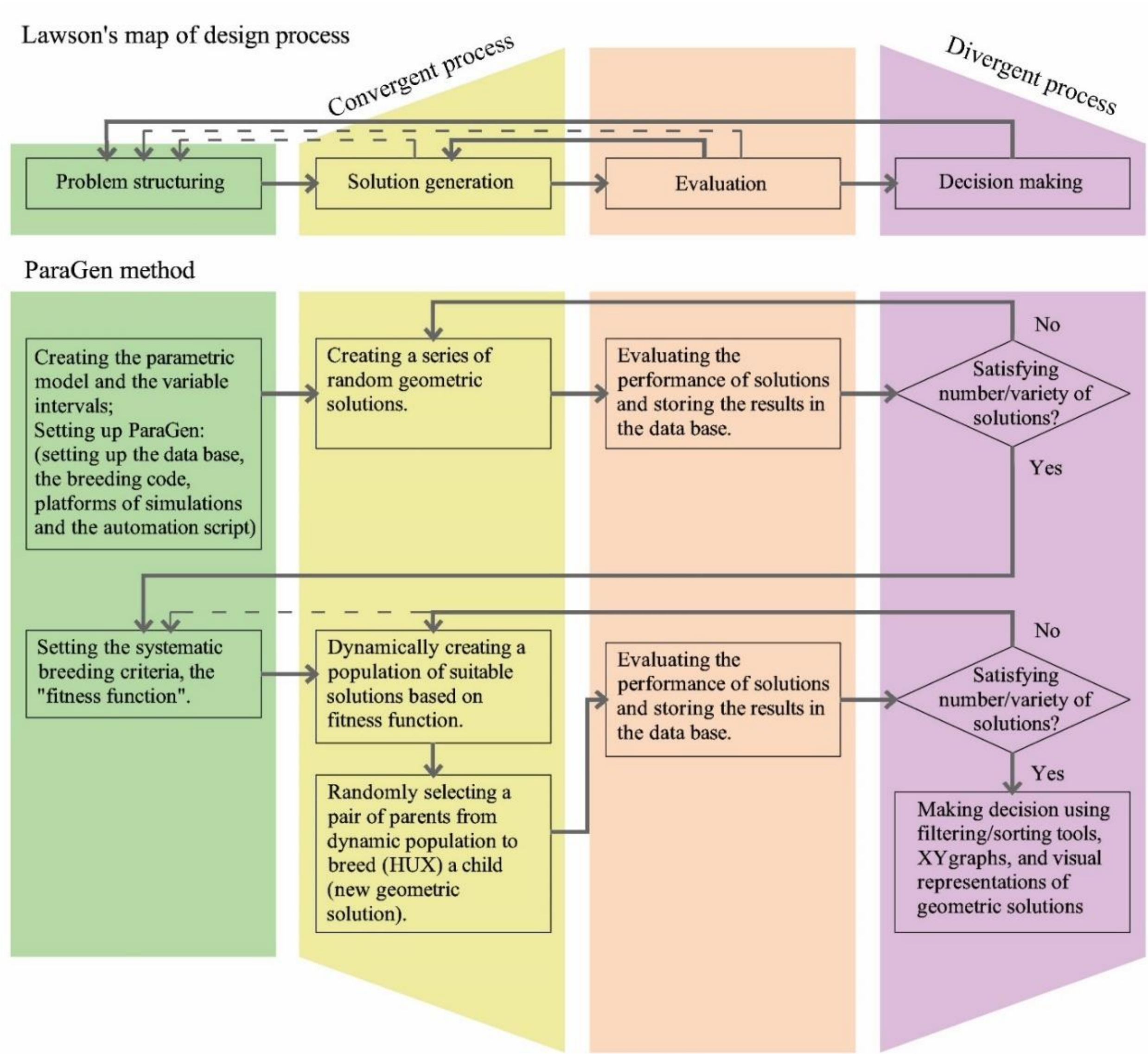


Figure 12: Parallelism of Lawson's map of the design process, Guildford's concept of convergent and divergent process, and the ParaGen method *[53]*

Third, ParaGen improves the readability of the information by three visualization techniques:

- The web interface provides both images and key performance values associated with each solution [1]. The images may display the geometrical configuration of the solutions or diagrams indicating some certain performance assessments (see Figure 13).
- The ParaGen website provides post-processing through scatter point graphs of solution clusters or Pareto fronts and parallel point graphs. These tools, combined with an array of solutions' images as shown in Figure 14, help the user explore the most desirable solutions [1].
- For any set of filtered solutions, the corresponding Parallel Coordinate Plot (PCP) is computed and represented in the ParaGen website [54]. The PCP is known as a common method of visualizing multivariate data in an n-dimensional space [55]. The plot consists of multiple vertical, equally spaced, parallel axes that represent the dimensions of all the dependent and independent design parameters. Each generated solution is represented by a polyline that intersects the parallel axes at the corresponding points. Some patterns of a PCP indicate on the relation among the variables. For instance, parallel lines between two axes confirm a direct relation, and X-shape lines (also known as rotation) express an inverse relation. In the ParaGen website, it is possible to alter the order of vertical axes and study the relation between any pair of variables. The weakness of PCP is the legibility problem, especially when there are several variables to study or the solutions cluster around a certain point. An example of PCP is shown in Figure 15. The plot demonstrates 12 generated solutions for designing a timber folded plate dome. This exploration project is discussed further in Chapter 3.

In Chapter 3 of this dissertation, examples of exploring solutions for a design problem using ParaGen method is described. Further examples of the application of ParaGen in conceptual design exploration can be studied in [52, 56, 9].

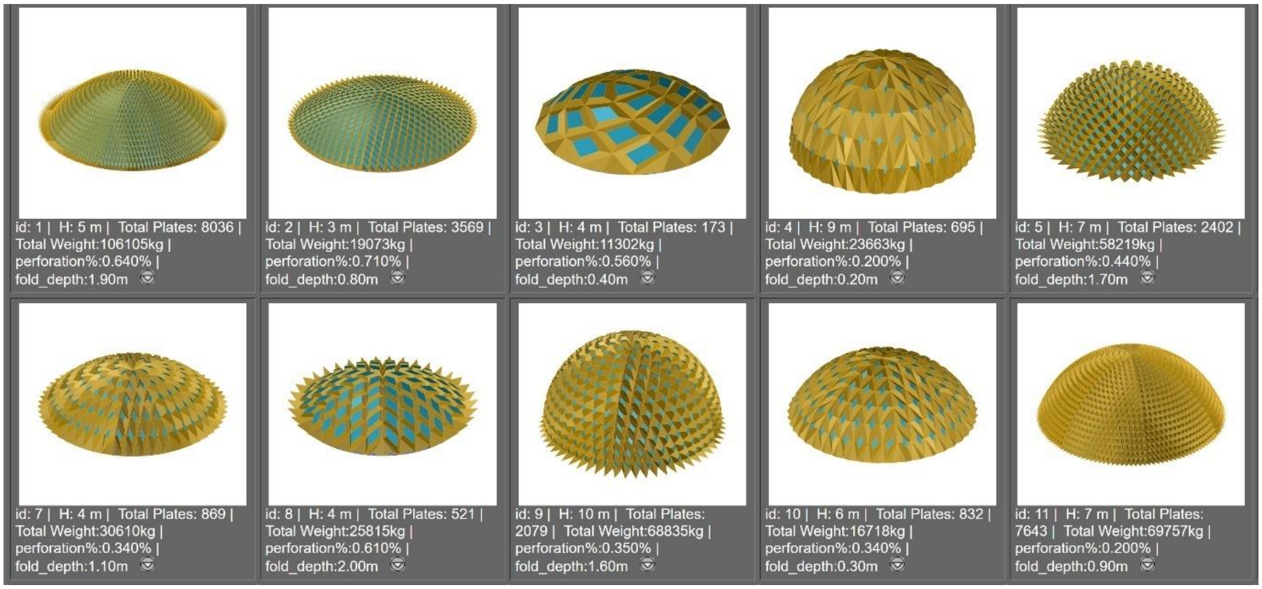


Figure 13: The ParaGen web interface provides both images and key performance values associated with each solution. Further information about the associated design exploration project of the images shown in this figure can be found in *[53]*.

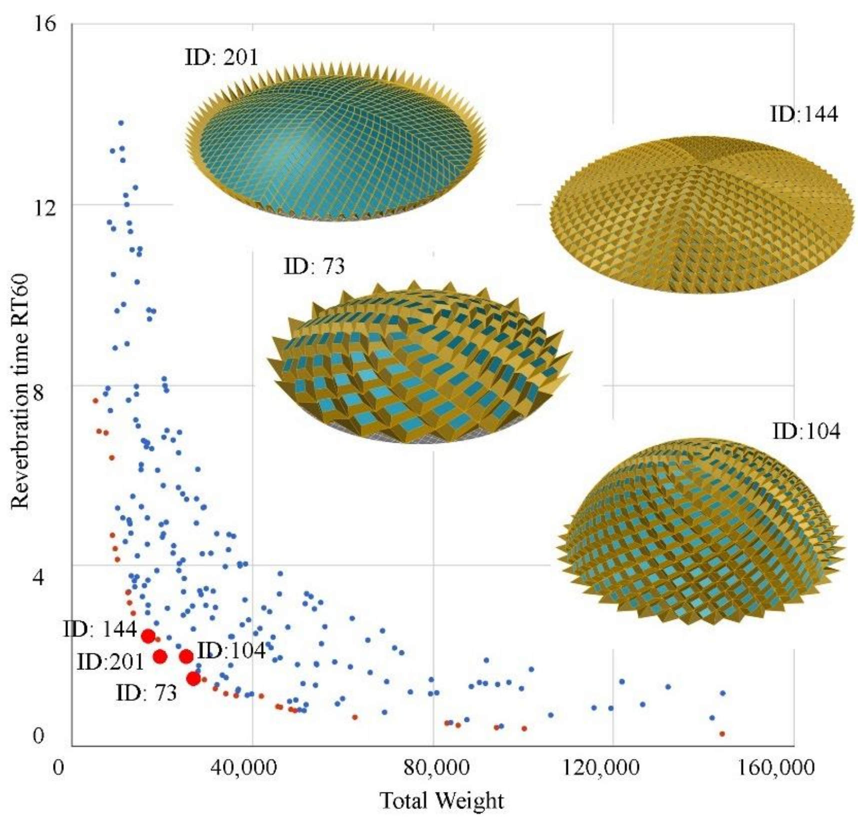


Figure 14: Distribution of solutions generated to obtain light-weight folded plate domes with low reverberation time (RT60). Further information about the associated design exploration project of the images shown in this figure can be found in *[53]*.

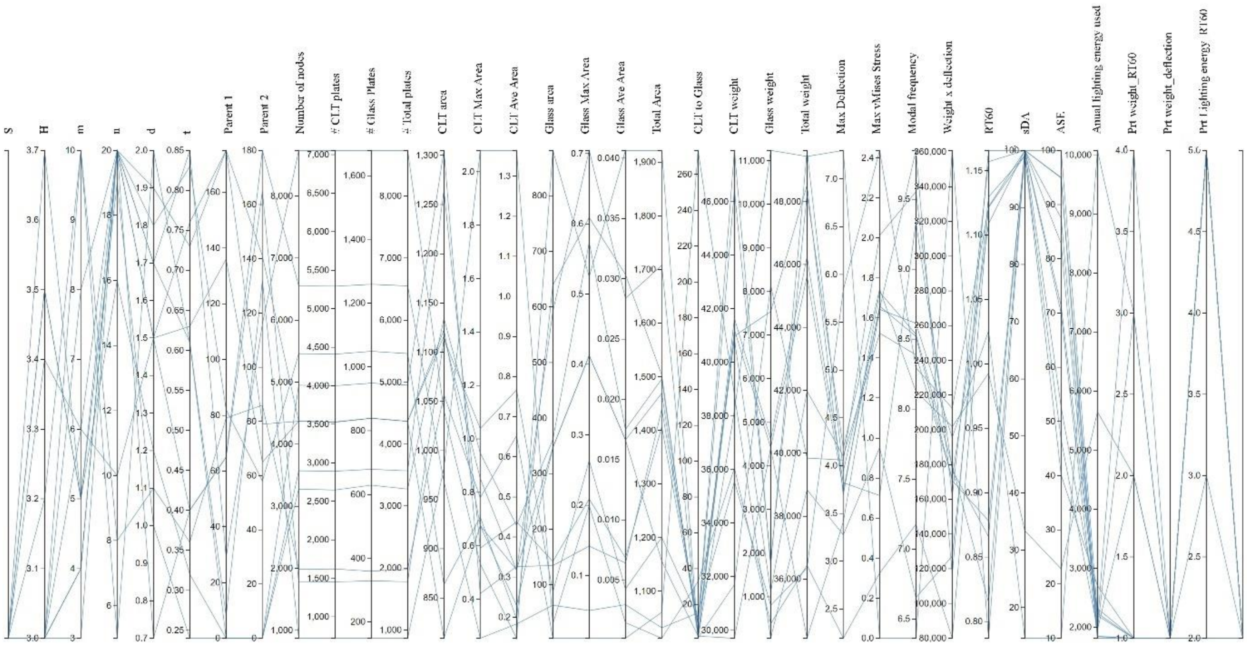


Figure 15: A parallel coordinate plot of 12 generated solutions for designing a timber folded plate dome. Further information about the associated design exploration project of the images shown in this figure can be found in *[53]*.

2.5.6. Efficiency enhancement techniques

Sometimes there are several different software engaged in the computational modeling and analyses or the simulation process requires hours to be completed. Then, the exploration of solutions may take days or even a month to be accomplished. To decrease the exploration time and to increase the efficiency of the application of GA in the search process, some specific methods are utilized. The first and most common method is parallelization where the computational load is distributed on parallel machines. Since the ParaGen method avoids duplication of solutions, it is possible to run the GA on several processors and speed up the entire exploration process.

The second efficiency enhancement technique is hybridization where a GA is coupled with a local search algorithm. Although this technique may slightly increase the computational time, it improves the quality of solutions. The local search algorithm may be something simple to act merely on a chromosome. Also, the local operator may be another search approach to assist in uncovering the design problem, selecting the breeding population, and setting the fitness function. In fact, the GA+TRIZ method, introduced in Chapter 3, is a hybridization of ParaGen method with the Theory of Inventive Problem Solving (TRIZ).

2.5.7. Summary and discussion

Using ParaGen method requires certain knowledge, skills, and facilities. Running the form exploration cycle involves programming and working with some specific software. Similar to many computational tools, used in any discipline or for any purpose, sometimes license requirements and the availability of the software may be an issue. Also, some bugs and problems with the compatibility of employed software systems may cause errors. However, all these matters are common in any CAD tool and in return will be paid off by assistance in design procedure and decision making. The ParaGen form exploration method can expand the designer's perspective by providing a number of suitable solutions with different geometry and performative properties. The result is not limited to a single best solution or an explicit quantitative evaluation. Considering the number of generated solutions, this procedure is relatively time efficient. Furthermore, the efficiency enhancement techniques can be utilized to improve the exploration process. Parallelization and hybridization which are employed in the GA+TRIZ method, are discussed in Section 2.5.7.

2.6. Revolutionary methods of problem-solving

Lawson cites Eastman and Agabani as the researchers who compare the phrase of *revolutionary thinking* in contrast to *evolutionary approach* [18]. In literature, revolutionary problem-solving approach refers to starting an entirely *new train of thought* while evolutionary methods rely on the gradual enhancement of solutions until being satisfied. To take a revolutionary action within a design process, the designer requires either to look for a new definition of the problem or investigate an entirely different aspect of the problem. The Theory of Inventive Problem Solving, as described in the following section, supports this alteration of the train of thought.

2.6.1. Theory of Inventive Problem Solving (TRIZ)

The Theory of Innovative Problem Solving, known with its Russian abbreviation TRIZ, was developed by Genrich Altshuller, the Soviet scientist and engineer, and his colleagues in the 1960s. Altshuller and his colleagues believed that invention is a predictable process governed by some certain laws [57] [58]. They tried to change the basis of thinking from *trial and error* to *learn from the past successes* [59]. They studied certain regularities and basic patterns of about 400,000 technological patents to devise TRIZ concepts and methods. Later, the scientists and theorists expanded the essential TRIZ principles by examining 2.5 million inventions and combined this theory with other methods to employ it in diverse fields of knowledge [59]. Many other theories such as CROST (Constructive Resources-Oriented Strategy of Thinking and Transforming) and bioTRIZ were developed based on TRIZ essence [59] [60]. Accordingly, TRIZ has been developed not to be merely a theory or a set of principles. It is a knowledge-based systematic methodology of innovative problem solving for technical problems [61].

Several studies have been published that explain the way novice and expert designers work and how their approaches differ. Novice designers usually begin with gathering information and then use *trial and error* to generate, modify, evaluate, and regenerate solutions through many iterations [62] [63]. In contrast, experts have been exposed to a large number of problems and their corresponding solutions. Hence, they can recognize the underlying principles rather than focusing on the surface features of problems [64]. They use explicit problem decomposition strategies and make a preliminary evaluation of their tentative decisions before making a final evaluation [63] [62]. Correspondingly, TRIZ allows practitioners to act similar to experts: make use of past success, synthesizing the problem into its basic factors, and concentrating on principles.

There are several problem-solving methods such as TRIZ tools, brainstorming, mind mapping, lateral thinking or morphological analysis. Most of these methods are to provide specific factual solutions to specific factual problems directly. However, the distinctive feature of TRIZ is the process in which a specific technical problem is reduced to its essentials and restated as a generic problem. Then, the problem can be matched with one or more of the generic solutions. The designer or decision maker should innovatively transform the generic solution to a specific factual one (see Figure 16).

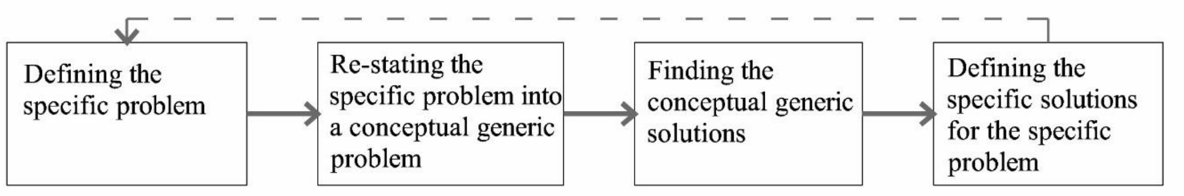


Figure 16: The main structure of the TRIZ problem-solving process

There are several TRIZ tools and concepts such as contradiction matrix, ideality, and patterns of evolution [61]. In this study, the matrix of contradiction and the 40 inventive principles are chosen to be integrated with the GA-based method of ParaGen because of three reasons. First, TRIZ is a systematic way of problem-solving while some of the other problem-solving methods merely provide a list of discovered patterns that one may explore. Edward Allen's Rules of Thumb [65], Alexander's 253 patterns of problem-solving or 15 geometrical properties are examples of such lists [66, 67]. Second, some of the other methods, are less abstract and more applicable in some specific disciplines or contexts. Third, TRIZ principles are analytical, formulaic and teachable. In particular, the contradiction matrix, has the potential to be represented in the form of software or code. There, it is possible to combine it with another computational design tool and benefit from their synergic effect.

2.6.2. The matrix of contradiction and 40 inventive principles

The contradiction matrix addresses the incompatibility of desired features within a system. A designer should study the pertinent functions, identify the useful functions and harmful ones, notice and uncover the contradictions among the design parameters. Then, the designer can refer to the matrix of contradiction where the 39 functions to be improved, and those which are getting worse are listed along the rows and columns respectively (see Figure 17). The 39 functions, also known as 30 engineering parameters, are listed in Table 1. Within the corresponding cells of the matrix, some of the inventive principles which may help to resolve the contradictions are listed [59, 62, 68]. The list of 40 inventive principles is provided in Table 2. The complete matrix of contradictions can be found in Appendix 1. Furthermore, Appendix 2 provides descriptions and some examples of each 40 inventive principles.

To demonstrate how this matrix can innovatively be applied to resolve contradictions among design objectives in the field of architecture, an example of designing a one-bedroom unit, can be given. If the goal of our design is to obtain a unit with large windows, large floor area, and low energy demand, we will encounter a conflict between the first two goals and the last one. The contradiction matrix of this design problem can be set as it is done in Table 3. The suggested inventive principles from Table 2 to solve the contradictions are:

- Transition into a new dimension
- Nesting dolls (matryoshka)
- Flexible membranes or thin films

In architectural language, these suggested inventive principles may respectively be interpreted as:

- Trying different configurations of windows and floor plan to reduce loss of energy, or thinking of a skylight instead of placing the windows on the walls
- Choosing double glazed windows or double layer exterior walls to reduce energy loss
- Using retractable shading screens to control the sunlight exposure

Characteristics			Characteristic that is getting worse						
			1	...	4	...	13	14	...
Characteristic to be improved	1	Weight of a mobile object			-		1, 35 19,39	28, 27 18, 40	
	...	...							
	4	Length of a stationary object	-				39, 37 35	15, 14 28, 26	
	...	...							
	13	Length of a stationary object	21, 35 2, 39		37			17, 9 15	
	14	Length of a stationary object	1, 8 40, 15		15, 14 28, 26		13, 17 35		
	...	...							

Figure 17: A selected part of the contradiction matrix. Characteristics that may get worse are listed along the columns, and the characteristics that may be improved are listed in the rows. There are 39 parameters along the columns and the same numbers along the rows. Within the matrix, the suggested principles to solve the contradictions between the two parameters are listed in the respective cells.

Table 1: The list of 39 parameters *[69]*

	Engineering parameters		Engineering parameters
1	Weight of a mobile object	21	Power
2	Weight of a stationary object	22	Loss of energy
3	Length of a mobile object	23	Loss of substances
4	Length of a stationary object	24	Loss of an information
5	Area of a mobile object	25	Loss of time
6	Area of a stationary object	26	Amount of substance
7	Volume of a mobile object	27	Reliability
8	Volume a stationary object	28	Accuracy of measurement
9	Speed	29	Accuracy of manufacturing
10	Force	30	Harmful factors acting on an object from outside
11	Tension/Pressure	31	Harmful factors developed by an object
12	Shape	32	Manufacturability
13	Stability of composition	33	Convenience of use
14	Strength	34	Repairability
15	Time of action of a moving object	35	Adaptability

16	Time of action of a stationary object	36	Complexity of a device
17	Temperature	37	Complexity of control
18	Brightness	38	Level of automation
19	Energy spent by a moving object	39	Capacity / Productivity
20	Energy spent by a stationary object		

Table 2: The 40 TRIZ inventive principles *[69]*

	Inventive principles		Inventive principles
1	Segmentation	21	Rushing Through
2	Extraction (Extracting, Retrieving, Removing)	22	Convert Harm into Benefit
3	Local Quality	23	Feedback
4	Asymmetry	24	Mediator
5	Consolidation	25	Self-service
6	Universality	26	Copying
7	Nesting doll (Matryoshka)	27	Dispose
8	Counterweight	28	Replacement of Mechanical System
9	Prior Counteraction	29	Pneumatic or Hydraulic Constructions
10	Prior Action	30	Flexible Membranes or Thin Films
11	Cushion in Advance	31	Porous Material
12	Equipotentiality	32	Changing the Color
13	Do It in Reverse	33	Homogeneity
14	Spheroidality	34	Rejecting and Regenerating Parts
15	Dynamicity	35	Transformation of Properties
16	Partial or Excessive Action	36	Phase Transition
17	Transition into a New Dimension	37	Thermal Expansion
18	Mechanical Vibration	38	Accelerated Oxidation
19	Periodic Action	39	Inert Environment
20	Continuity of Useful Action	40	Composite Materials

Table 3: The contradiction matrix of the one-bedroom unit design project

	22. Loss of energy
6. Area of a stationary object (windows)	17. Transition into a New Dimension, 7. Nesting doll (matryoshka), 30. Flexible Membranes or Thin Films
6. Area of a stationary object (floor area)	17. Transition into a New Dimension, 7. Nesting doll (matryoshka), 30. Flexible Membranes or Thin Films

Another example is the design of a truss bridge with the widest free span and the least possible weight. The matrix of contradiction will be as Table 4. Having a bridge with a wide free-span may also be considered as having a stronger and more stable structure. The matrix of contradictions offers different suggestions. The principle number 40 is offered in all the cells of the matrix, which is using composite materials to increase the useful functions and reduce the undesirable one. The designer may also consider other suggested solutions.

Albeit, employing the matrix of contradiction is not always as simple as the two given examples. First of all, the designer is required to identify the contradictions among the design objectives correctly. Occasionally, the initial objectives that are in contradiction are not apparent, and the designer should use some equations or analysis to synthesize the conflicting parameters into their basic factors. Second, interpreting the generic solutions into specific solutions may not be straightforward. Although there are some useful tables that explain more details about each of the 40 inventive principles, the designer still should be creative to understand the hint and take the appropriate action.

Table 4: The contradiction matrix of truss bridge design project

	2.The weight of a stationary object (the bridge)
4. Length of a stationary object (length of the bridge)	35. Transformation of Properties 28. Replacement of Mechanical System 40. Composite Materials 29. Pneumatic or Hydraulic Constructions
13. Stability of composition (stability of bridge)	26. Copying 39. Inert Environment 1. Segmentation 40. Composite Materials
14. Strength (structural strength of the bridge)	40. Composite Materials 26. Copying 27. Dispose 1. Segmentation

In a design problem, the contradictions may be physical or technical. A physical contradiction appears when there is inconsistency within a certain function in a system. In other words, existence of a physical contradiction means we want opposite benefits. For example, in a house, we may want large windows to provide more daylight while we want to have small windows to reduce the loss of thermal energy in winter. The physical contradiction may be resolved by separating the solutions in time, in place, in scale or on condition. In the given example, we can separate the time that we need large windows and small windows. We can use additional layer or shading system on the windows to change the dimension of the exposed glass area during the daytime to benefit from daylighting and have a wider view in the morning but avoid heat transmission at night. In the list of 40 inventive principles, we can find ideas to help us solving physical contradictions.

A technical contradiction emerges when improvement of some certain attributes cause deterioration of other attributes within a system. For example, increasing the length of a bridge leads to having a relatively heavier structure.

In the matrix of contradiction, the same parameters along columns and rows intersect at blank diagonal cells. The blank cells indicate the applicability of all the 40 inventive principles for finding a suitable solution for resolving physical contradictions. The solutions suggested in the other cells of the matrix can help to resolve the technical contradiction [70].

2.6.3. The background of application of TRIZ in the architecture design

Hue et al. reviewed the literature of integration of TRIZ with other problem-solving techniques from 1995 to 2006 [71]. Chechurin and Borgianni have explored papers, published by 2016, where TRIZ or the Theory of Inventive Problem Solving is in their title, abstract or keywords [72]. They analyzed the 102 most cited paper about TRIZ in Scopus and classified their topics in 10 different groups:

- Presentation of classical TRIZ and relevant concepts and principles; Through this cluster of papers, potential benefits and experienced challenges of TRIZ application are discussed
- Transferring systematic technology from biology to engineering using TRIZ, developing Bio-TRIZ inventive principles and representation of the biology-tailored contradiction matrix
- Integration of TRIZ and computer-based frameworks
- Supporting creativity techniques using TRIZ
- The contribution of TRIZ in practice; (However the common context of the experiments is educational)
- Mutual use of TRIZ and other design exploration techniques
- The synergy of TRIZ and quality management tools
- Application of TRIZ in sustainable design
- Decision-making using TRIZ principles

- TRIZ in information processing and intellectual properties

Chechurin and Borgianni assert that studied references reflect the positive role of TRIZ in improving ideation and problem-solving procedure. However, some references indicate the inefficacious application of TRIZ in tackling complex problems. Often it is believed that the TRIZ practitioners find the application of its toolkit effective when they master the relevant principles. Some attempts have been reported to introduce General Theory of Powerful Thinking (OTSM-TRIZ) to overcome such limitation [73]. But studies rarely targeted the expansion or redefinition of TRIZ techniques, and the research works ended up with justification of the contradiction matrix or the inventive principles for a specific field of knowledge.

In several references, the combination of TRIZ and other ideation/problem-solving methodologies has been represented. The literature includes conjoining of TRIZ and Case-Based Reasoning, Quality Function Deployment (QFD), Axiomatic Design (AD), Design for Manufacturing (DFMA), Value Engineering (VE), Theory of Constraints (TOC), Six Sigma, or Genetic Algorithm (GA) [72]. Furthermore, the integration of TRIZ and computer-aided innovation/design, in particular computational optimization, has been addressed in many references. There are also examples of producing a computational design coach that through a natural-language dialog-like interaction assists the designer in solving a problem [74]. However, most of the relevant publications are centered in the field of mechanical engineering which is traditionally the main domain for TRIZ application.

In addition to TRIZ concepts and principles, Altshuller's approach to analysis of patented inventions and classification of their innate innovative principles has been inspiring for some scholarly works. For example, Jugulum and Frey studied a large number of patents documented in the United States to extract a set of problem-solving strategies [75].

Narrowing down the scope of published papers to the topics addressing the application of TRIZ in the field of conceptual architectural design, four main subjects can be identified:

- An introduction to TRIZ concepts and tools along with examples in the field of architecture
- Comparison between TRIZ and some architecture design theories and rules of thumb and an attempt to architecturally interpret the TRIZ concepts and principles

- Investigation of the feasibility and impediments of TRIZ application in architecture field
- Examples of using TRIZ in the designing building components such as windows, ramps, façades, and roofs

Ilevbare et al. studied the TRIZ tools, benefits, and challenges. They asked a group of TRIZ enthusiasts, practitioners, and industry professionals from several parts of the world to identify the fields where they have applied TRIZ principles and to indicate the tools that were used most often [76]. Also, the participants were asked about the benefits they have gained and the challenges they have faced in applying such methodology. The study provides good insights into the issues associated with TRIZ application, but it is not as accurate as expected. The studied population does not seem to be homogenized, regarding the participants' level of knowledge, their proficiency in applying TRIZ, and the field of specialization to generalize the result as it has been done. Furthermore, the size of the studied population is 40 individuals and according to Kukran formula [77], it is insufficient to conclude the respondents' feedbacks.

Cathain compared TRIZ with Aristotle's definition of rhetoric and offered a philosophical narration of TRIZ [78]. Najari compared *the 40 inventive principles* with Christopher Alexander's 253 recurrent patterns of problem-solving employed in the design and construction of towns and buildings. He also contrasted *the patterns of evolution* with Alexander's 15 Geometrical Properties of architectural spaces analyzed and defined by empirical methods. Najari pointed out the differences among the two theorists' perspectives and concluded that Alexander is concerned about *what are the recurring architectural problems* and *what are their known solutions* and he tends to adapt them to a context. Alexander emphasized *socio-spatial aspects* while Altshuller focused on *technical aspects*. Alexander's patterns are less abstract, and the models of solutions are less generic and consequently, less successful to be broadly employed [79].

Labuda [80], Mann and Cathain [81] made attempts to architecturally interpret TRIZ concepts and principles. They represented several examples of the 40 inventive principles applicable in the field of architecture. TRIZ works through suggesting a generic solution for a generalized problem. Then, the designer is encouraged to creatively think of specifying the generic solution to fit the specific problem. Basically, the idea of specifying the 40 inventive principles to a list of examples applicable in the field of architecture seems suitable to broaden the designer's perspective to find her own specific solution.

Nazidizajia et al. compared the *concept of ideality*, *patterns of evolution* and *contradictions* in the viewpoint of TRIZ practitioners and architects [82]. However, sometimes comparison of such notions in two different literatures may be misleading. For example, ideality and evolution in TRIZ literature point to certain definitions and principles. While in architecture literature, the definition of *ideality* varies from person to person or culture to culture, and *evolution* is rather a vague trend.

There are some cases of application of TRIZ in the field of architectural technology that describe the TRIZ concepts and principles for architect [12] [83] [84] [85] [86]. However, they do not contribute to the computational design field at the same time. Hannan discusses the feasibility of integration of TRIZ with a decision-making system called Miles Value Methodology (MVM) (see Figure 18). He believes that TRIZ facilitates the idea generation but does not follow the problem situation to the implementation phase. He points out that those who require employing the tool within not only the preliminary phase of their project but also the implementation and operation phases should take this into account [13].

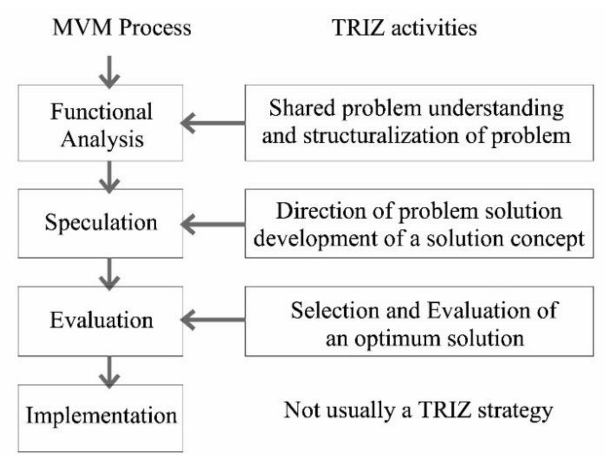


Figure 18: The combination of MVM and TRIZ. The figure is re-drawn by Anahita Khodadadi with minor modifications *[87]*.

Lee and Deng integrated TRIZ with CBR method. CBR method is a process of creating a new design solution by combining and/or adapting previous design solutions. A general CBR cycle retrieves the most similar case or cases and reuses the information and knowledge in that case to solve the problem. Then, the proposed solution is revised, and the useful parts of this experience for future problem solving is retained. The CBR+TRIZ approach includes three steps: (1) analyzing the design problem, (2) identifying the problem, (3) acquiring the innovation idea. TRIZ integrates into the process between the first and second step (see Figure 19) [87]. This model seems supportive for case studies that learn from previous experiences, but it is not suitable for population-based exploration systems.

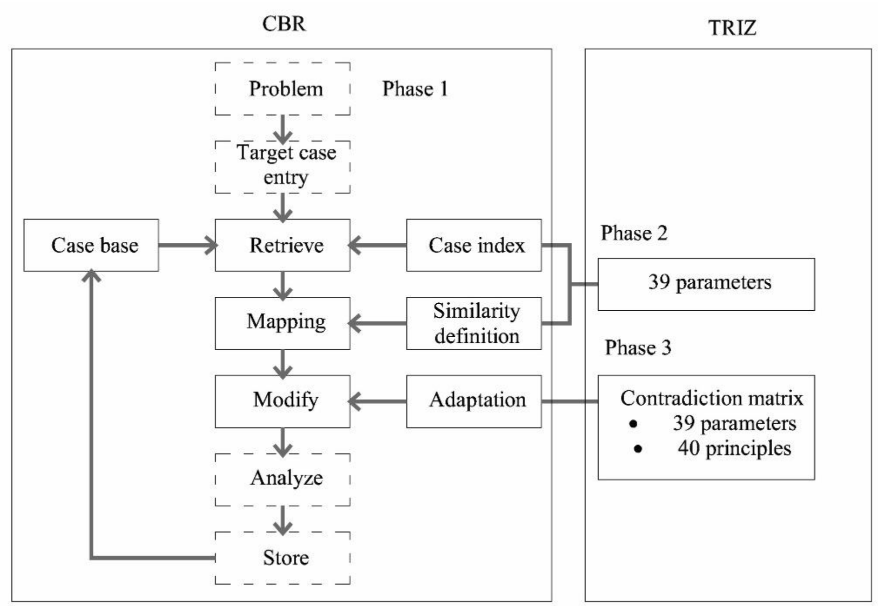


Figure 19: The combination of CBR and TRIZ. The figure is re-drawn by Anahita Khodadadi with minor modifications *[87]*.

Najari et al. [88] also accomplished a case study to explore the possibility of adapting the TRIZ concept of contradiction as a conceptual strategy in the phase of conceptual design. His case includes the project of extension of INSA de Strasbourg which is formulated in the form of a graph using the Inventive Design Method (IDM-TRIZ). The focus of the related paper is more on the problem definition and examining the combination of IDM and TRIZ methodology rather than design computation. The main achievement of Najari et al. are the development of a legible illustration of contradiction among design objectives and constraints in the form of a graph (see Figure 20). The corresponding graph of a certain design problem can be further utilized in computational design exploration.

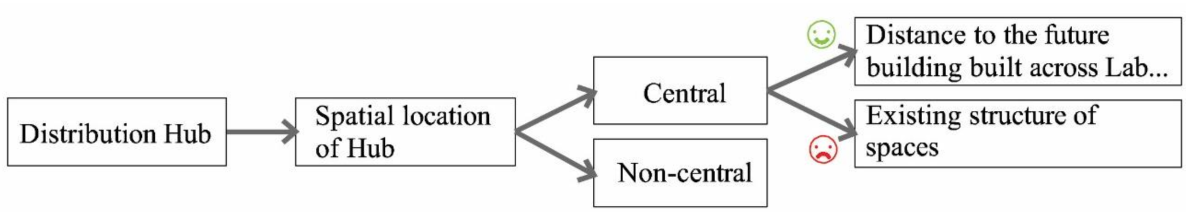


Figure 20: The illustration of contradiction among the design objectives and constraints of the INSA project developed by Najar et al. Useful and harmful functions are highlighted to be able to employ the matrix of contradiction. The figure is re-drawn by Anahita Khodadadi with minor modifications *[88]*.

2.6.4. Summary and discussion

TRIZ tools, such as the 40 inventive principles, are derived from the observation and analysis of over 2.5 million inventions, and practitioners can benefit from the treasures of the past engineering experiences. One may argue how TRIZ can contribute to the field of architecture, while its principles have been primarily developed to assist inventors in proposing patentable technical systems. In response, two matters should be addressed: the technological aspect of architecture and the benefits of interdisciplinary exchange of knowledge. A building is assumed to be a technical system since it performs a function and like other technical systems it is composed of some sub-systems, such as mechanical and structural systems. Also, a building relates to some super-systems such as a neighborhood, region, and city. Therefore, the application of scientific and other organized knowledge is acceptable in the technological aspects of architecture design. Moreover, in the conceptual design phase where multiple disciplines interact to make principle decisions, TRIZ application can facilitate the procedure.

TRIZ can contribute to conceptual architectural design regarding its technological aspect and the benefits of interdisciplinary exchange of knowledge. TRIZ is a systematic way of problem-solving, and its principles are analytical, formulaic and teachable. In particular, the contradiction matrix has the potential to be represented in the form of software or code. Thus, it is possible to combine it with another computational design tool such as ParaGen and benefit from the advantages of an interactive evolutionary form exploration technique and TRIZ at the same time.

In this study, TRIZ in combination with a genetic algorithm is employed in the early phase of architecture design, and it is expected to:

- Work through a multi-objective setting.
- Prevent the designer from thinking that the elements and rules of the design problem are given and unquestionable.
- Help the designer to state the design problem better and include the pertinent variables in the initial parametric model. This allows the reduction or even elimination of the need for re-doing the simulations and evaluations.
- Work with contradictions among the design objectives and offer inventive solutions.

- Expand the designer’s perspective by providing higher-level information (implicit search goals) while she searches for suitable solutions and is blocked between two conflicting design parameters - There, TRIZ allows the designer to determine different fitness functions and the set of filters to obtain the desired solutions.
- Help to keep the solution exploration relevantly time efficient.
- Provide a strong interaction between the computational design aid and designer while determining the goals and choosing the strategy to solve the problem.
- Allow the designer to determine different fitness functions and filters to obtain the desired solutions.

Chapter 3: Developing the GA+TRIZ Method

3.1. Methodology

The GA+TRIZ method is built using the underlying principles of Lawson's design process and the ParaGen framework. First, the ParaGen steps are compared and aligned with the four main design steps described by Lawson. Then, the TRIZ inventive principles are connected to the GA-base form exploration process at couple of steps.

Presenting the GA+TRIZ exploration method, four design case studies are carried out first using only ParaGen and second using the GA+TRIZ map of work. The four case studies include:

- Form exploration of a timber folded plate dome for a sports facility
- Form exploration of a truss bridge over Huron River in Ann Arbor, Michigan
- Form exploration of a tapered lattice tower comparing with Shukhov Water Tower
- Form exploration of a mid-rise apartment complex in Montreal

In each case, the design process and the result of exploration are compared to the corresponding process and solution space. Four metrics are defined to carry out the comparison:

1. Diversity or similarity: In some design experiences, the designer intends to select a certain configuration among a series of suitable solutions. But she still desires to enhance the performative outputs. In this situation, the similarity of the final solution with the configuration of those suitable solutions is important. On the other hand, sometimes the GA generator yields solutions with the most desirable performance. However, the designer prefers visually diverse solutions to make the final decision. Diversity and similarity are two opposite metrics that allow the evaluation of the visual representation of generated solutions by using the TRIZ inventive principles. The goal is to study the extent to which TRIZ can help to increase the diversity or, in some other cases, the similarity of the solutions. Diversity and similarity can be described either qualitatively, referring to

solutions images provided on the ParaGen website, or quantitatively, studying the database for geometrical values.

2. Performative cost: When performative parameters conflict with one another, improving one parameter means getting far from the optimum value of the other parameter. The distance between a certain performative value of a selected design alternative and that of the generated solution is called performative cost. This metric examines whether all the relevant performative outputs remain in the acceptable interval while we employ TRIZ.
3. Time efficiency: The fitness function allows the convergence of exploration around specific performative outputs by choosing the individuals which are in the select population. Also, it is possible to manually select one or both parents for breeding the new offspring and gain a similar child. The application of TRIZ is expected to support the deliberate convergence. Time efficiency follows the number of generations needed to achieve the final solutions.
4. Amount of data provided for decision making: When the designer is to make the final decision and choose a single solution out of the Pareto set, limiting the selection between two design parameters may be difficult. The matrix of contradictions can bring implicit search goals into account. For example, the designer may want to make a trade-off between the acoustic quality of a dome-shaped space and the total weight of the construction. The TRIZ related analysis may indicate on considering the height and the area of the surface of the dome in place of acoustic outputs. In this case, the designer can decide which of the two suggested parameters is less important for her to make a trade-off with the total weight of the building. The number of parameters relevant to a certain design objective is measured as the amount of data provided for decision making. The greater the number of relevant parameters, the designer can consider different aspects of the design problem and make a better decision.

The case studies are selected from design explorations I have previously accomplished using the ParaGen method. Because within these design cases some conflicts among objective functions have been experienced that triggered the idea of combining a GA-based search algorithm with a problem-solving method. In the four described design cases, various objectives have been proposed to apply the GA+TRIZ method in different contexts. Similar to many real-world problems, in each design case some constraints, such as using a certain building material, have been determined to examine the proposed GA+TRIZ method in complicated situations.

3.2. The GA+TRIZ method

Chapter 2 describes that the ParaGen method includes the following main steps:

1. Problem structuring and preparatory setup
2. Solution generation and primary evaluation and adjustments
3. Systematical solution generation and evaluation until satisfaction and termination of exploration
4. Making the final decision

Also, remember that ParaGen steps take place iteratively, and in each iteration, four tasks of problem structuring, solution generation, evaluation and decision making are carried out. These four tasks are analogous to Lawson's design process (see Figure 12). It is noteworthy that steps of problem structuring and decision making rely only upon the designer's thinking skills and personal experiences. Similar to several computer-aided exploration methods, determination of the design variables, their acceptable intervals, constant parameters and their values and, additionally, making a final decision are carried out without any aid. Here, the TRIZ concept of problem-solving can come into play. TRIZ, itself, is composed of four steps:

1. Defining the specific problem: The designer should define the demanded useful functions of the design and the harmful functions that are to be avoided.
2. Re-stating the specific problem to a generic one: The useful and harmful functions are required to be synthesized into their basic factors.
3. Finding a generic solution: The matrix of contradiction suggests some generic ideas for resolving the technical conflicts.
4. Interpreting the generic solution into a specific one.

These four steps can be added to the ParaGen process in three junctures:

1. Before creating the parametric model, when the design objectives are determined: TRIZ assists in recognizing the relation among design objectives, to see if they are in contradiction or accordance, and to find solutions. At this point, the designer should see if the initial design sketch conforms with the design objectives. Also, she should see if all the pertinent design parameters, which are possible to be considered as variables, are included.
2. While defining the fitness function for the systematic solution generation: TRIZ helps to understand the parameters dependencies better, and it provides implicit search goals. Then, the designer can consider a greater number of relevant applicable parameters to set the breeding criteria.
3. Final decision making and post-processing step: TRIZ allows a more directed convergence around a certain performative output. Additionally, when the designer is interested in a particular configuration and would like to enhance its performance, TRIZ gives hints to the suitable post-processing action.

Figure 21 demonstrates the procedure of the GA+TRIZ method. As this chapter unfolds, design exploration examples are described, and the application of the GA+TRIZ method will be clearer, and its advantages will be evaluated.

3.3. Implementation

The ParaGen website, developed at the University of Michigan Hydra Lab, hosts a set of interactive form exploration projects. Each exploration project is presented in a separate tab. Each project tab includes some drop-down lists, which allow filtering and sorting the solutions, and also information about the generated solutions (see Figure 22). For each project, the array of images of the *solutions* are displayed. The details of the input and output parameters of each solution along with the visual representation of some performative analyses are available under the *detail* tab [89](see Figure 23). It is possible to study the distribution of solutions regarding two selected parameters using an *XY graph*. Within the process of form generation, the designer can manually pick a pair of parents and generate a new offspring under the *select* tab. The .csv file, including the geometric and performative data, along with the images and analysis files can be transferred to the server using the upload tab.

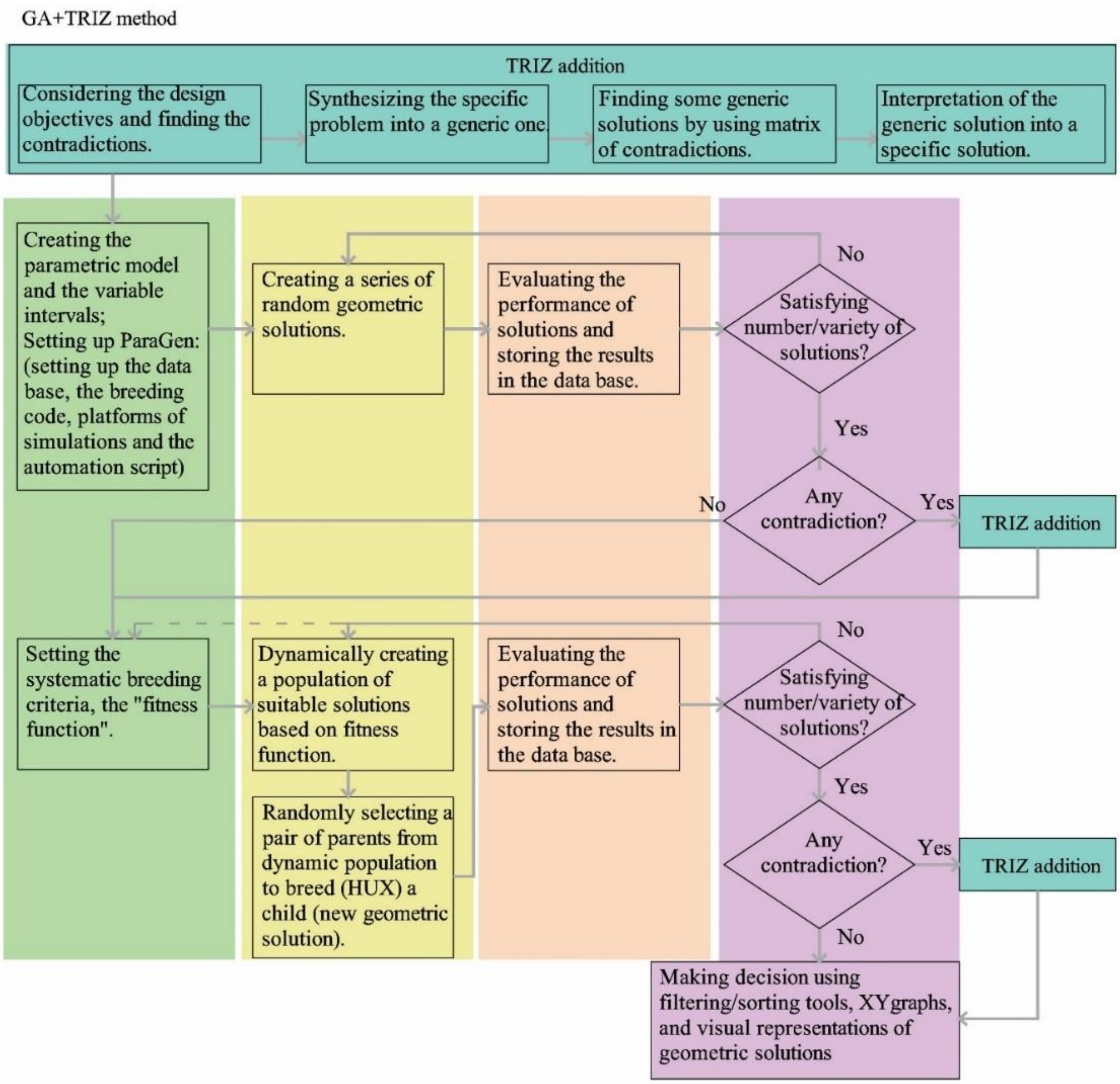


Figure 21: The plan of work in the GA+TRIZ design method

To add the TRIZ application to the ParaGen website, the matrix of contradictions along with the tables of 39 parameters and 40 inventive principles are defined in the database (see Figure 24). Relevant PHP scripts are provided to allow the designer to choose the useful and harmful functions from the respective dropdown lists (see Figures 25 and 26) and get the corresponding generic solutions from the matrix of contradictions. The PHP scripts correspond to TRIZ application on the ParaGen website are provided in Appendices 3 and 4.

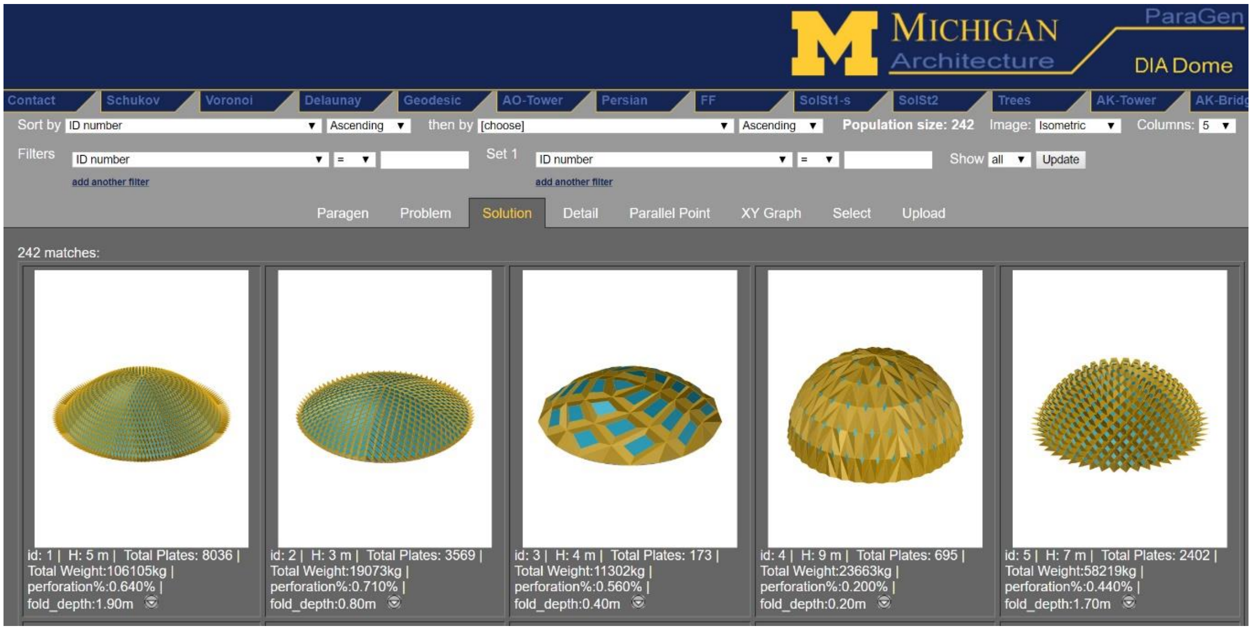


Figure 22: The ParaGen interface

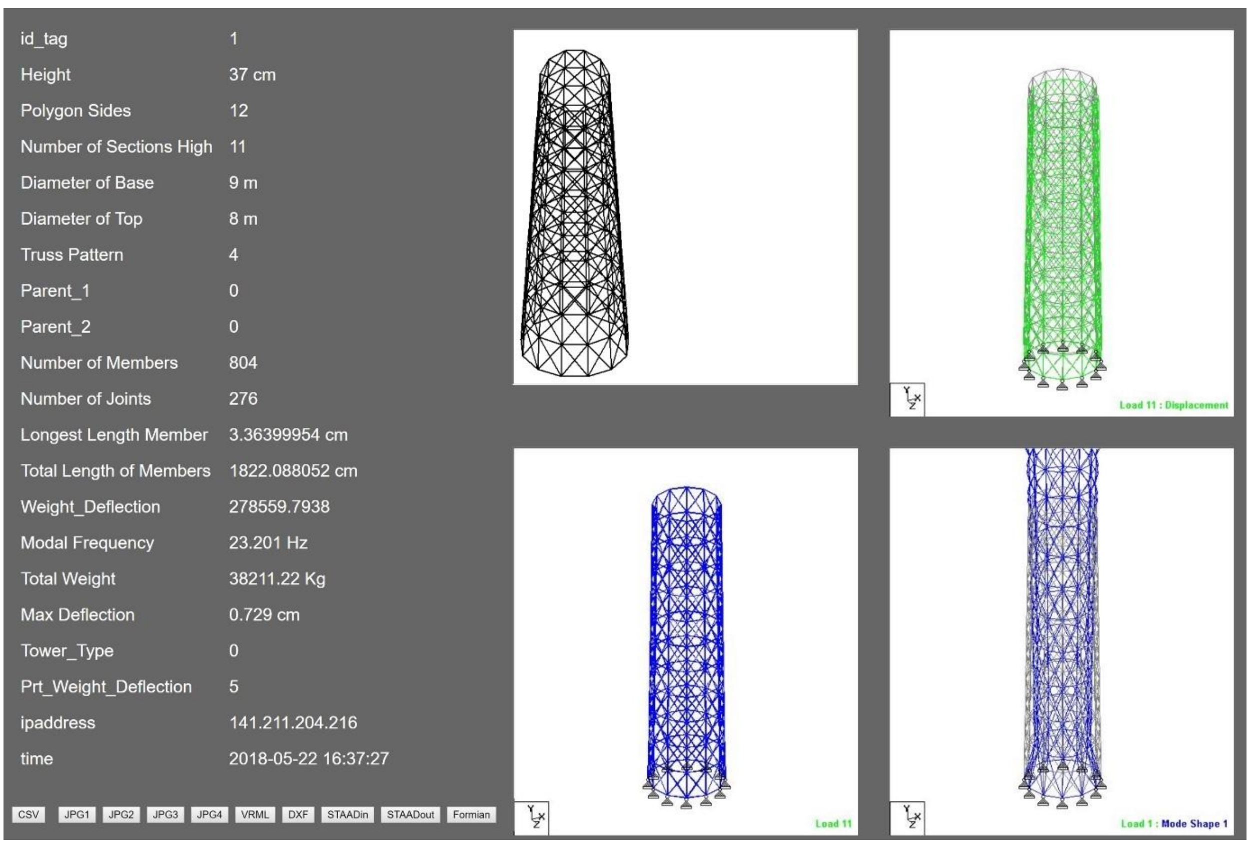


Figure 23: Details of summary of one solution showing both quantitative data and images of performative analyses

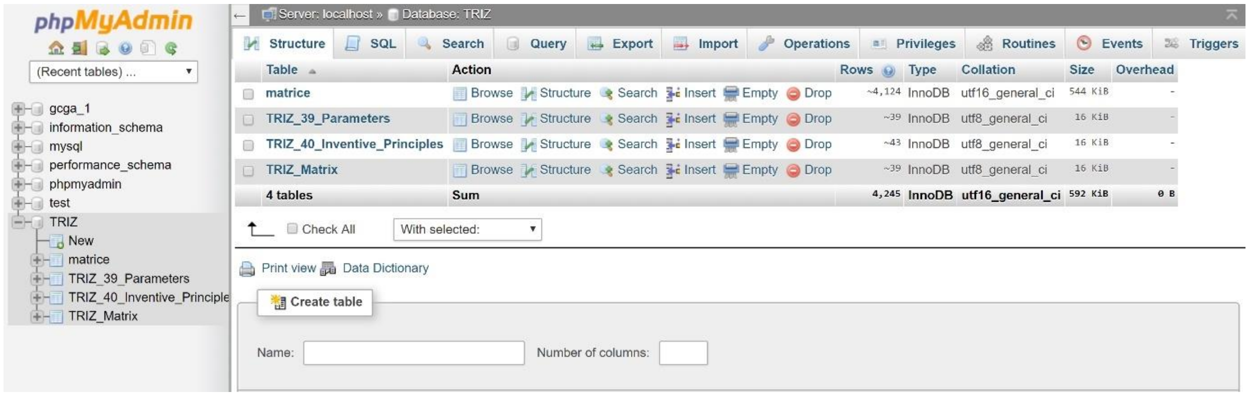


Figure 24: The matrix of contradictions and the tables of 39 parameters and 40 inventive principles are added to the database.

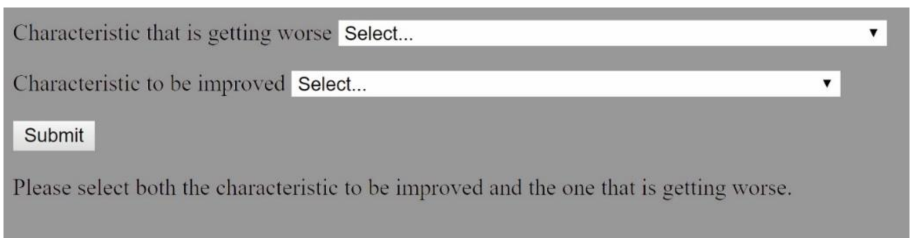


Figure 25: The TRIZ addition interface

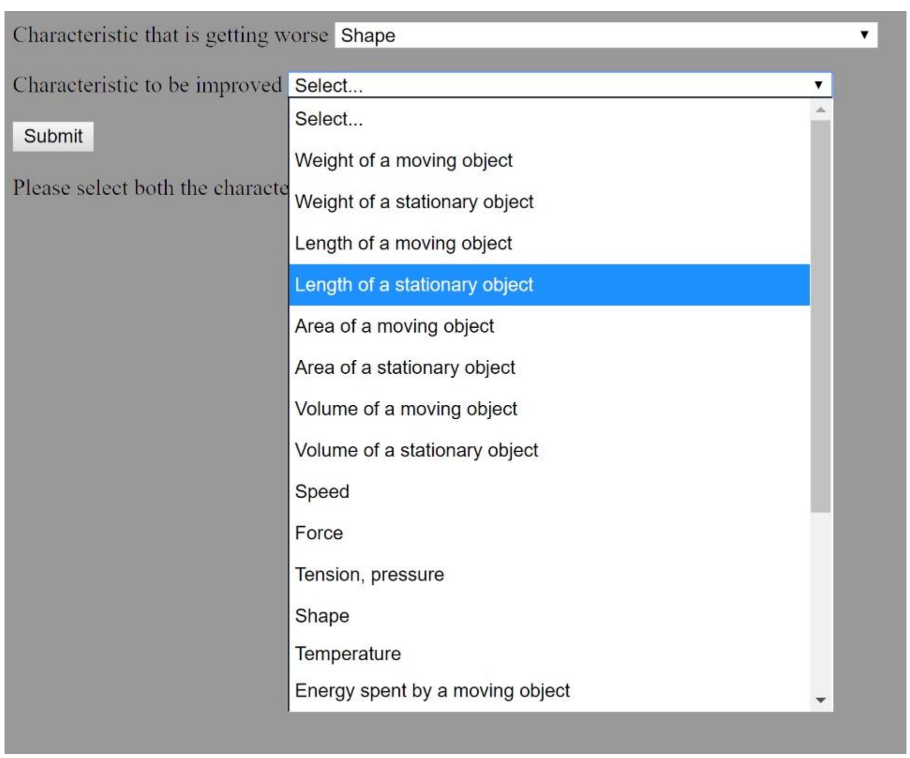


Figure 26: List of the 39 parameters is provided in drop-down lists

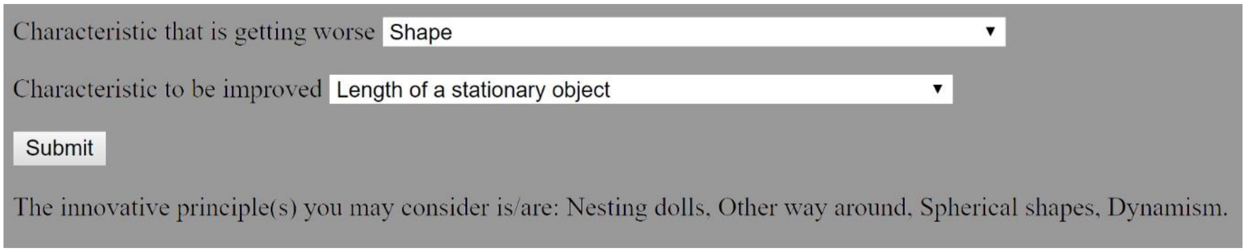


Figure 27: Provided generic solutions for two conflicting parameters of harmful shape and useful length

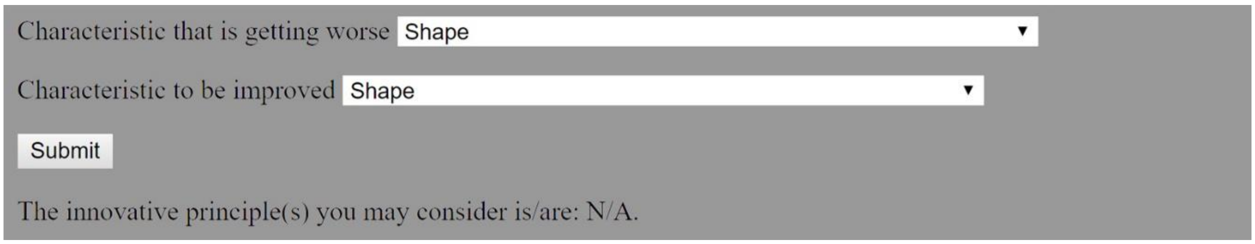


Figure 28: In case of choosing the same parameters in the dropdown lists, the TRIZ application alerts that there is a physical conflict (not a technical contradiction) among the objectives and we should employ the separation in place, type, scale, etc. to resolve it.

3.4. Case study 1: Designing a folded plate dome for a sports facility

3.4.1. Overall description

The topology of the folded plate dome was inspired by some of Yoshimura's origami patterns (see Figure 29). A triangular geometric base seems appropriate to transfer such patterns. Among different topologies, compatible with origami patterns, a diamatic dome was chosen. The diamatic dome consists of a number of sectors with a triangular-based pattern (see Figure 30). The reason to opt for a diamatic topology is the advantage of avoiding the problem of plates cluttering around the crown of the dome (see Figure 31 to compare a diamatic dome with a lamella dome to recognize this advantage). Then, the parametric model was created using the concepts of Formex algebra and its associated programming software, Formian 2.0 [90]. Formex algebra is a mathematical system that allows a designer to define the geometrical formulation of forms through concepts such as movement, propagation, deformation and curtailment [91]. Within this mathematical system, the plates are defined as discrete surfaces, which are arranged beside their edges.

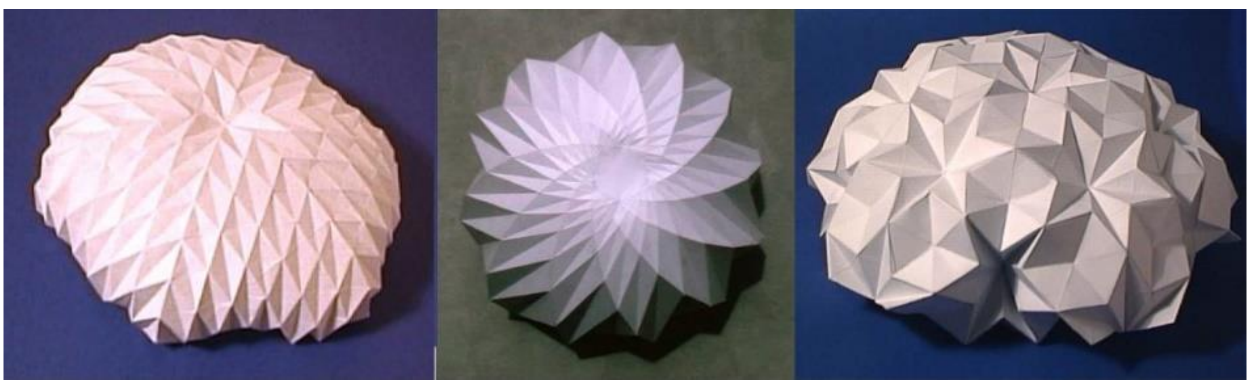


Figure 29: Some origami-based forms, Yoshimura's Pattern variations

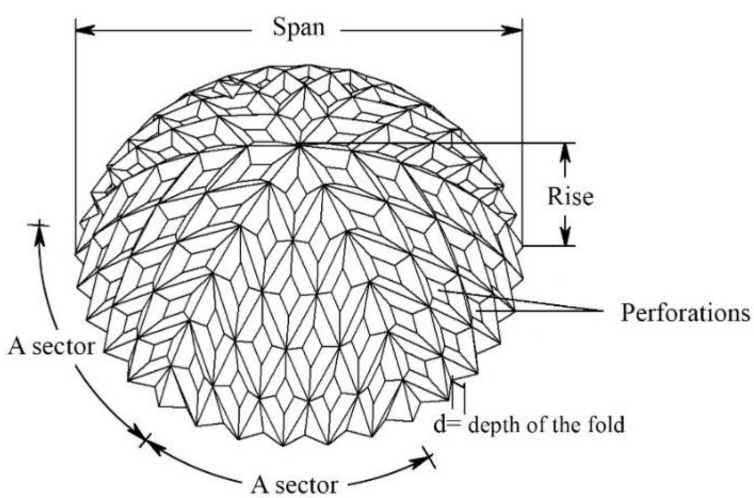


Figure 30: A typical form of a diamatic folded plate dome that is to be explored *[10]*

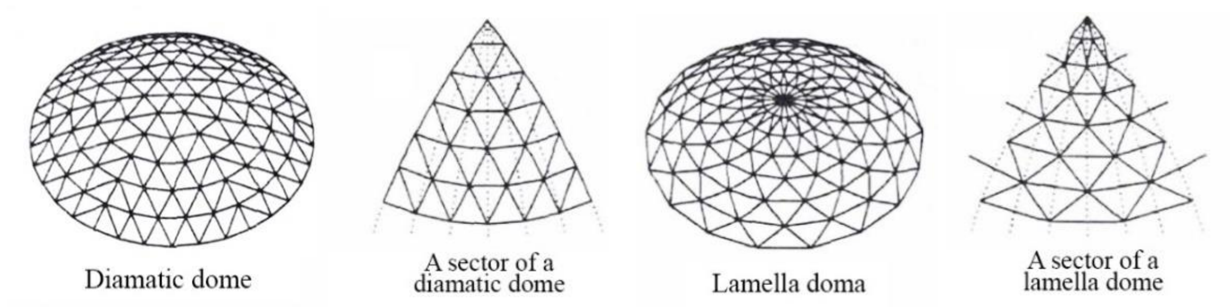


Figure 31: Comparison of a lamella dome and a diamatic dome *[90]*

The dome is considered to be built by cross-laminated timber (CLT) plates. The geometrical, environmental, and structural properties of this design problem are described in Table 5. The structural analysis has been carried out based on the FEA method using STAAD. Pro version 2007.11.90 [92] and the associated OpenSTAAD library. Daylight evaluation is done in DIVA 4.0 plugin [93] for Rhino and Grasshopper. Acoustics analysis is based on Sabine's equation [94] [95].

(Reverberation Time in s) $RT_{60}=k \,.\, V/A$ (Equation 1)

V= space volume (m^3)
(Equivalent absorption surface) A= α . S
S= absorbing surface area (m^2)
α= absorption coefficient
K= 0.161 (m)

Table 5: The geometrical, environmental, and structural properties used in design exploration of the folded plate dome

Geometrical properties		
Span of the dome = 20m (65 ft)	Dome height = [3,10] m , [10-32] ft	Depth of folds = [0.2, 2) m [0.5,7) ft
Percentage of perforations = [0,100]		
Frequency of sectors = [2,10]	Frequency of plates along one of the boundaries of a sector = [5-20)	
Material and load properties		
CLT plates: Spruce-Pine-Fir	Density = 400 kg/m^3 (25 lb/ft^3)	Thickness = 0.9 cm ($\frac{3}{8}$in)
Glass plates: density = 2500 kg/m^3 (156 lb/ft^3)		Thickness = 0.5 cm ($\frac{1}{8}$in)
Load = self-weight + 2.0 kPa (42 lb/ft^2) snow load		
DIVA daylighting simulation factors		
Ambient accuracy (aa) =0.15	Ambient bounces (ab) = 1	Ambient divisions (ad) = 512
Ambient super-samples (as) = 64	Ambient resolution (ar) = 256	Direct relay (dr) = 2
Direct sampling (ds) = 0.2	Limit reflection (lr) = 6	Limit weight (lw) = 0.004
Direct jitter (dj) = 0	Specular jitter (sj) = 1	Specular threshold (st) =0.15
Location = Chicago OHare.Intl.AP., IL, USA		
Ground reflectance = 0.2	Direct sun threshold = 50 W/m^2	
Lighting power density = 10.76 W/m^2		
Dimming setpoint = 300 lux	Ballast loss factor = 20%	
DA threshold = 300 lux	sDA time threshold = 50%	
ASE threshold =1000 lux	ASE time threshold 250 hrs/yr	
Occupancy = 8 to 6 with DST 60 min.occ		

Each cycle of the form exploration process includes form generation, simulation of building performance and analysis, evaluation of solutions, and storage of data. To perform these repetitive tasks automatically, AutoHotKey v1.1.22.02 (AHK) and Visual Basic for Application (VBA) macros are used. AHK creates the framework of the automation model, and VBA macros link the spreadsheets in Excel including input and output data. Also, OpenSTAAD gives access to the STAAD Pro. internal functions and retrieves the required data and transfers from/to the spreadsheets [96].

3.4.2. Form exploration of the folded plate dome using only the ParaGen method

To explore the design alternatives of the folded plate dome using ParaGen the steps described in Chapter 2 were taken. After creating the parametric model, setting up the database and scripting the required programmatic codes, the iterative process of form generation, evaluation of performance and storing the results in the database took place. In the first 100 cycles, random values are assigned to variables to generate the geometry of solutions. Then, the fitness function is set regarding the design objectives to generate a number of solutions systematically. This task is carried out until the decision maker is satisfied. The SQL inquiry, the graphs displaying the Pareto set, and images of the solutions support the designer to make a decision. Figure 32 demonstrates the distribution of solutions regarding the reverberation time (RT60) versus the total weight of the dome. The dome is designed for a sports facility. Therefore, it requires having a reverberation time of 1.5s or less [97] [98]. Total weight is also preferred to be less than 50000 tons. Figures 33 shows the solutions obtained by this filtering criteria.

The graphs in Figures 32 and 33 show that the two objectives are conflicting. Thus, the designer should choose the preferred solutions exploring the Pareto sets that are commonly expected to be the best trade-off solutions. Exploring the Pareto sets, the designer may refer to her past experiences, personal preference or impression based on the dome appearance. The designer can also study other performative values of the solutions such as the von Mises stress to determine the most suitable one (see Figure 34).

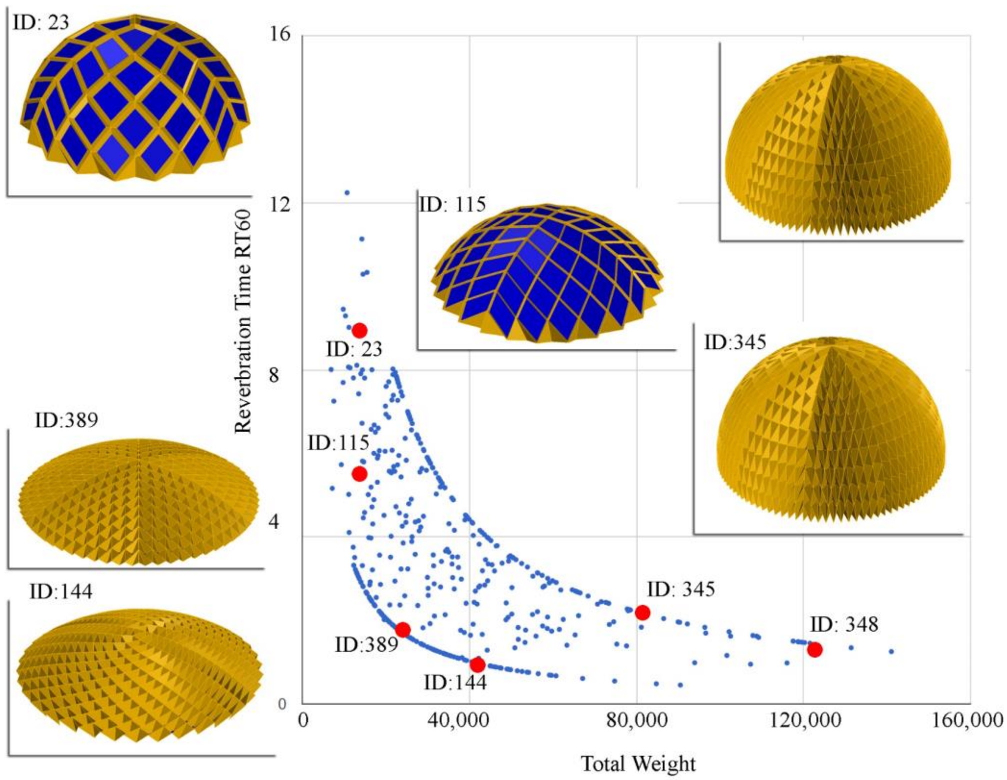


Figure 32: The distribution of solutions regarding the reverberation time (RT60) and the total weight

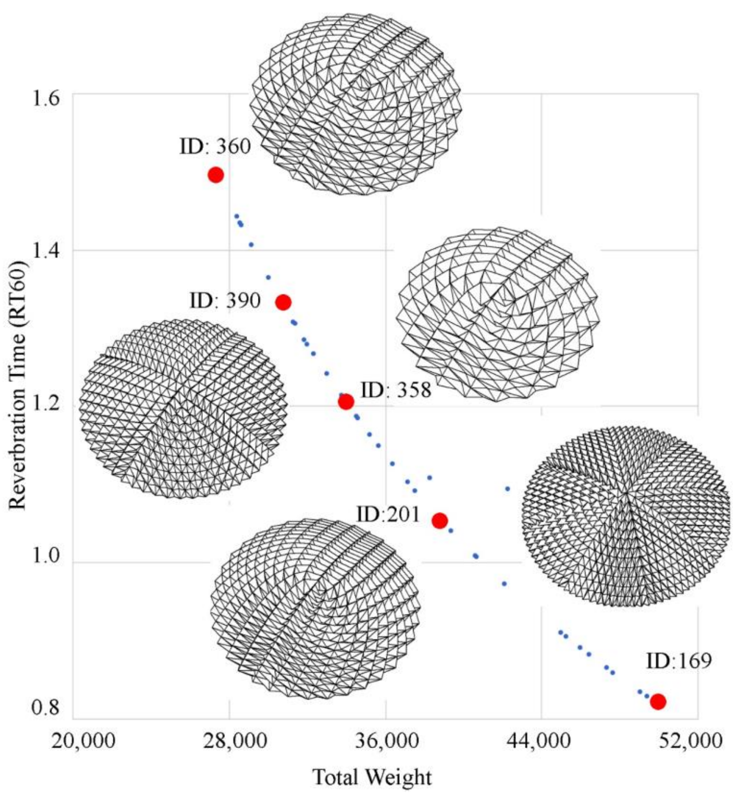


Figure 33: The graph displays the Pareto front to choose suitable solutions that weight less than 50000 t and have a reverberation time of less than 1.5 s.

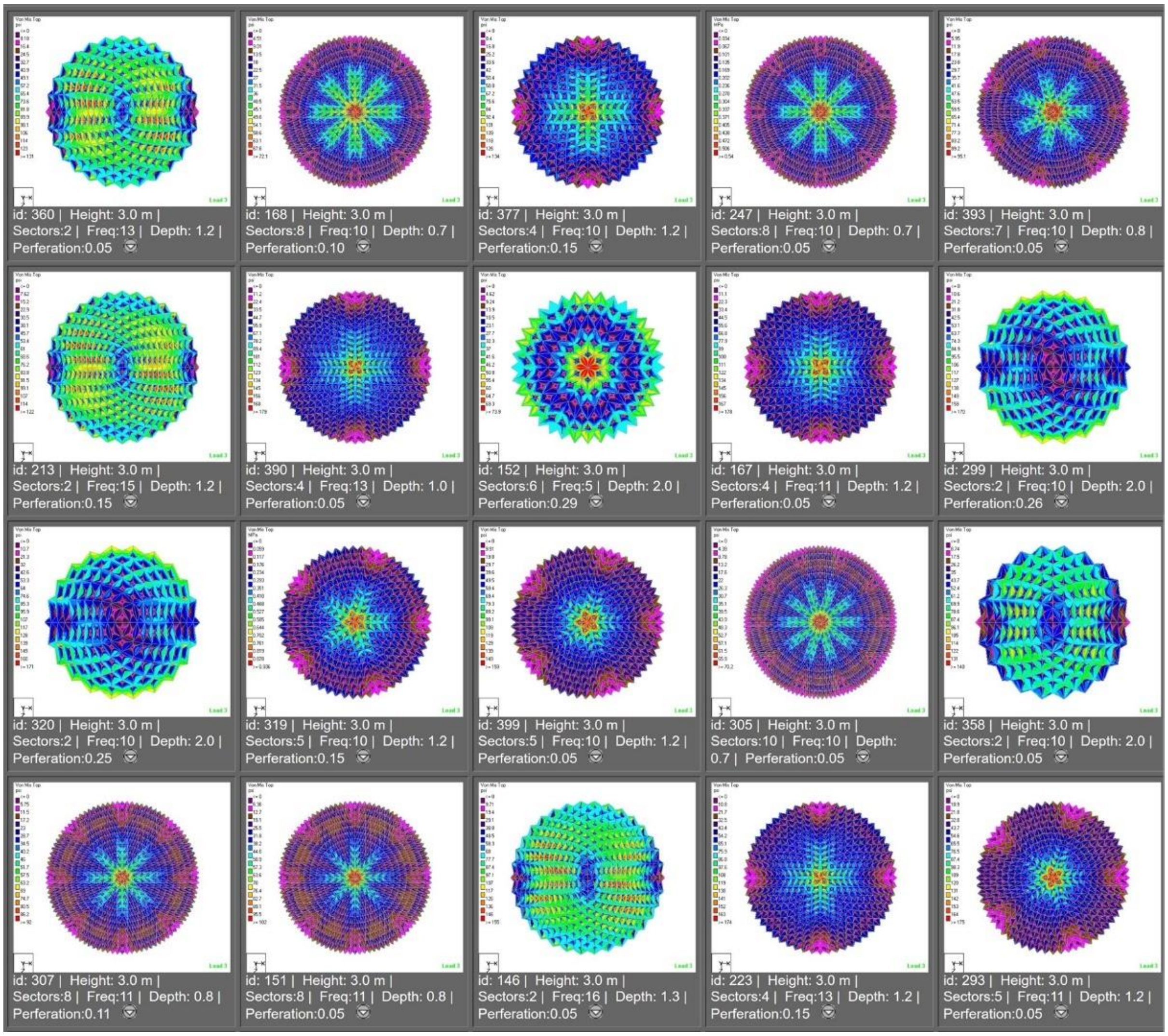


Figure 34: The display of von Mises Stress of some of the solutions that weight less than 50000 t and have a reverberation time of less than 1.5 s.

The solution space may also be searched for the alternatives with appropriate quality of daylight. Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) are the two metrics used in the daylight analysis. According to the Illuminating Engineering Society (IES), sDA and ASE are both climate-based metrics that allow rigorous building performance assessment. sDA indicates whether a certain space receives enough daylight during the standard operating hours (8 a.m. to 6 p.m.) on an annual basis. Generally, sDA assists in approximating the manual operation of window blinds. In the case of designing a folded plate dome for a sports facility, it may be preferred to find solutions with less demand on manual operation of blinds. Solutions in which occupants can work comfortably without or with less use of electric lights are preferred. An sDA value of 75% means occupants almost do not need electrical light during operating hours and an sDA value between 55% and 75% indicates a partial need of electric lights.

As sufficient daylight comes into a space the potential for glare and overheating increases. ASE measures the presence of sunlight, not illuminance, and indicates the percentage of the floor area of a space which receives more than 1000 lux for at least 250 hours per year. An ASE value of greater than 10% will likely result in visual discomfort. According to the IES Daylight Metrics Committee (DMC), ASE is technically not a glare metric. But it allows to make relative comparisons among design alternatives and make decisions. As Figure 35 shows, the greater the value of sDA, the higher the amount of ASE. In this design task, avoiding glare and overheating has priority over decreasing the demand for electrical lighting. Therefore, we can study the alternatives with ASE values of less than 50% (see Figures 36 and 37).

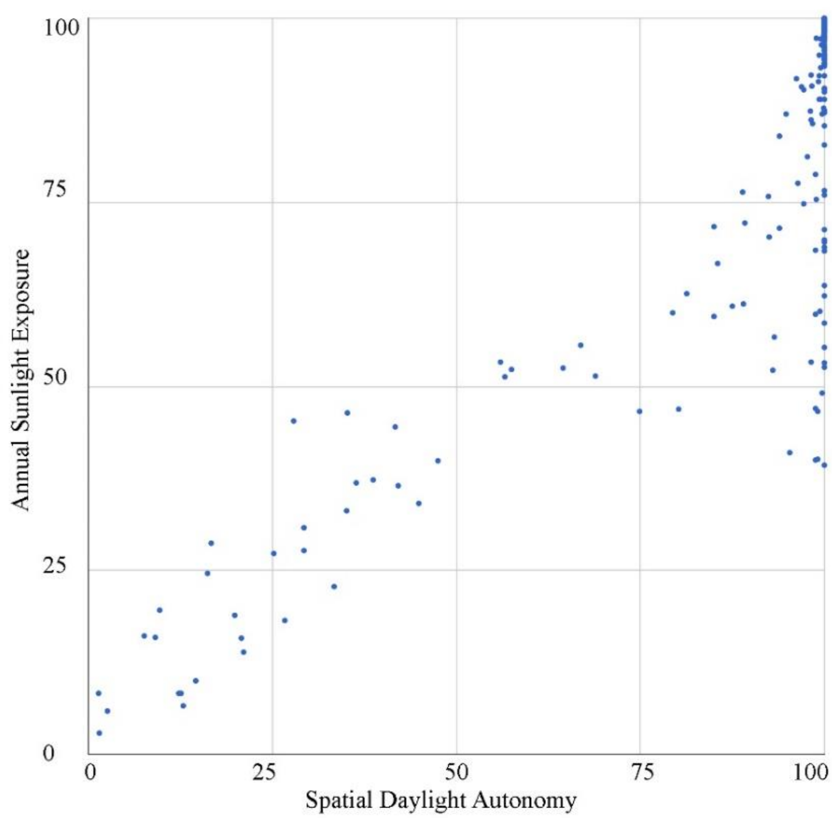


Figure 35: Distribution of solutions regarding sDA and ASE

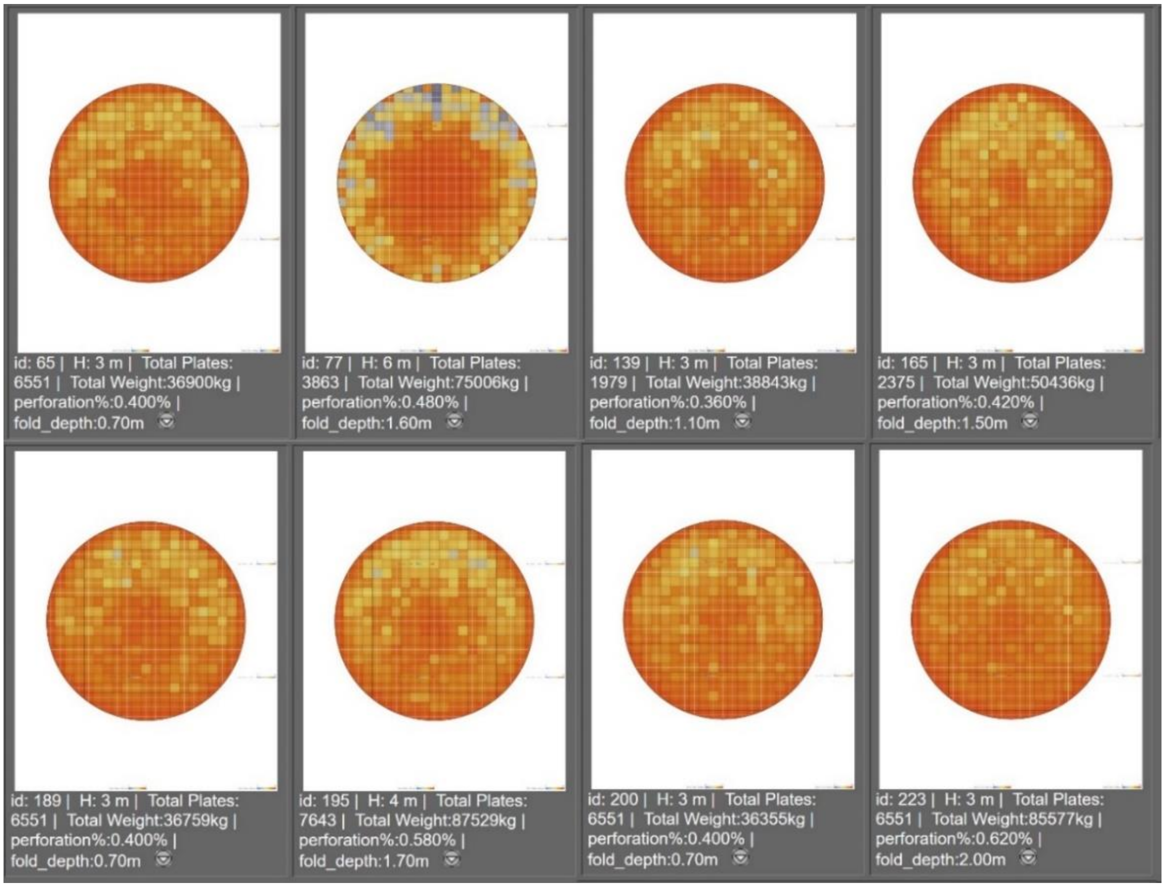


Figure 36: Solutions with ASE values of less than 50% and sDA of more than 55%. Also, RT60<1.5, Annual Lighting Energy Used<3000 kWh

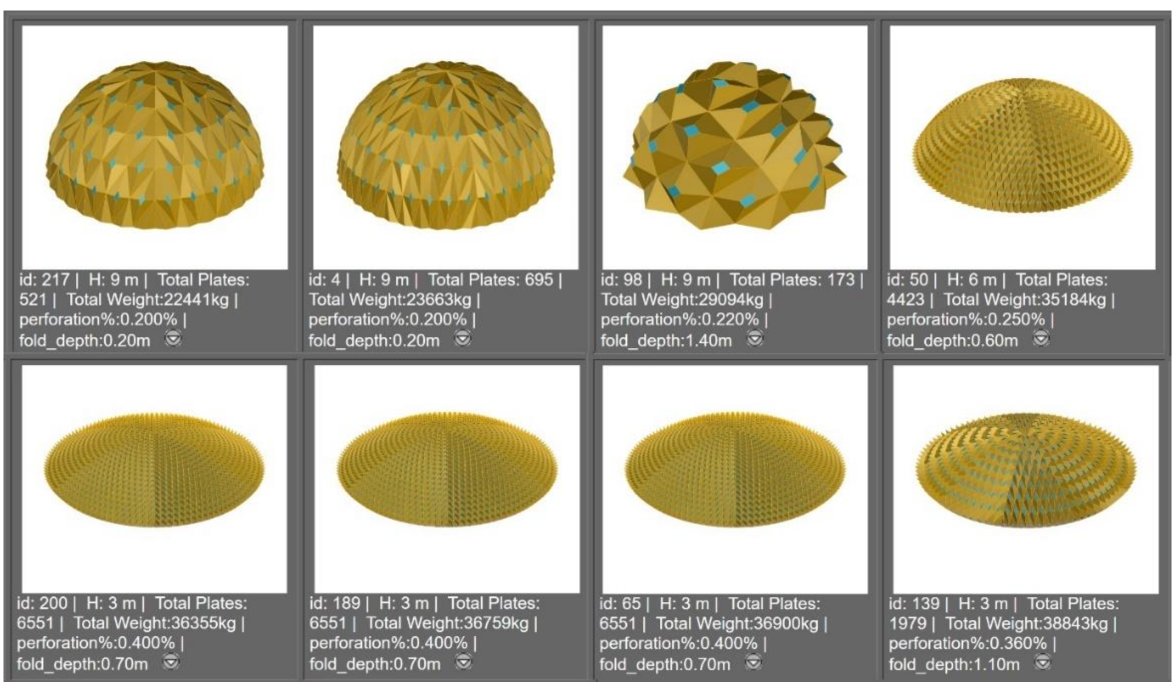


Figure 37: Some of the solutions which have ASE<50% and total weight < 50000 Kg

ParaGen allows the generation of Pareto sets for two or more variables [3] [52]. In this design case, four pairs of parameters are considered to define the Pareto sets:

1. Annual Lighting Energy Used vs. Deflection
2. Annual Lighting Energy Used vs. RT60
3. Total weight vs. Deflection
4. Total weight vs. RT60

For each case, the Pareto sets are defined and added to the SQL database. A separate C code updates the Pareto levels for each set every time a new solution is added to the database. As many Pareto level as is desired can be defined (see Figures 38, 39, 40, and 41) for each Pareto set. The Pareto level of each generated solution is stored in the database along with other relevant geometric and performative data.

A Pareto set can be displayed directly on the ParaGen website under the solutions tab to study the relation between the chosen parameter and its visual representation (see Figure 42). Furthermore, a Pareto set can be plotted in relation to other parameters as well (see Figure 43).

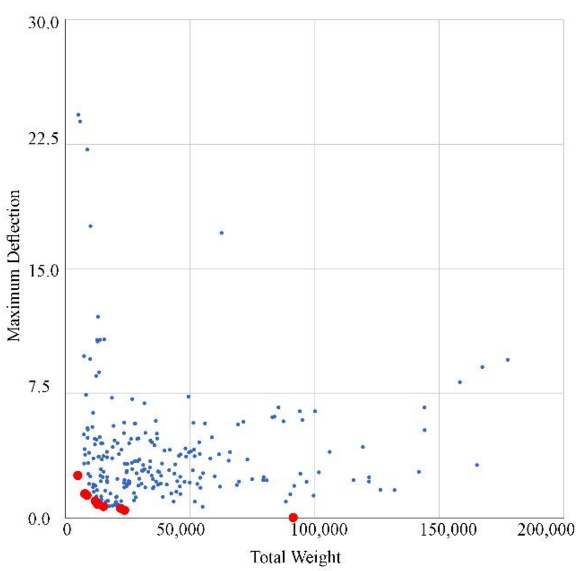


Figure 38: The plot shows the level 1 Pareto set for maximum deflection vs. total weight.

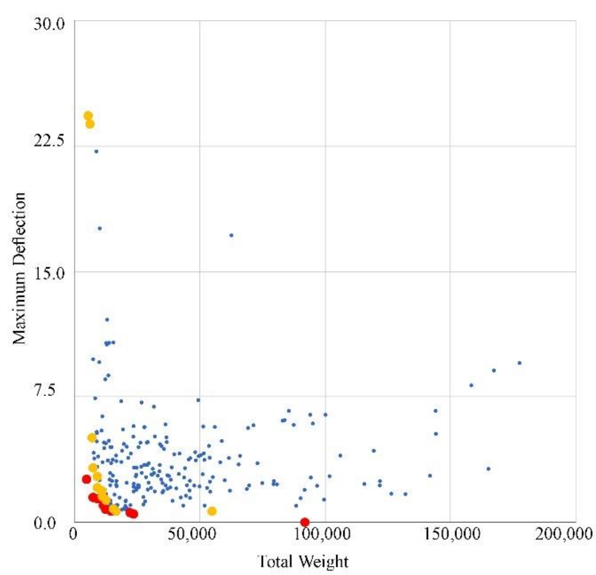


Figure 39: The plot shows the Pareto set including levels 1 and 2 for maximum deflection vs. total weight. Level 1is shown in red and level 2 in orange.

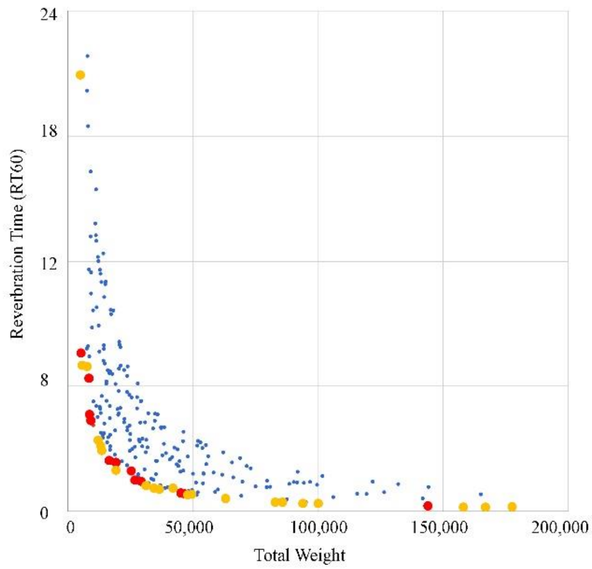


Figure 40: The plot shows the level 1 Pareto set for reverberation time vs. total weight. The solutions generated before Pareto breeding, are shown in red and the results of Pareto breeding are shown in orange.

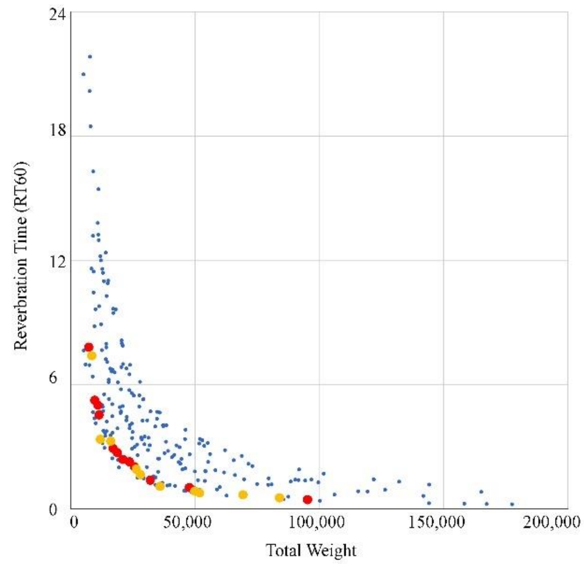


Figure 41: The plot shows the level 2 Pareto set, where the level 1 is excluded, for Reverberation time vs. total weight. The solutions generated before Pareto breeding are shown in red and the result of Pareto breeding is shown in orange.

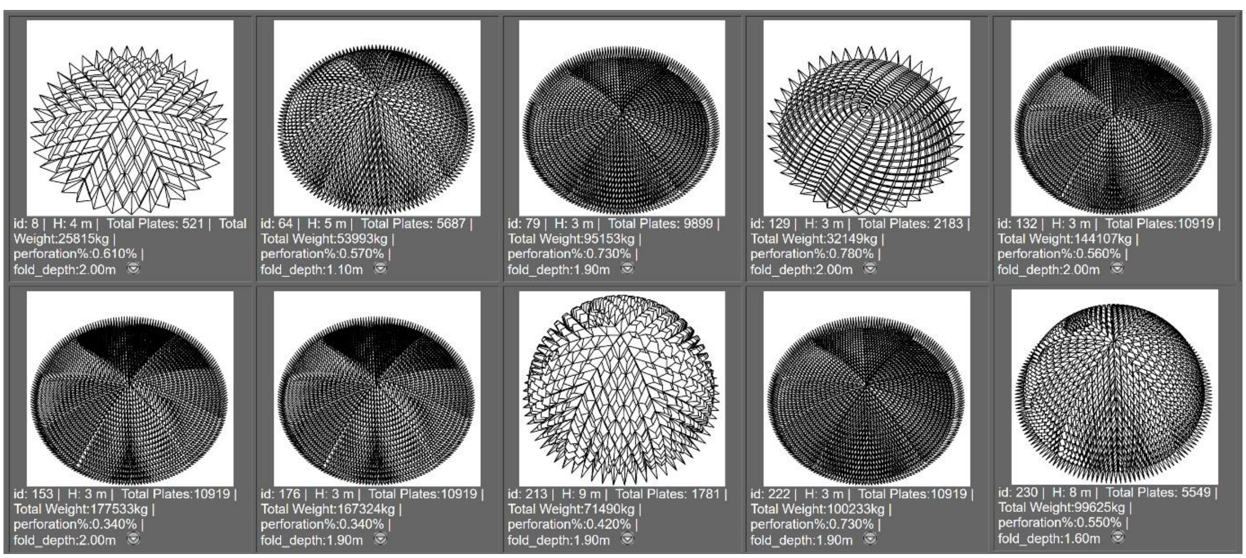


Figure 42: The plot shows the level 1 Pareto set for reverberation time vs. annual lighting energy used.

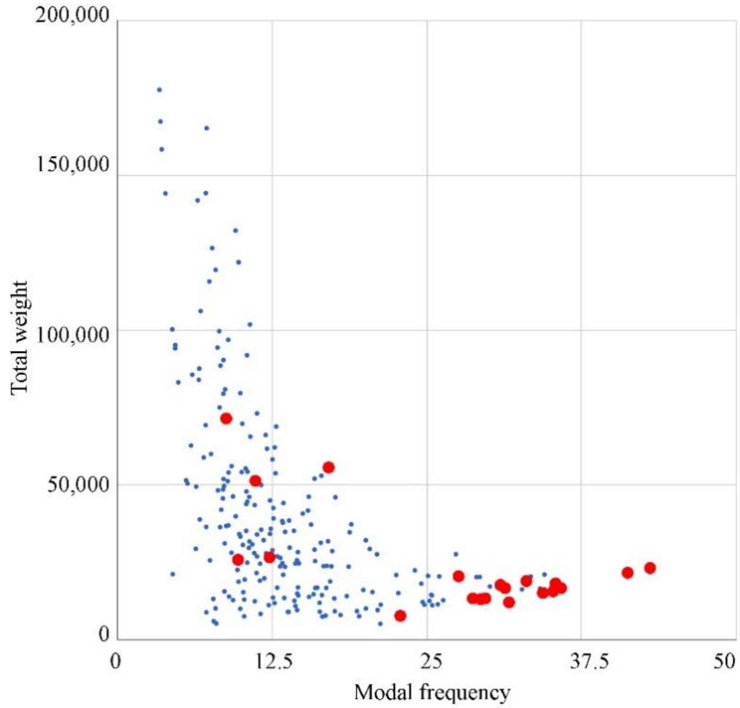


Figure 43: The plot shows the Pareto set including levels 1, 2, and 3 for maximum deflection vs. annual lighting energy used in relation to modal frequency and total weight.

3.4.3. Form exploration of the folded plate dome using the GA+TRIZ method

Design exploration using the ParaGen method begins with creating the parametric model. However, the GA+TRIZ includes an earlier action. When the design objectives are determined, TRIZ comes into play. There, it assists in recognizing the relation among design objectives, to see if they are in contradiction or accordance, and finding the solutions.

In this design case, first, the demanded useful functions and the avoided harmful functions are defined (see Table 6):

- Total weight of less than 50,000 tons
- Reverberation time of less than 1.5 s, which is an appropriate value for gymnasiums
- Maximum use of daylighting while avoiding glare and overheating
- Minimum annual lighting energy used
- Minimum structural deflection

Having defined the design objectives and categorized them into two sorts of useful and harmful functions, the designer should synthesize them into their basic factors. Then, she should reconsider the type of parameters and see if all the pertinent ones, which are possible to be considered as variables, are included (see Figure 44). In this design case, merely one type of glass plate and CLT panels are expected to be used, and their density and thickness must remain constant values. Therefore, the weight of the dome depends on the total area of CLT panels and glass plates. Since the density and thickness of the CLT panels are greater than the glass ones, between the design alternatives with the same topology, the one with a lower ratio of CLT plate area to glass plate area may be lighter.

Table 6: The performative objectives in the design of the folded plate dome

Demanded useful functions	**Harmful functions to avoid**
Daylight illuminance: spatial Daylight Autonomy (sDA) >50	Heavy weight: Total weight <50,000
	Glare and overheating: Annual Sunlight Exposure (ASE) < 50
	Reverberation time: RT60 < 1.5
	Annual daylight energy used <6,000
	Structural displacement

Regarding Sabine's equation, the reverberation time in spherical domes depends on the volume of the dome, the sound absorption coefficients of timber and glass plates, and the total area of the dome surface. Furthermore, each of these factors may be dependent on their basic factors. For example, the diameter of the base of the dome is determined to remain constant. Thus, the volume of the dome depends only on the dome height.

Spatial Daylight Autonomy of the interior space depends on the perforation area. The corresponding Annual Sunlight Exposure which causes glare and overheating is dependent on both outside brightness and the perforation area. In this design case, the height of the dome, depth of folds, areas of CLT and glass plates, weights and also the ratio of CLT and glass plates, are included in the database. Then, the designer should study the relation among the design parameters and identify the contradictions.

A designer may realize the contradictions among the design objectives at the first step by drawing a diagram similar to Figure 44 or by referring to her experiences and recognition of the relations among the design objectives. The latter does not seem convenient or possible for all designers. If a designer does not know the dependencies among parameters, she can generate about 100 random solutions and, then, use the relevant 2D graphs in the ParaGen website to notice the parameters' relations.

The diagram in Figure 44, we can call it the *relations diagram*, assists in understanding the connection between the design parameters better. It allows recognizing both harmful and useful functions. From left to right, as the background color fades into white, the definition of design parameters turns to be more generic rather than specific. Sometimes, a harmful or useful function emerges as a result of eliminating a harmful function or reinforcing a useful function. This newly emerged function is linked to its cause by dash lines. For example, in the following, we see that increasing the depth of folds triggers rainwater drainage problem and it is added to the graph by dash lines.

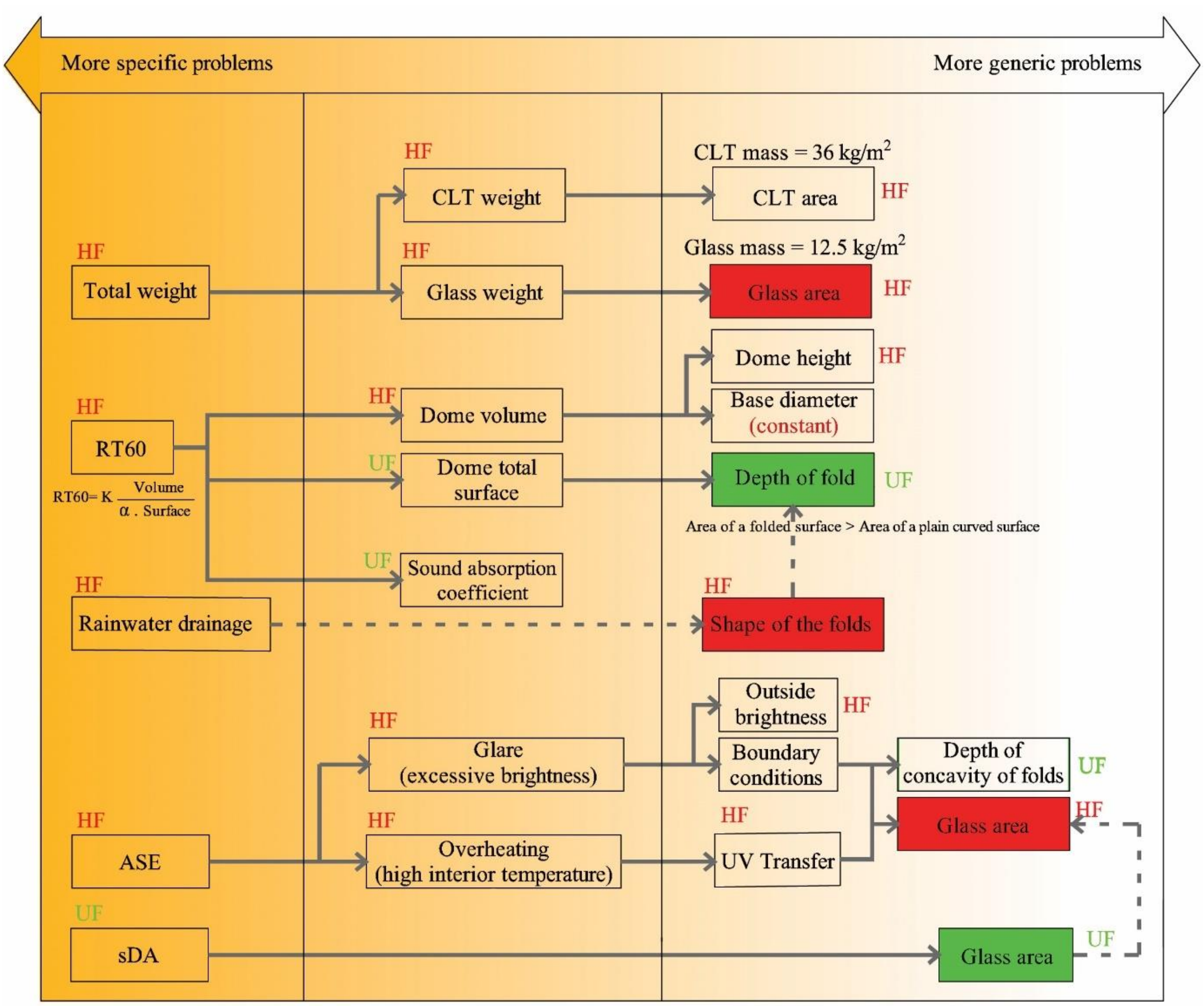


Figure 44: The relationship of the design objectives in the folded plate dome design project. The diagram allows recognizing the parameters with both useful and harmful functions.

The relations diagram reveals the contradiction between the total weight of the dome and the reverberation time. We can verify this contradiction by refereeing to the XY graphs in Figures 32 and 33. Increasing the depth of the folds may reduce the reverberation time, but it may provide a heavier dome. It is also possible to verify this relationship by the XY graphs shown in Figures 45 and 46. Furthermore, due to the shape of the folds, when the depth of the folds increases to augment the total area of the surfaces, drainage of the rainwater becomes complicated on the top part of the dome.

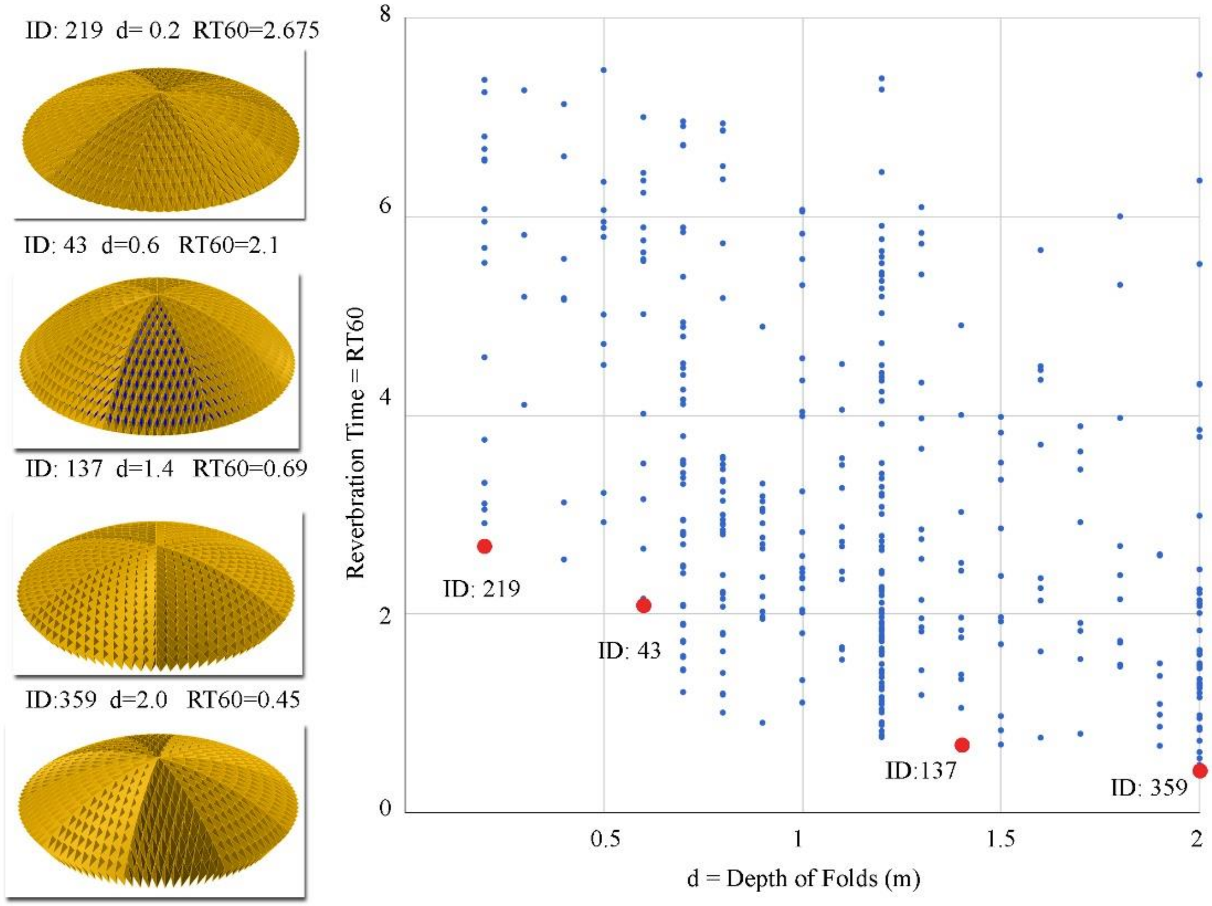


Figure 45: Increasing the depth of the folds can reduce the reverberation time

Moreover, the relations diagram shows that increasing the glass area is consistent with the desired spatial Daylight Autonomy of the interior space, but it acts against the effort to reduce the Annual Sunlight Exposure. Graphs in Figures 47 and 48 verify this contradiction. Higher amount of sDA is desirable, however, as ASE value increases, the glare and overheating are more probable in the space.

In conclusion, the depth of folds and the shape of the folds are technically in contradiction. Also, the total area of the dome surface and the area of glass plates cause physical contradictions. The former improves the reverberation time but increases the total weight. The latter act usefully regarding the sDA but adversely regarding the ASE. In the third step, the designer can refer to the concept of *separation* for resolving the physical contradictions. Then she can study the matrix of contradiction and the 40 inventive principles to find some generic ideas for resolving the technical conflicts. The corresponding matrix of contradictions is shown in Table 7.

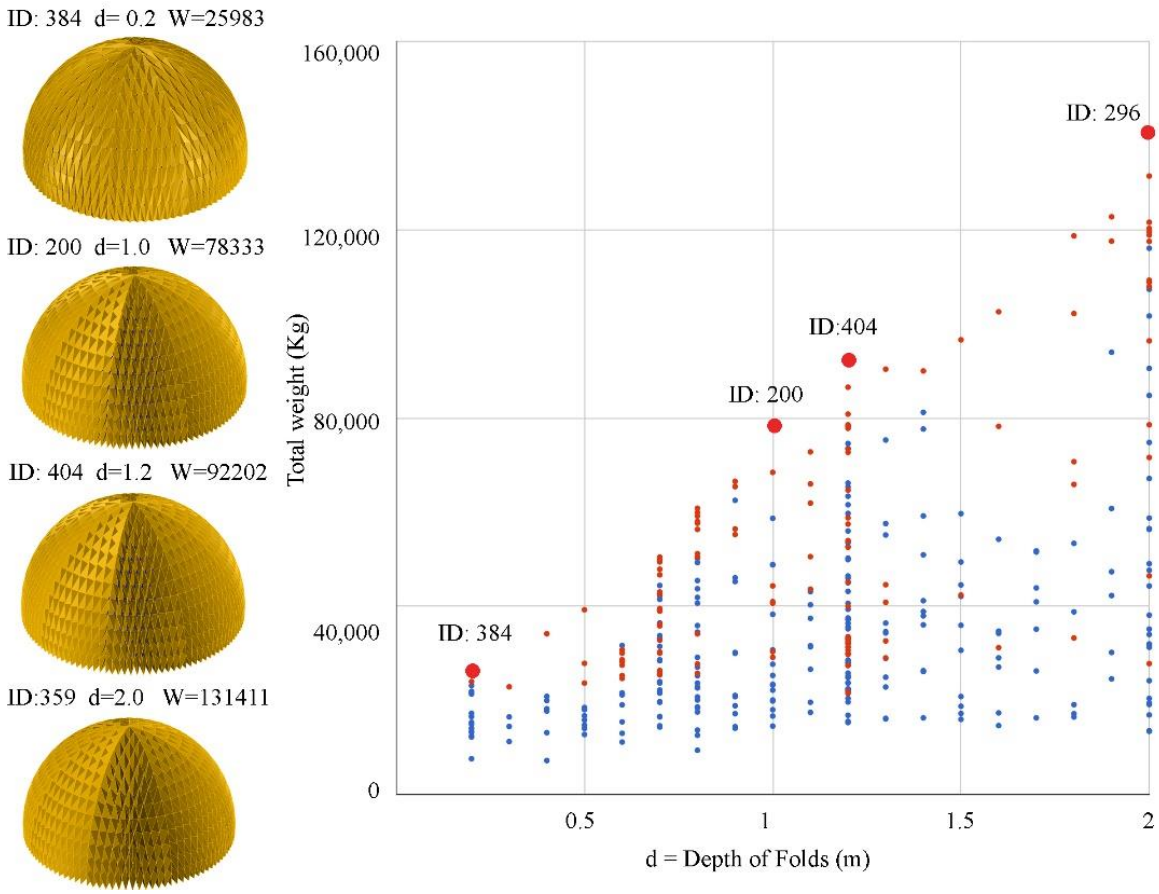


Figure 46: Increasing the depth of folds rises the total weight of the dome. The alternatives shown in the figure have a height of 10m.

The fourth step is to interpret the generic solutions innovatively and restate a/some specific solution(s) to resolve the conflicts. First, the matrix of contradiction suggests *other way round* to resolve the conflicts between increasing the *depth of folds* and the *drainage problem*. In other words, the designer may think of creating the folds in a convex shape and not a concave form. Then, the rainwater can flow down along the edges of the plates (see Figure 49). There are three other suggestions to resolve this conflict, and a designer may innovatively interpret any of them to a more convenient solution. Second, there are two parameters that cause physical conflicts: the total area of the dome surface and the area of glass plates. According to the TRIZ concept of separation, among all the 40 inventive principles we can choose the idea of applying *flexible thin films or membrane* to separate the surfaces acting acoustically and structurally. By adding acoustic surfaces to control the quality of sound in the pavilion or utilizing a kind of coating, as a thin film, on the CLT plates to increase the sound absorption coefficient, we can resolve the conflicting desire of both increasing and decreasing the total area of the dome [99].

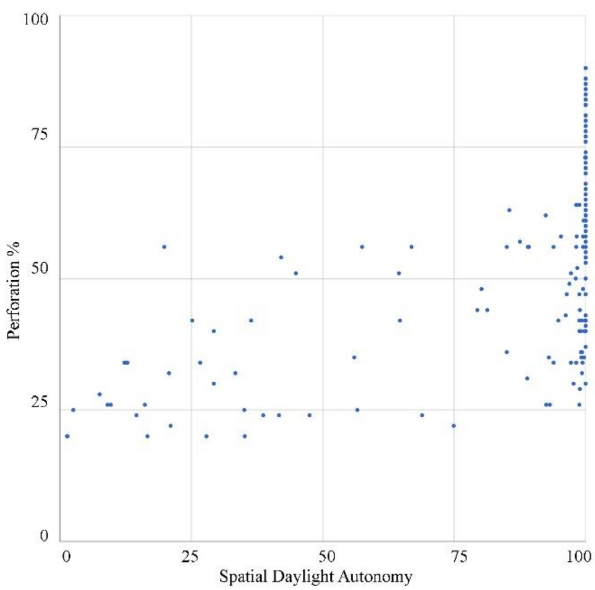


Figure 47: sDA vs. percentage of perforation

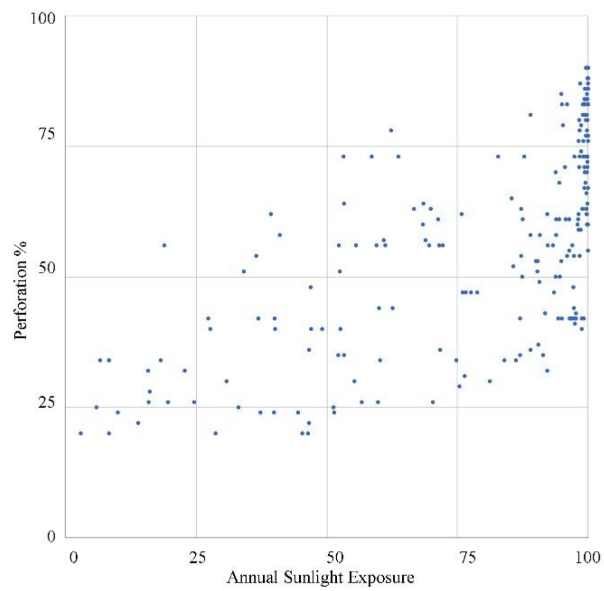


Figure 48: ASE vs. percentage of perforation

Table 7: The matrix of contradictions of the dome project

<table>
<tr><td colspan="3" rowspan="3">Characteristics</td><td colspan="3">Characteristic that is getting worse (HF)</td></tr>
<tr><td>6</td><td>12</td><td>6</td></tr>
<tr><td>Area of a stationary object (total area of the dome surface)</td><td>Shape
(drainage problem)</td><td>Area of a stationary object (area of glass plates)</td></tr>
<tr><td rowspan="3">Characteristic to be improved (UF)</td><td>4</td><td>Length of a stationary object (depth of folds)</td><td></td><td>13-Other way round
14-Spherical shapes
15-Dynamism
7-Nesting dolls</td><td></td></tr>
<tr><td>6</td><td>Area of a stationary object (total area of dome surface)</td><td>All</td><td></td><td></td></tr>
<tr><td>6</td><td>Area of a stationary object (area of glass plates)</td><td></td><td></td><td>All</td></tr>
</table>

Also, CLT plates are more massive than glass plates. The designer may achieve lighter domes with a certain amount of surface area by considering the weight of the two types of plates separately and reducing the ratio of CLT to glass plates. For instance, among the design alternatives with a reverberation time of less than or equal to 1.5s, solution number 40 is chosen as a desirable one (see Figure 50). Then, the idea of reducing the ratio of CLT to glass plates is employed to achieve a lighter dome. Solution 241 is a dome which has the same input parameters as that of dome number 40 except the percentage of perforation which has increased to be 45%. Solution 241 has less weight, greater sDA, and higher ASE (see Figure 51). The reverberation time has been increased because of the lower sound absorption coefficient of glass plates. But still the value of RT60 is in the desirable range. Solution 241 could be the final solution if it had ASE of less than 50%. The list of 40 inventive principles suggests *moving into a new dimension*. Hence, maybe by deepening the folds we can provide indirect sunlight and prevent glare. Solution 242 is generated with the same input parameters as that of number 241 but with a fold of depth of 2 m (see Figure 52). There, we can verify the idea inspired by the matrix of contradiction. Solution number 242 has less weight in comparison to solution number 40, sDA of 100% and ASE of 49.3%. Reverberation time is 1.09 s that is close to that of number 40 and less than number 421.

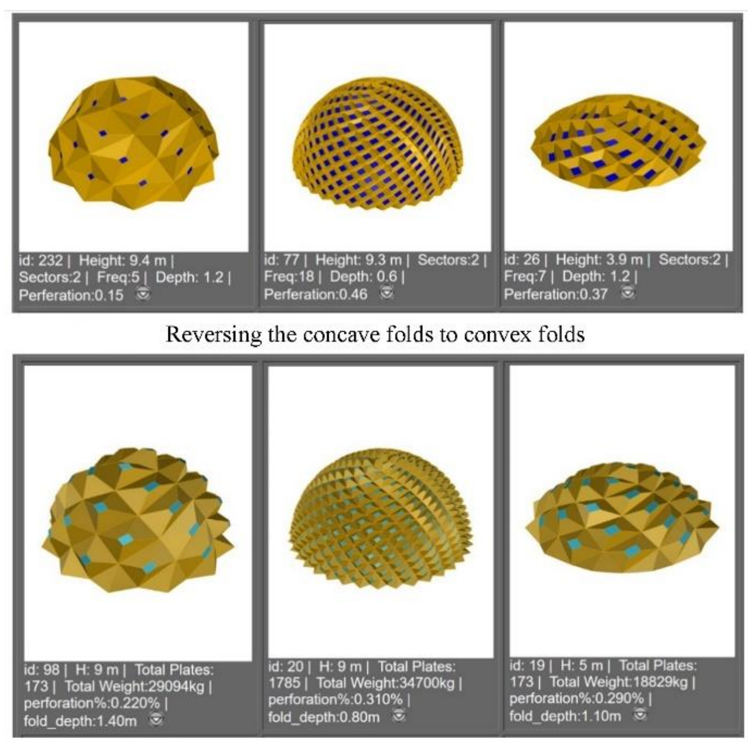
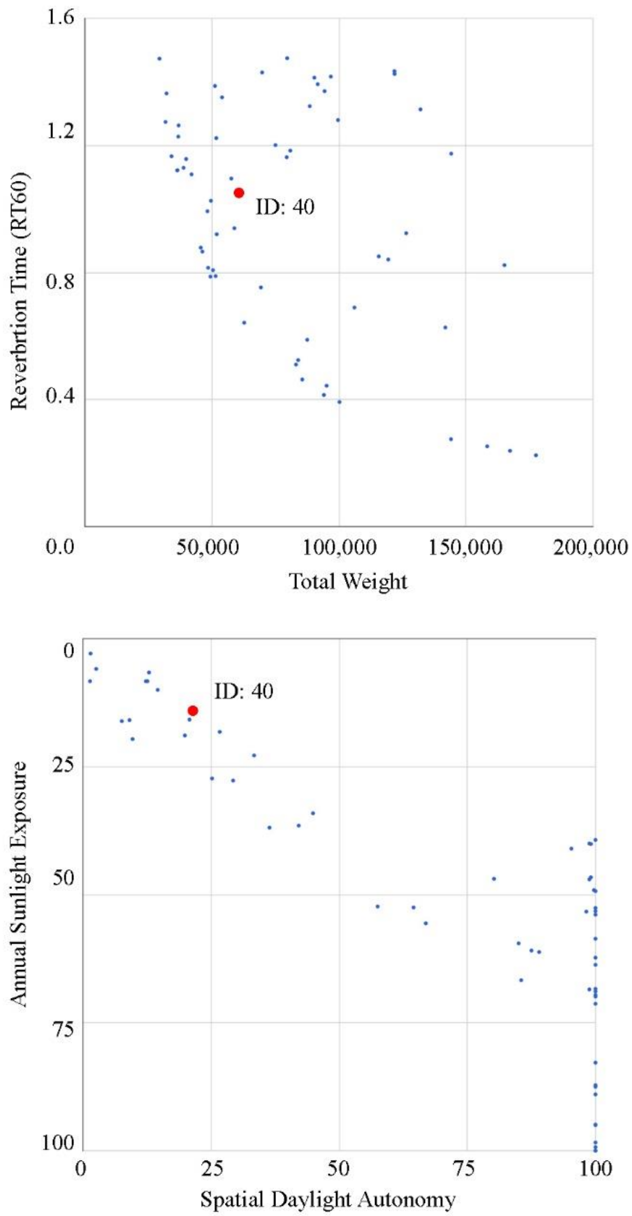
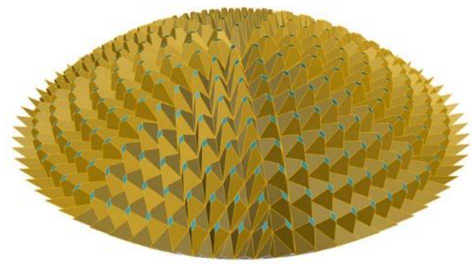


Figure 49: Creating the folds in a convex shape instead of concave form

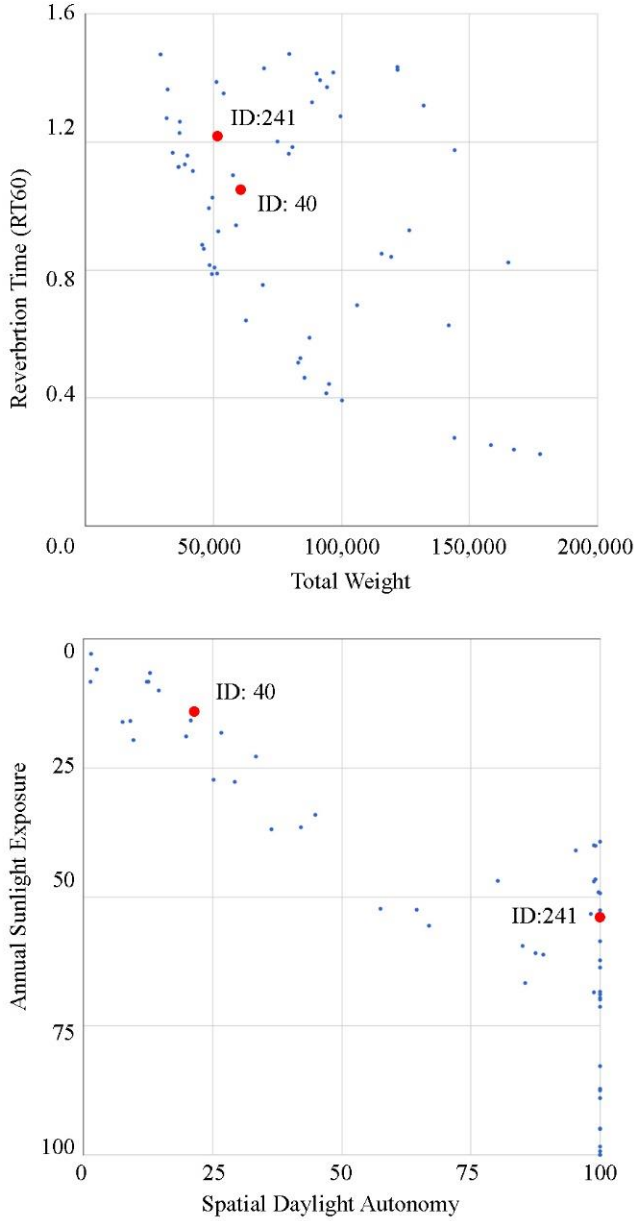
Furthermore, using double or triple-glazed glasses and adding shades can be taken into account as respectively proposed in terms of *Nesting dolls (Matryoshka)* and *Flexible films or membrane*. These ideas can eliminate the physical contradiction caused by the total area of the glass plates.





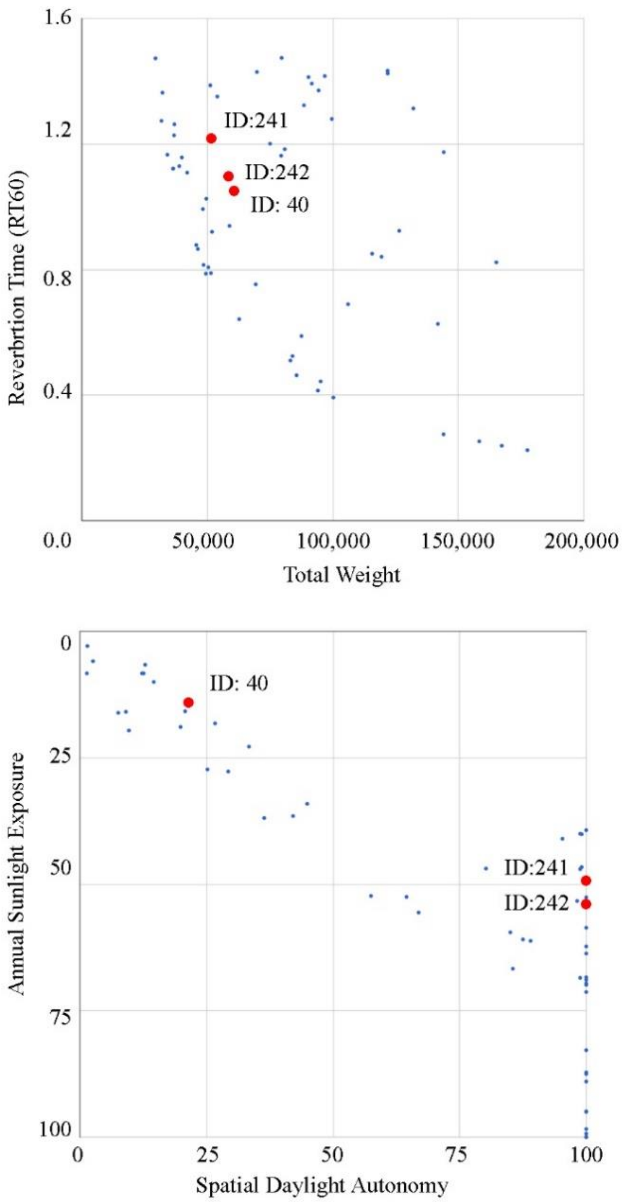
Span	20
Height	4.5
number of sectors	7
number of elements along longitudinal	9
depth of folds	1.8
percentage of perforation	0.22
Number_of_Nodes	1716
CLT_Plates	1400
Glass_Plates	314
Total_Plates	1714
CLT_Area	1592.521
CLT_MaxArea	1.314668
CLT_AvgArea	1.137515
Glass_Area	119.5569
Glass_MaxArea	0.379546
Glass_AvgArea	0.005885
Total_Area	1712.078
CLT_to_Glass	13.3202
CLT_Weight	58461.04
Glass_Weight	1523.927
Total_Weight	59984.96
Max_Deflection	2.499
Max_vMises_Stress	0.904
Modal_Frequency	7.562
Weight_x_Deflection	149902.4
Reverb_Time_RT60	1.05582
Spatial_Daylight_Autonomy	21.1
Annual_Sunlight_Exposure	13.9
Annual_Lighting_Energy_Used	8135.4

Figure 50: Solution number 40 with reverberation time (RT60) of less than 1.5 s



Span	20
Height	4.5
number of sectors	7
number of elements along longitudinal	9
depth of folds	1.8
percentage of perforation	0.45
Number_of_Nodes	1716
CLT_Plates	1400
Glass_Plates	314
Total_Plates	1714
CLT_Area	1367.896
CLT_MaxArea	1.314668
CLT_AvgArea	0.977069
Glass_Area	119.5569
Glass_MaxArea	0.379546
Glass_AvgArea	0.005885
Total_Area	1487.453
CLT_to_Glass	11.44138
CLT_Weight	50215.1
Glass_Weight	1523.927
Total_Weight	51739.03
Max_Deflection	2.767
Max_vMises_Stress	0.94
Modal_Frequency	8.202
Weight_x_Deflection	143161.9
Reverb_Time_RT60	1.222938
Spatial_Daylight_Autonomy	100
Annual_Sunlight_Exposure	53.9
Annual_Lighting_Energy_Used	2102.3

Figure 51: Solution number 241 is generated with the same parameters as that of number 40 but with the percentage of perforation of 0.45.



Span	20
Height	4.5
number of sectors	7
number of elements along longitudinal	9
depth of folds	2
percentage of perforation	0.45
Number_of_Nodes	1716
CLT_Plates	1400
Glass_Plates	314
Total_Plates	1714
CLT_Area	1513.708
CLT_MaxArea	1.45419
CLT_AvgArea	1.08122
Glass_Area	163.885
Glass_MaxArea	0.52027
Glass_AvgArea	0.008068
Total_Area	1677.593
CLT_to_Glass	9.236406
CLT_Weight	55567.83
Glass_Weight	2088.952
Total_Weight	57656.78
Max_Deflection	2.604
Max_vMises_Stress	0.904
Modal_Frequency	7.625
Weight_x_Deflection	150138.3
Reverb_Time_RT60	1.095691
Spatial_Daylight_Autonomy	100
Annual_Sunlight_Exposure	49.3
Annual_Lighting_Energy_Used	1842.1

Figure 52: Solution number 241 is generated with the same parameters as that of number 241 but with the depth of fold of 2 m.

3.4.4. Discussion

Using the ParaGen method allows the designer to explore a great number of possible solutions and obtain a series of suitable ones. During the phases of decision making, the designers may study the distribution of solutions in XY graphs and compare certain performative parameters. TRIZ is to support a better problem structuring and a more systematic decision making. The efficiency of this assistance can be evaluated using the four metrics of diversity/similarity, performative cost, time efficiency, the amount of data provided for decision making.

Using the ParaGen method, the designer obtains a series of solutions filtered by the criteria derived from the design objectives. In this design case, as shown in Figure 53, the configurations of suitable solutions within the 240 generate design alternatives are almost the same, and the designer may wish to obtain a broader diversity. Studying the dependencies of the design parameters and bringing higher-level information into account, allow for an increase of the *diversity* of desirable solutions in a relatively short time. By changing the depth of folds and the percentage of perforations, solution number 242 appears to have a different appearance while the corresponding *performative cost* remains within the acceptable interval.

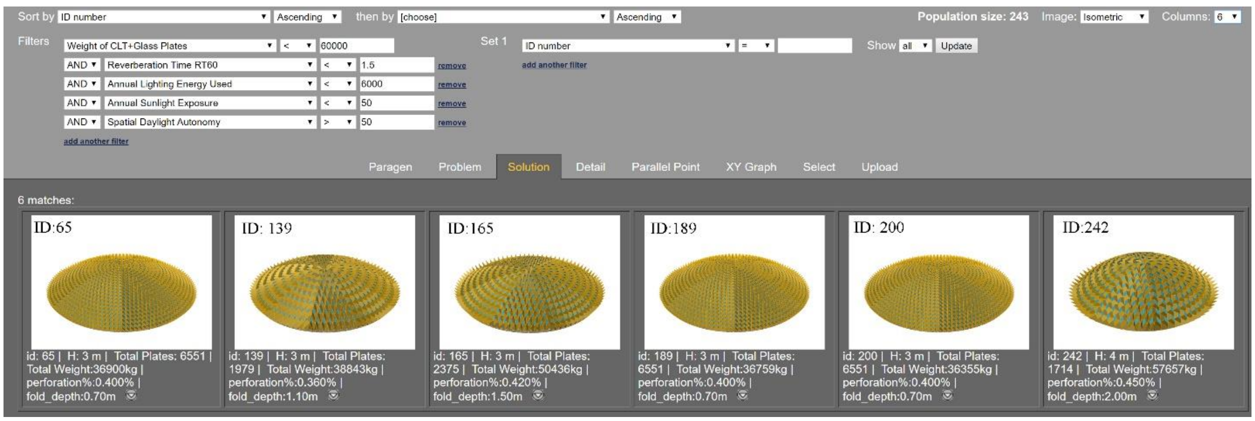


Figure 53: Increasing the diversity of solutions using TRIZ. Solution number 242 has a different appearance.

Considering the problem of rainwater drainage, the application of TRIZ could prevent wasting time in generating a range of inappropriate solutions at the very beginning. Also, the possibility of a direct convergence at any point could promote the *time efficiency* of the form exploration procedure. Furthermore, Figure 52 shows that the application of TRIZ leads to the exploration of a lightweight dome with better values of sDA and ASE while remaining in the desired interval of RT60.

Using the GA+TRIZ method, the designer can set the fitness functions and select the breeding criteria with a better understanding of parameter dependencies. For example, the designer recognizes that increasing the depth of the folds reduces the reverberation time, but it provides a heavier dome. Thus, by minimizing the ratio of CLT to glass plates, it is possible to gain suitable solutions. Also, it becomes obvious that the lower the height of the dome is, the less reverberation time it may have. Therefore, the designer may shift the conflicts between the two desirable parameters by taking higher-level information into account. Then, by increasing the *amount of data* for making decisions, further series of solutions can be explored.

3.5. Case study 2: Designing a truss bridge over Huron River in Ann Arbor, Michigan

3.5.1. Overall description

It is more than a decade that students at the University of Michigan, School of Architecture, have been participating in a truss bridge design contest in the context of a structure course. The truss bridge is to be designed as an alternative to the Foster Bridge built in 1876 by the Wrought Iron Bridge Co. over the Huron River in Ann Arbor, Michigan (Figure 54). This contest is based on physical modeling, but it was inspiring to explore more than 2000 solutions using the ParaGen method [7]. The bridge has two traffic lanes and is composed of two 2D trusses on the two sides that are braced together laterally. The deck may be located above, below or at the middle of the trusses (Figure 55). For the ParaGen form exploration, the design objectives were to obtain lightweight solutions with deflection of 4.8 cm or less (< Span/1000) [100]. Since limiting the deflection cannot really decrease the deformation-induced structural damages and psychological user-discomfort from excessive bridge vibration, a higher modal frequency is preferred [100]. Furthermore, compatibility with the surrounding environment and visual representation of the bridge are considered.

The bridge was parametrically modeled in Formian 2.0 using concepts of Formex algebra [101] [47]. The 2D truss patterns above and below the bridge deck are chosen among the nine variable patterns illustrated in Figure 56. The structural analysis and evaluation have been carried out based on the FEA method using STAAD. Pro V8i version 20.07.07.32 [92] and AASHTO Standard. The geometrical and structural properties of the truss bridge are described in Table 8.

Figure 54: The Foster Bridge, Ann Arbor, Michigan

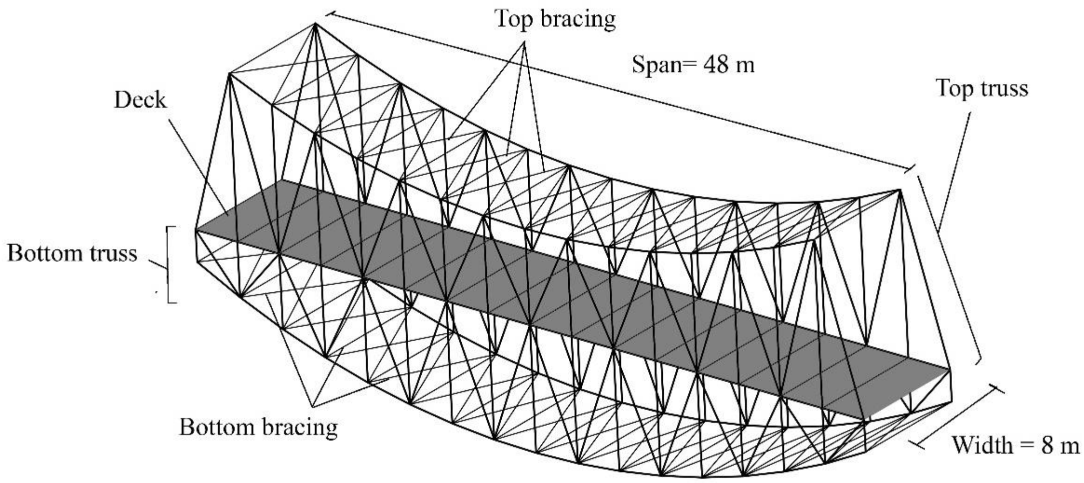


Figure 55: A typical form of the truss bridges that are to be explored

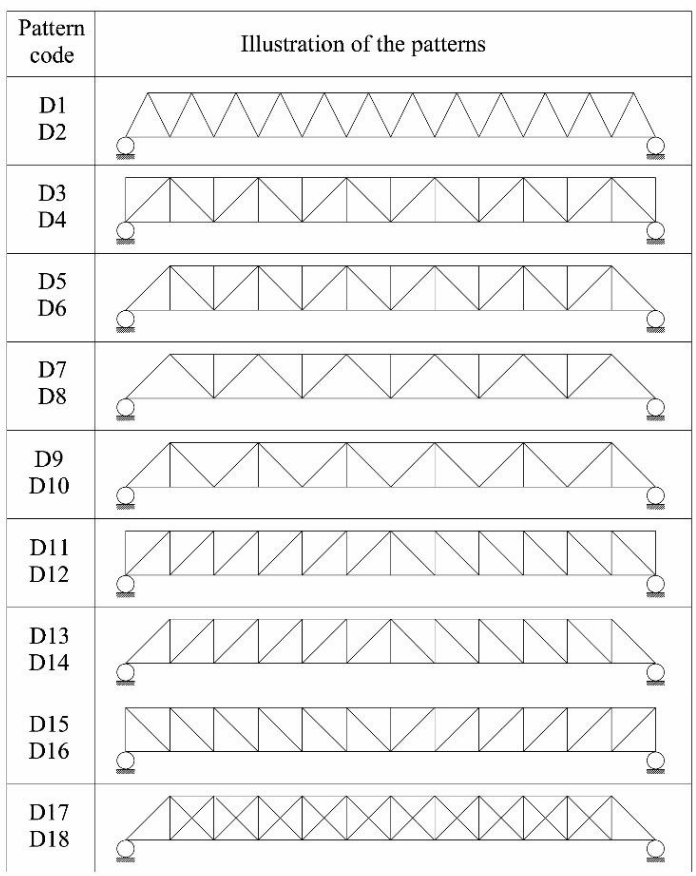


Figure 56: The truss patterns that are used for the top and the bottom parts of the bridges

Table 8: The geometrical and structural properties considered in design exploration of the truss bridge

Geometrical properties
Span of the bridge = 48 m (157 ft) bridge width = 8 m (26 ft) The frequency of geometrical modules = number of deck panels along the bridge (m) = [4-20] The total height of the bridge = [-16,16] m , [-52,52 ft], height minimum values = 0.5 m [1′7″) The total rise of the arch at the trusses = [-16,16] m The trusses can have positive, negative curvature or be flat (zero curvature).
Material and load properties
Deck composition: • 30 cm concrete plates 281.227 kg/cm^2(4000 psi) Density = 2.4kg/m^3 (0.150 lb/ft^3) , E=21.718 kN/mm^2 (4.5×10^8psf), Poisson=0.17 • W6×8.5, and W6×15 Density=7833.37 kg/m^3 (490 lb/ft^3) , E=199.947 kN/mm^2(4.17×10^9psf), F_y=344.7 kPa (7200 psf), F_u=448159.2 kPa (9.360×10^6 psf), Poisson=0.3 Load: self-weight + 237.07 kg/m^2 (48.5 psf) uniform traffic load Supports: • Pinned • Fixed But Fz M_y M_z • Fixed But F_x M_y M_z • Fixed But F_x F_z M_y M_z

3.5.2. Form exploration of the truss bridge using only the ParaGen method

The form exploration begins by creating a parametric model of the truss bridge in Formian. Then, the database is set up to store the results of the FEA analysis. For the first 100 solutions, random values are assigned to variables to define the geometry of bridges and evaluate their performance. Then, the fitness function is set to explore lighter solutions with less deflection and higher modal frequency. The graph shown in Figure 57 illustrates the distribution of solutions whose maximum deflection is less than 4.8cm. The graph indicates that bridges with less maximum deflection are more likely to be heavier. The appropriate solutions may be found within the Pareto set for least weight versus least deflection. Figure 58 displays ten solutions along the levels 1 and 2 Pareto sets whose weights are less than 1000kg and have a maximum deflection less than 1cm.

The other design objective is to obtain greater modal frequency. This parameter seems to be in accordance with having less maximum deflection and generating lighter bridges (see the two graphs in Figures 59 and 60). Similar to many form exploration projects accomplished using the

ParaGen method, the designer can use the 2D graphs, SQL database and visual representation of generated solutions to find a series or suitable solutions and make a final decision.

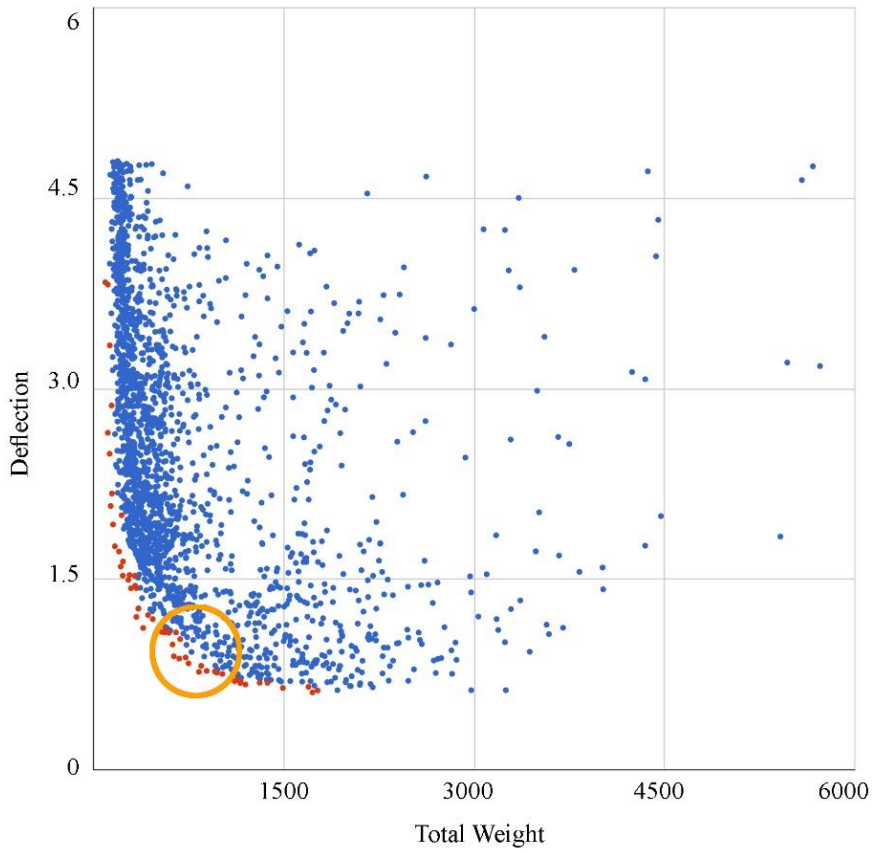


Figure 57: The distribution of solutions regarding the maximum deflection versus the total weight. The plot shows the Pareto levels 1 and 2 in red dots. The solutions within the circle might be appropriate and have less weight and less deflection.

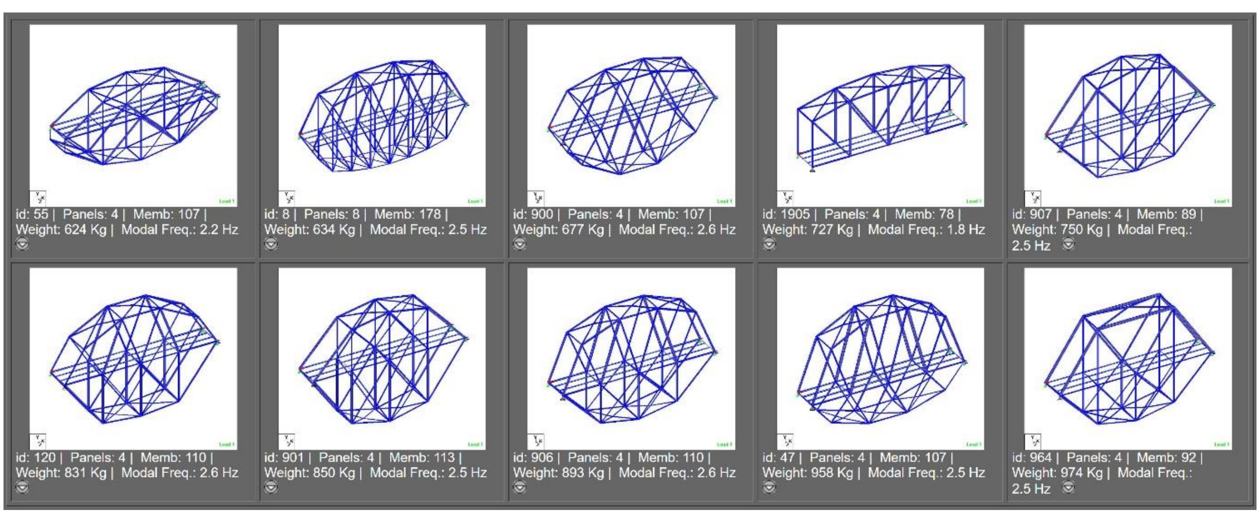


Figure 58: A display of solutions along the levels 1 and 2 Pareto sets whose weights are less than 1000 kg and have maximum deflection less than 1 cm

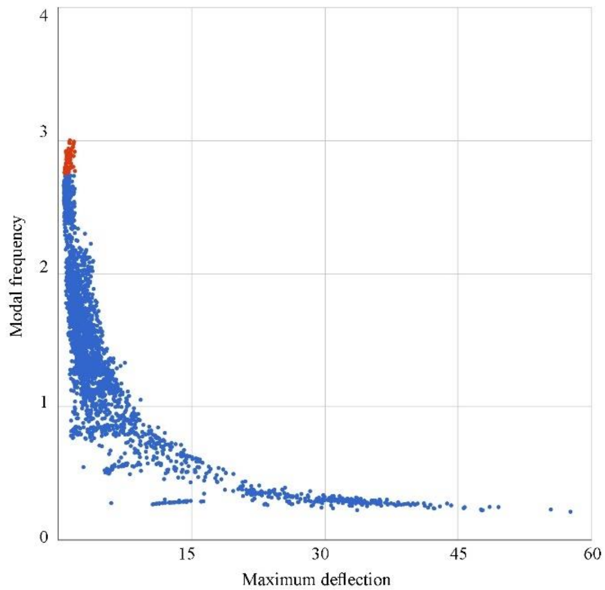


Figure 59: The distribution of solutions regarding the maximum deflection versus modal frequency

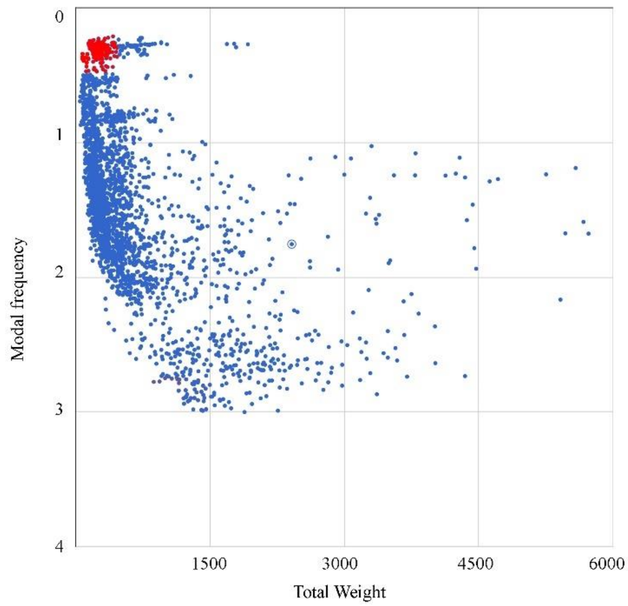


Figure 60: The distribution of solutions regarding the total weight versus modal frequency

3.5.3. Form exploration of the truss bridge using the GA+TRIZ method

First, design objectives, harmful, and useful functions, and the design parameters are determined. The goal is to obtain a series of appropriate solutions which are relatively light, have a maximum deflection of 4.8m or less, and a high modal frequency. Second, relevant design parameters are synthesized into their basic factors. The diagram in Figure 61 represents the relations among the design parameters. Accordingly, increasing the height of the truss, on the one hand, can reduce the maximum deflection of the truss, and on the other hand, adversely affect the total weight. This physical contradiction is verified by studying the sorted solutions regarding the value of maximum deflection in ascending order. Figure 62 shows that the reduction of maximum deflection in trusses required greater height in the middle of the span. This means using more steel and consequently, a heavier bridge. On the other hand, to obtain a lighter bridge, it seems better to reduce the number of structural elements. In other words, we can consider a single truss at the top or bottom of the deck but not at both sides (Figure 63).

In the third step, the matrix of contradiction, as shown in Table 9, along with the concept of separation are used to find generic solutions for the physical contradiction. The matrix suggests consideration of *all* the 40 inventive principles. Within the list of the 40 inventive principles, we look for an idea to support some sorts of *separation* in time, place, scale, or condition.

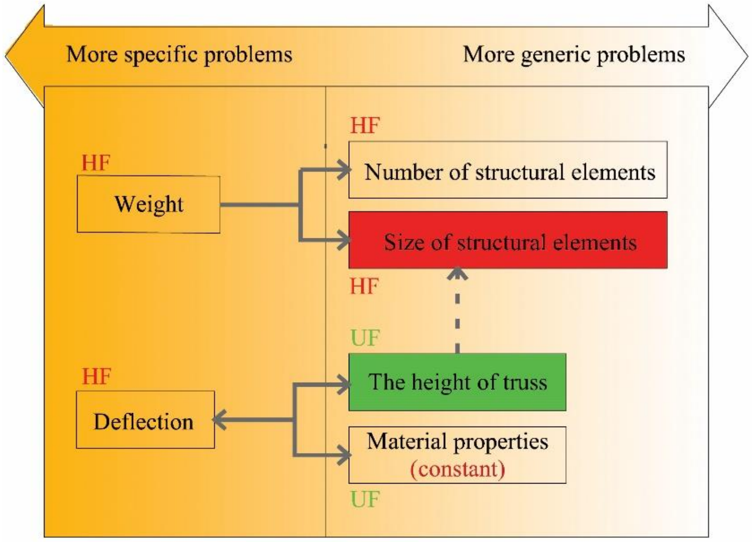


Figure 61: The relation of the design parameters in the case of designing the truss bridges. The height of the truss has both useful and harmful functions that indicate the existence of a physical contradiction.

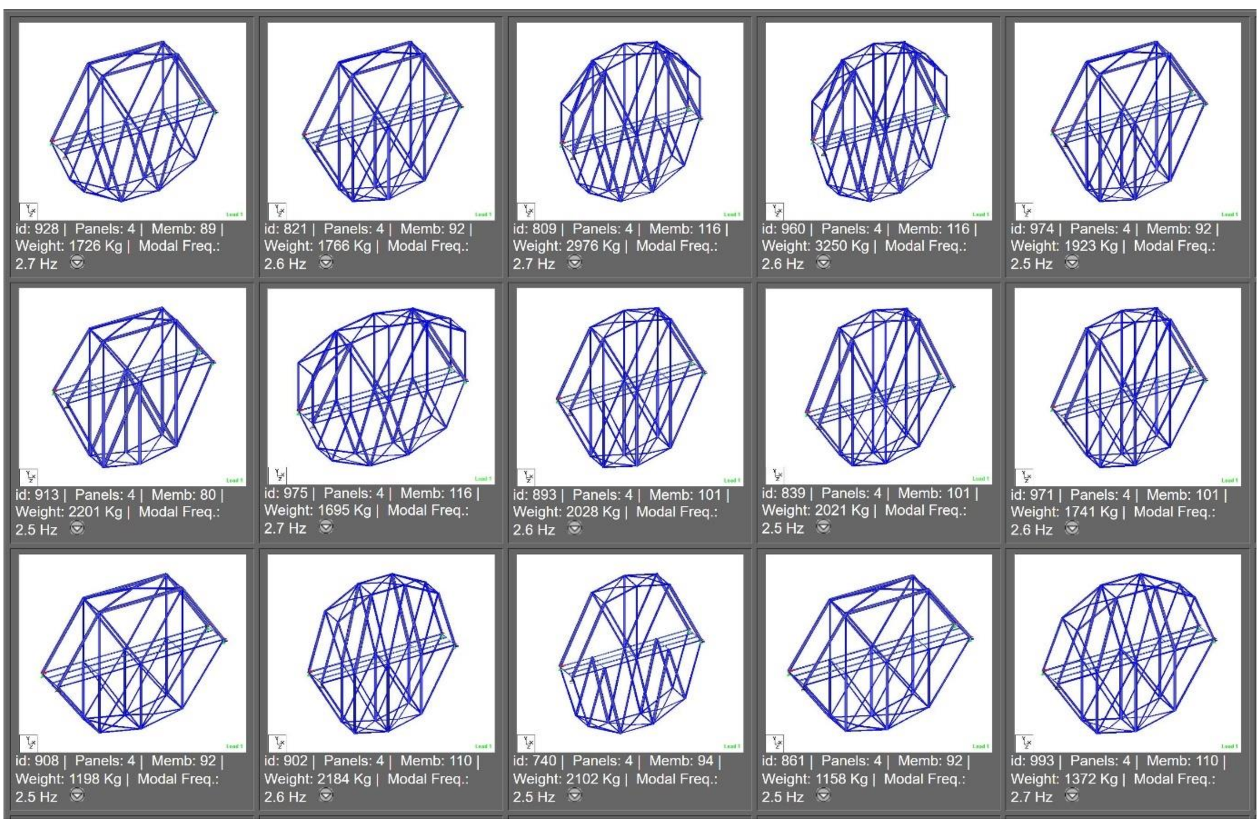


Figure 62: A display of solutions sorted regarding the maximum deflection in ascending order

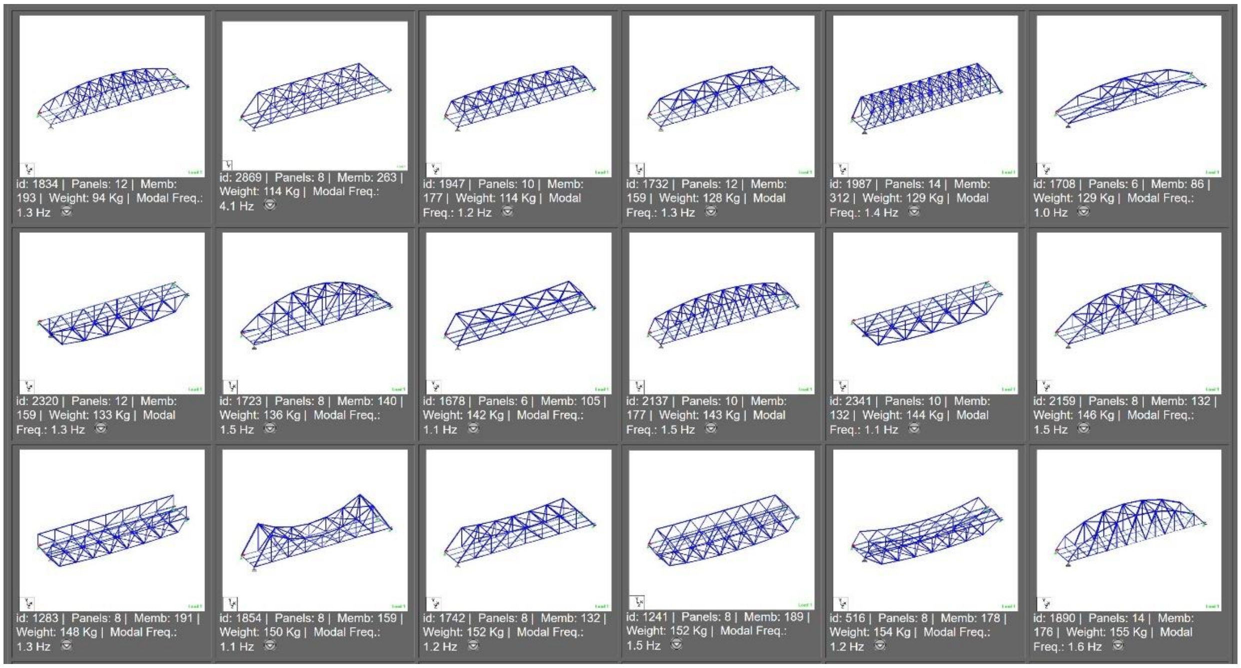


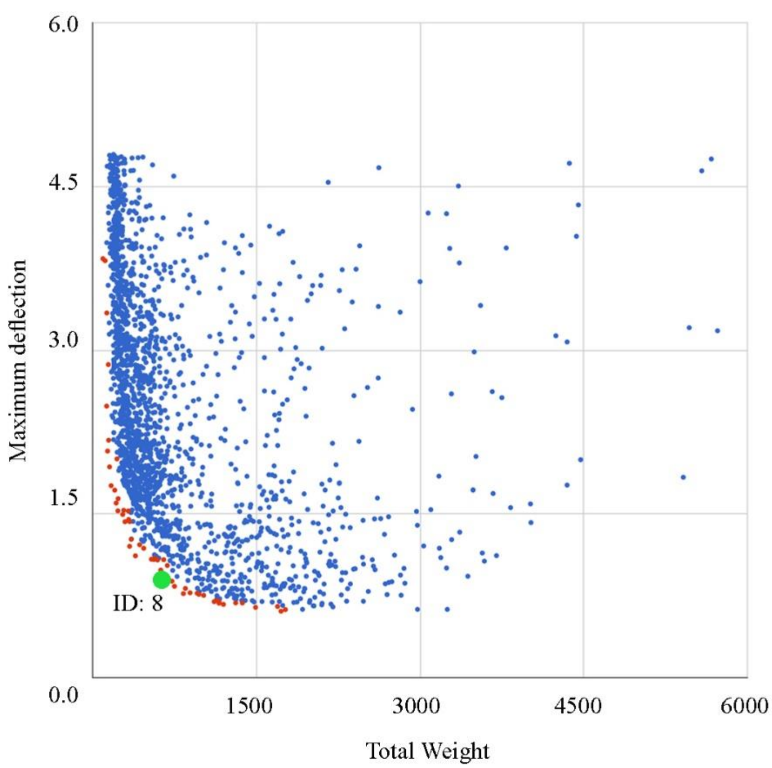
Figure 63: A display of solutions sorted regarding the total weight in ascending order

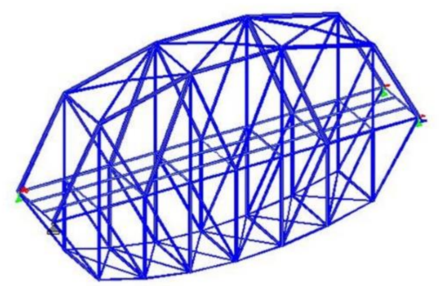
Table 9: The matrix of contradictions of the dome project

Characteristics			Characteristic that is getting worse (HF)
			4
			Length of a stationary object (height of truss)
Characteristic to be improved (UF)	4	Length of a stationary object (height of truss)	All

The fourth step is to interpret the generic solution into a more specific solution. In this design case, only one physical contradiction is recognized. The relation diagram indicates both the number of structural elements and their size affect the total weight of the bridge. Accordingly, we can separately consider the geometrical properties affecting the total weight and the maximum deflection. Reducing the density of the truss elements can decrease the total weight while its height can support reduction of the maximum deflection. Thus, placing only a single truss on top or at the bottom of the deck or selecting trusses with less density of elements can eliminate the contradiction among design objectives. Therefore, increasing the height may less adversely affect the total weight if we select a suitable truss pattern or density (number of panels).

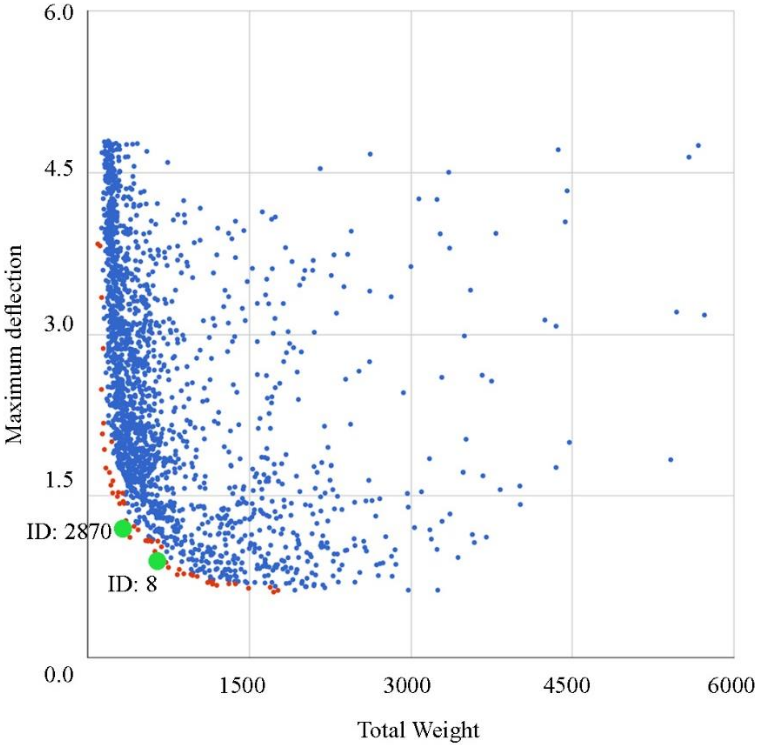
To verify the validity of this idea, a suitable solution is selected and enhanced using the TRIZ principles, and its performance is evaluated. For instance, the designer may choose bridge number 8 which has a maximum deflection of 0.89 and a total weight of 634.4 kg (see Figure 64). This bridge has eight panels and consists of a truss at the top and one at the bottom. The top truss pattern is D9 and has a height of 14.74 m, and the bottom truss pattern is D14 and has a height of 12m. We can reduce the density of elements either by employing a suitable truss pattern or omitting a truss at top or bottom. Bridge number 2870, generated by eliminating the bottom truss, has significantly less total weight. However, its maximum deflection of 1.2 cm is greater than that of bridge number 8 (see Figure 65). Bridge number 2871, generated by increasing the height of the bridge, has a maximum deflection of 1.1cm while its weight has just increased from 338.65 kg to 391.9 kg (see Figure 66).

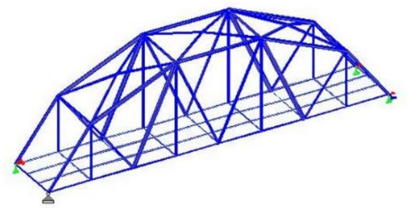




Number_of_Panels	8
Span	4800
Width	798
Top_Pattern	9
Bottom_Pattern	14
Total_Top_Height	1474
Total_Bottom_Height	1200
Number_of_Members	178
Number_of_Joints	67
Longest_Length_Member	15.56684
Total_Length_of_Members	1386.41
Modal_Frequency	2.46
Total_Weight	634.4328
Max_Deflection	0.893

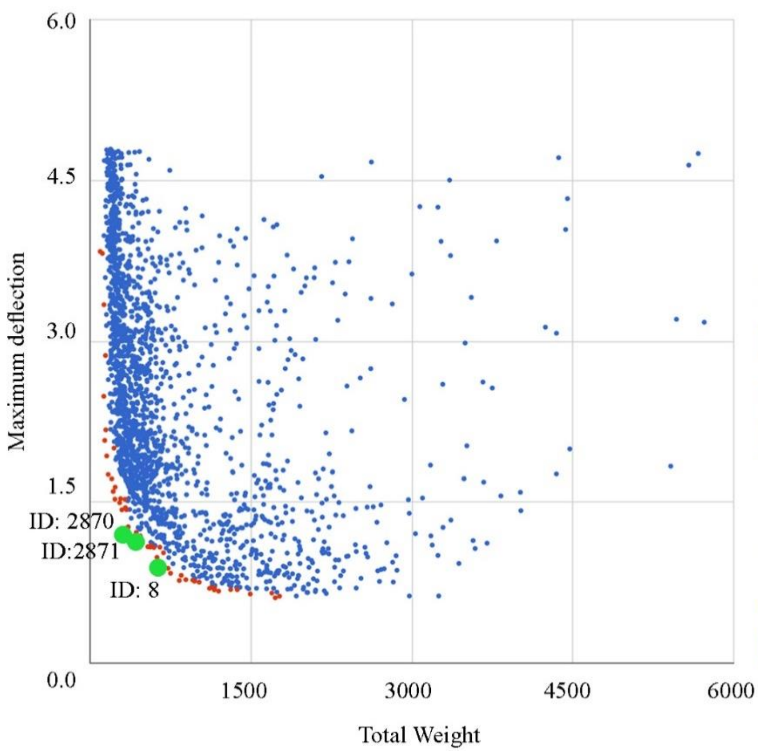
Figure 64: Bridge number 8 with a total weight of 634.4 kg and maximum deflection of 0.89 cm

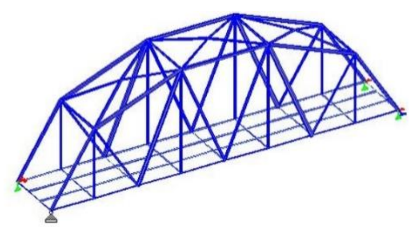




Number_of_Panels	8
Span	4800
Width	798
Top_Pattern	9
Bottom_Pattern	0
Total_Top_Height	1374
Total_Bottom_Height	0
Number_of_Members	105
Number_of_Joints	47
Longest_Length_Member	14.45212
Total_Length_of_Members	741.8955
Modal_Frequency	1.888
Total_Weight	338.6508
Max_Deflection	1.203

Figure 65: Bridge number 2870 is generated with the same truss pattern and number of panels as of bridge number 8 but the bottom truss is eliminated, and the top truss height is one meter less than that of number 8.





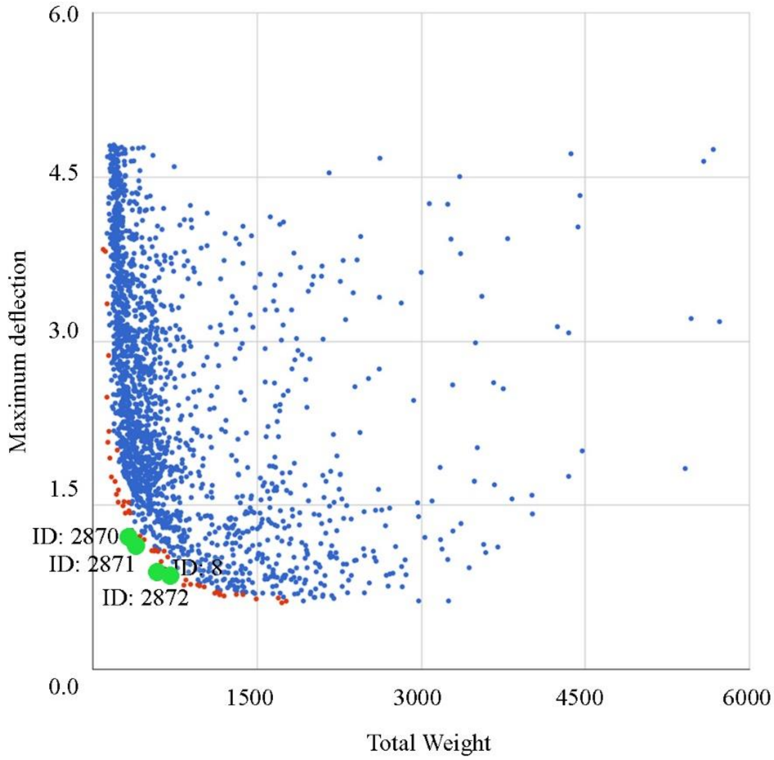
Number_of_Panels	8
Span	4800
Width	798
Top_Pattern	9
Bottom_Pattern	0
Total_Top_Height	1490
Total_Bottom_Height	0
Number_of_Members	105
Number_of_Joints	47
Longest_Length_Member	15.54359
Total_Length_of_Members	771.3153
Modal_Frequency	1.965
Total_Weight	391.9
Max_Deflection	1.11

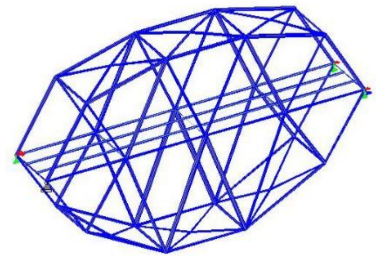
Figure 66: Bridge number 2871 is generated with the same truss pattern and number of panels as of number 8 and bridge number 2870, but the top truss height modified to be 14.9 m to decrease the maximum deflection.

3.5.4. Discussion

In this design case, it is assumed that the designer finds solution number 8 both visually pleasant and functionally acceptable and wills to obtain a final solution with a similar configuration but with better performance. Thus, the similarity of generated solutions to number 8 is preferred. TRIZ application allows modification of solutions with a better understanding of influential factors. Accordingly, the designer can keep the relevant parameters such as the truss pattern, and number of panels the same (similarity) and modify the height of the bridge to achieve better performance. Solutions 2870 and 2871 or another one with very similar geometry may be generated using a genetic algorithm. However, using TRIZ inventive principles can accelerate the convergence and in only a few runs of the exploration cycles obtain the desirable solution (time efficiency).

TRIZ inventive principles may offer other ideas to set the fitness function to generate new solutions. Instead of compromising the total weight and the maximum deflection in trusses, the designer can consider the number of panels, the height and the pattern of the truss to explore possible design alternatives (amount of data for decision making). In this example, further exploration may be carried out by minimizing the weight and maximum deflection within the bridges by reducing the number of panels, choosing another truss pattern and maintaining the trusses both at top and bottom of the bridge with similar height. Figure 67 shows a bridge generated with trusses at top and bottom with different truss pattern and number of panels as of number 8. But it is attempted to keep the truss height great. The total weight and the maximum deflection of the bridge are still minimum.





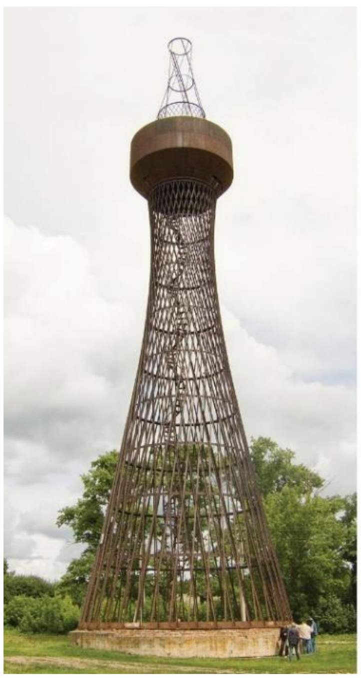
Number_of_Panels	4
Span	4800
Width	798
Top_Pattern	3
Bottom_Pattern	4
Total_Top_Height	1017
Total_Bottom_Height	1353
Number_of_Members	107
Number_of_Joints	42
Longest_Length_Member	16.57728
Total_Length_of_Members	1021.557
Modal_Frequency	2.198
Total_Weight	623.9936
Max_Deflection	0.986

Figure 67: Bridge number 2872 is generated with trusses at top and bottom of the bridge with different truss pattern and number of panels as of number 8, but it is attempted to maintain the truss height. The total weight and the maximum deflection of the bridge are still minimized.

3.6. Case study 3: Designing a tapered lattice tower to compare with the Shukhov Water Tower

3.6.1. Overall description

In this case study, the design process of a tapered lattice tower with a polygonal base is studied. Generated towers are geometrically and structurally compared to Shukhov Water Tower (see Figure 68) as a well-known successful design. Accordingly, the Shukhov Water Tower is used to set the design target, the fitness function, and filtering combinations. The height and the top diameter of the generated towers are set to be 37 m and 8 m respectively, the same values as that of Shukhov Water Tower. The other variables which define the topology of the towers are shown in Figures 69 and 70 and listed in Table 10.



Height	37
Polygon_Sides	40
Height_Sections	22
Diameter_of_Base	15.77
Diameter_of_Top	6
Truss_Pattern	9
Number_of_Members	2678
Number_of_Joints	920
Longest_Length_Member	6.27
Total_Length_of_Members	3573
Weight_Deflection	3.03
Modal_Frequency	15.58
Total_Weight	101895
Max_Deflection	2.974
Tower_Type	1
Prt_Weight_Deflection	5

Figure 68: The Shukhov Water Tower was built in 1896 for the All-Russian Exposition, in Nizhny Novgorod, Russia, (photo by Arssenev).

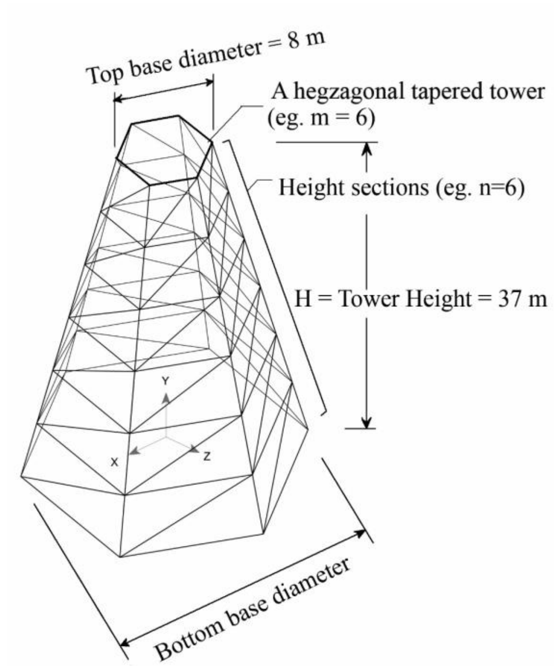


Figure 69: A typical form of the lattice towers and its geometrical parameters

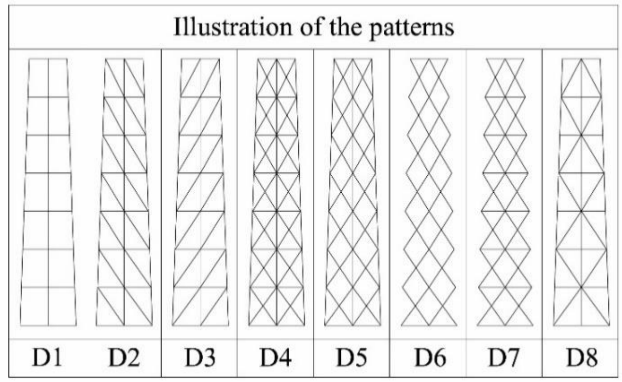


Figure 70: The patterns that are used in designing the tapered lattice towers. All joints are fixed.

Table 10: The geometrical and structural properties considered in design exploration of the tapered lattice towers

Geometrical properties
The height of the truss = 37 m, The top diameter = 8 m The bottom diameter = [8,24] m Height sections (n) = [4-37] Number of sides of the tower polygonal base (m) = [3,12]
Material, structural, and load properties
• Structural material: A-36 structural pipe sections Density = 7833.368 kg/m^3 (490 lb/ft^3), E = 199.947 kN/mm^2 (4.175 × 10^9 psf), Poisson=0.3 F_y=0.2482 kN/mm^2 (5.183 × 10^6 psf), F_u=0.3999 kN/mm^2 (8.352 × 10^6 psf) • Load: self-weight + 26883.4 kg/m (59267 lb/ft) water tank load +wind load of 0.815773 kg/m (1.8 lb/ft) in X, Z, -Z, -X directions and wind load of 0.577159 kg/m (1.25 lb/ft) in XZ, -XZ, -ZX, -X-Z directions • Joints are all fixed , Supports: Pinned

3.6.2. Form exploration of the lattice towers using only the ParaGen method

First, the geometrical configuration processing of the towers is described through the concepts of Formex algebra and using the Formian software [90]. Having processed the parametric model of the towers, the DXF file of each tower is sent to STAAD.Pro. for structural analysis and evaluation. The obtained structural data and graphic depictions are stored in a database which is linked to a visual exploration interface. In the next step, pairs of towers are selected based on the design objectives to breed further solutions. The new generations of towers are produced within the iteration of these steps to yield an array of suitable solutions. Ultimately, a fitness function, based on performative characteristics of Shukhov Water Tower, is used to pull out the desirable solutions from the pool of generated forms. Further information on form exploration of lattice towers using ParaGen can be found in [8].

Finally, through the series of suitable solutions, the designer can choose the desirable ones regarding their structural performance and visual appearance. Figure 71 displays the variety of generated solutions whose total weight and maximum deflection are less than 120 tons and 3cm respectively. Moreover, the graph in Figure 72 shows the distribution of solutions based on the total weight and maximum deflection. In this graph, the levels 1, 2, and 3 of the Pareto sets are displayed in red and Shukhov Water Tower is also marked as a design target. The designer may explore and select a series of suitable solutions regrading some other preferences such as minimum number of joints for less labor-intensive construction. Other fabrication considerations such as required joint fixity can be quickly observed and taken into account by viewing the solution images. In this way, trade-offs can be made regarding the various parameters.

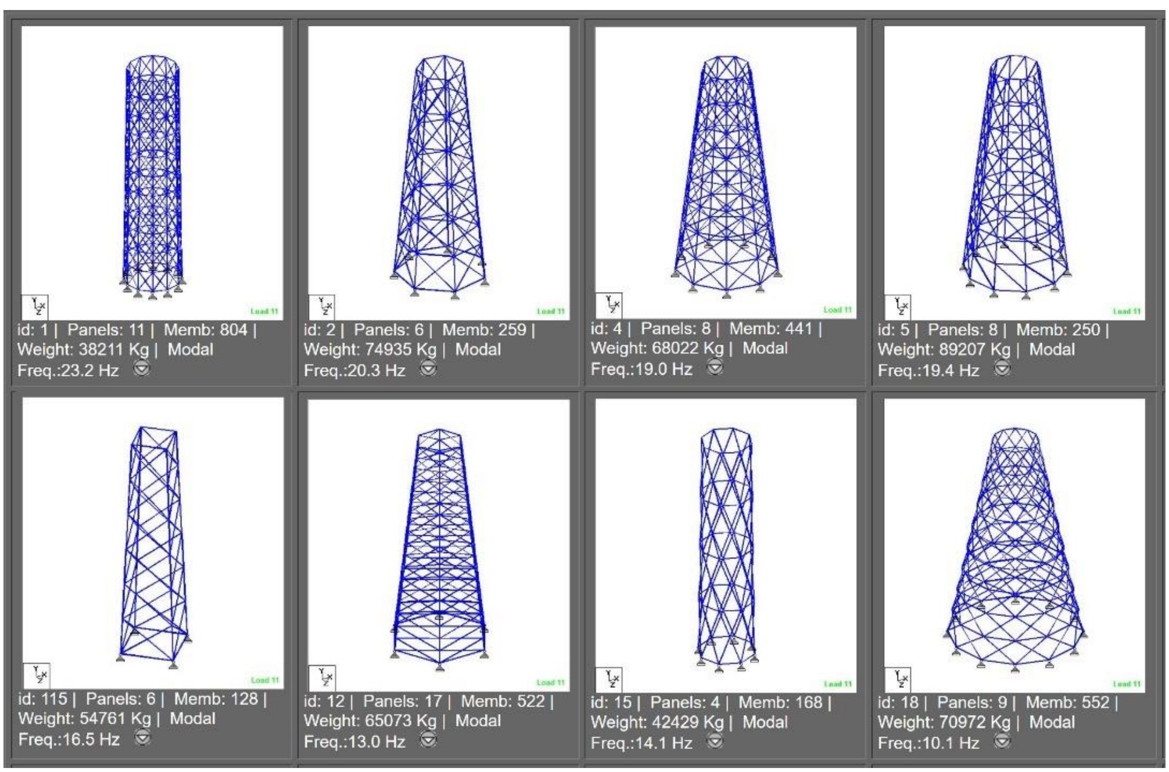


Figure 71: The variety of solutions whose total weight and maximum deflection are less than 120 tons and 3 cm respectively

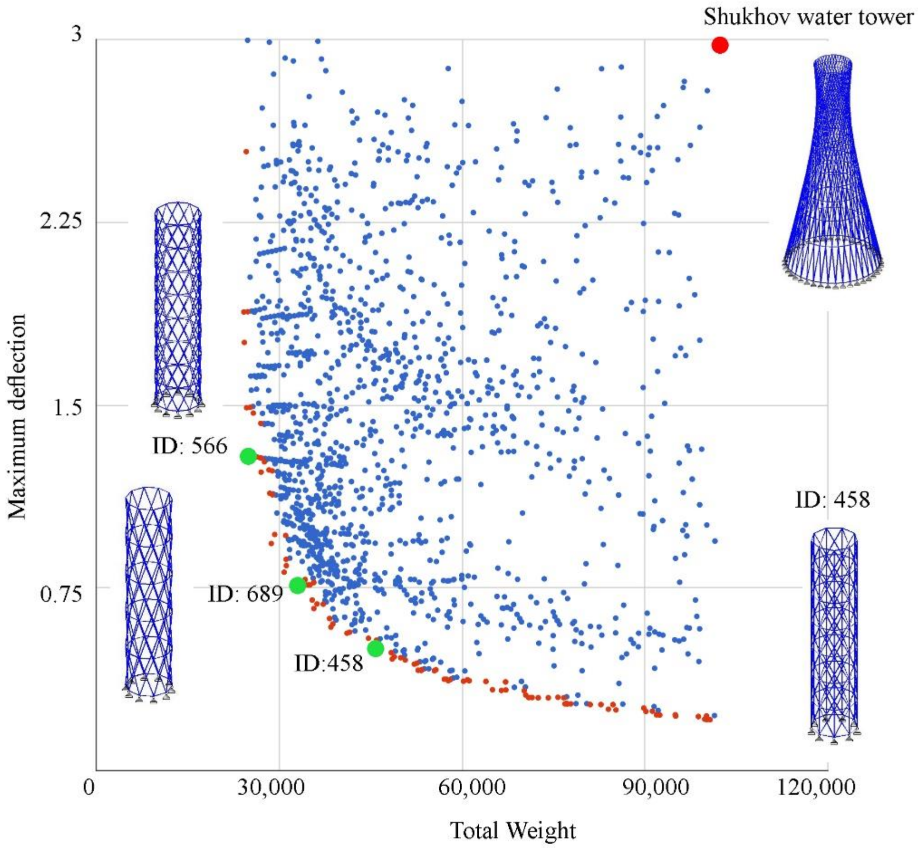


Figure 72: The plot displays the distribution of solutions whose total weight and maximum deflection are less than 120 tons and 3 cm respectively. Shukhov Water Tower is marked on the plot as a design target.

3.6.3. Form exploration of the lattice towers using the GA+TRIZ method

The main objective of this design case is to gain comparable good solutions whose maximum deflection and total weight is less than that of Shukhov Water Tower. According to the GA+TRIZ method, the preliminary step of conceptual design phase is the determination of objectives, useful and harmful functions. Total weight and maximum deflection are set to be less than 102 tons and 3 cm respectively.

Next, these two parameters are required to be decomposed into their basic factors and studied for any probable conflict. At the first glance, total weight depends on the weight of steel elements. But no specific factor may come into the designer’s mind in relation to the maximum deflection unless she refers to some structural equations or carries out some calculation manually. Then, the parametric model can be built including the relevant parameters. Having generated 200 random solutions, we can study the relation among the design parameters. A 2D graph where total weight and maximum deflection of the 200 random solutions are compared, may not reveal any conflict (see Figure 73). Hence, the designer may proceed to set the fitness function to systematically generate solutions using a genetic algorithm and explore further possible solutions.

The more solutions are generated, the more likely one is to recognize the conflicts among design parameters. The graph in Figure 72 hints the contradiction among the total weight and maximum deflection but the basic factors triggering the conflict may not be clear to the designer. One useful way to recognize the causes of the conflicts is to filter or sort the data base and study the relation among the geometrical and performative parameters of the design alternatives. Studying the first 1000 light weight solutions reveals that:

- 61% of the solutions have the same top and bottom diameters and are not tapered. Also, 27% are tapered very lightly.
- 34% of the lattice towers have the pattern 1, 26% have pattern 5, and 15% have pattern 7 (see Figure 74).

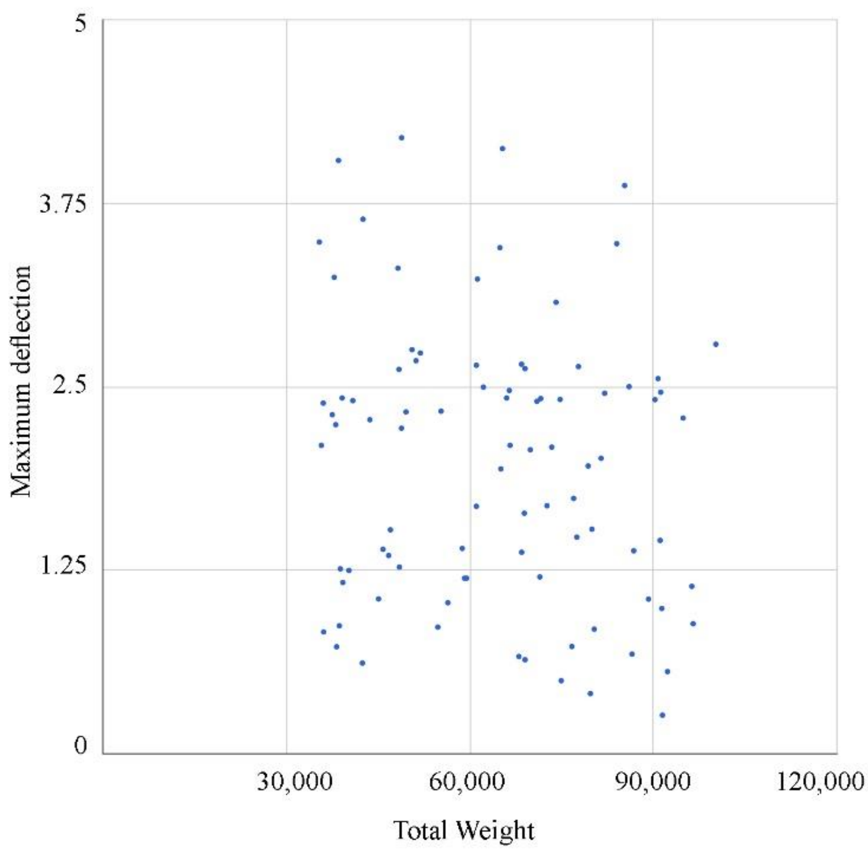


Figure 73: The distribution of 200 randomly generated solutions based on the maximum deflection versus the total weight

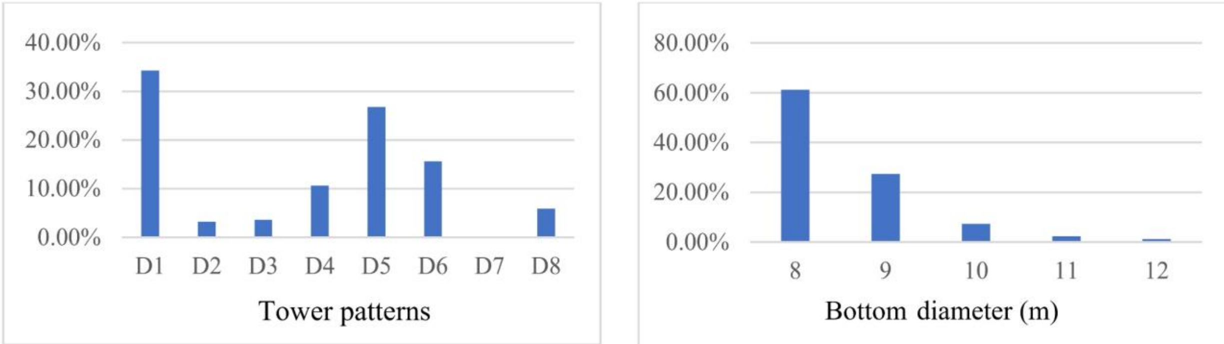


Figure 74: The clustered column charts illustrate the percentage of the lightweight generated solutions based on the tower patterns and bottom diameter.

In the same fashion, exploring the database for the least maximum deflection indicates:

- 28% of the solutions have pattern 4, 26% have pattern 5, and 24% have pattern 8.
- Towers with less maximum deflection are less tapered.
- Towers with less maximum deflection have fewer elements along their height (see Figure 75).

At the second step of the GA+TRIZ method, a specific problem is restated into a generic problem. According to the diagram in Figure 76, it can be concluded that the technical contradiction between decreasing the total weight and maximum deflection is basically due to the tower patterns.

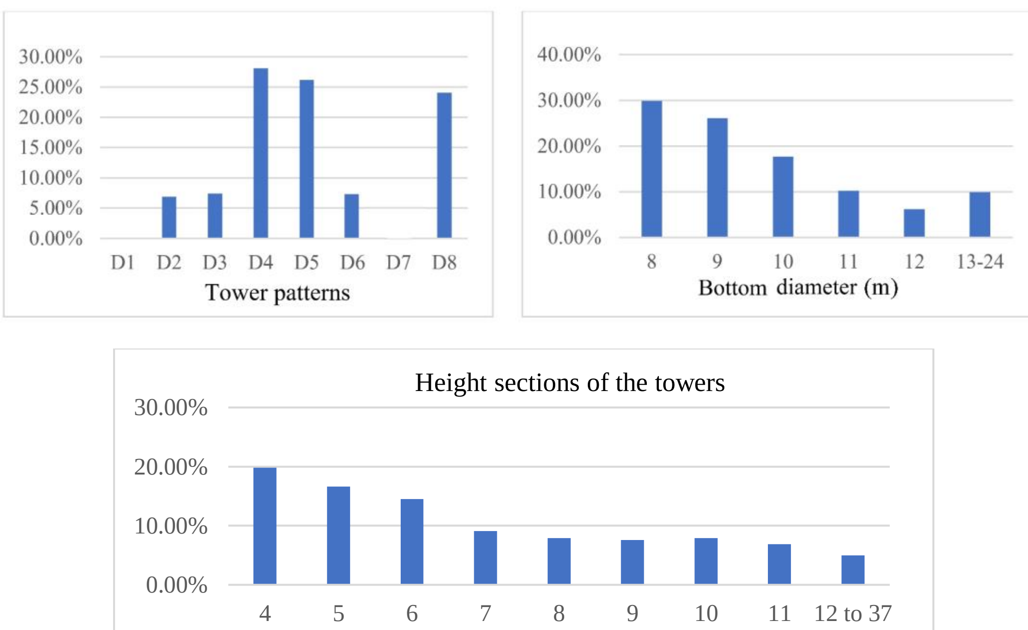


Figure 75: The clustered column charts illustrate the percentage of generated solutions with lower maximum deflection based on the tower patterns, bottom diameter, and height sections.

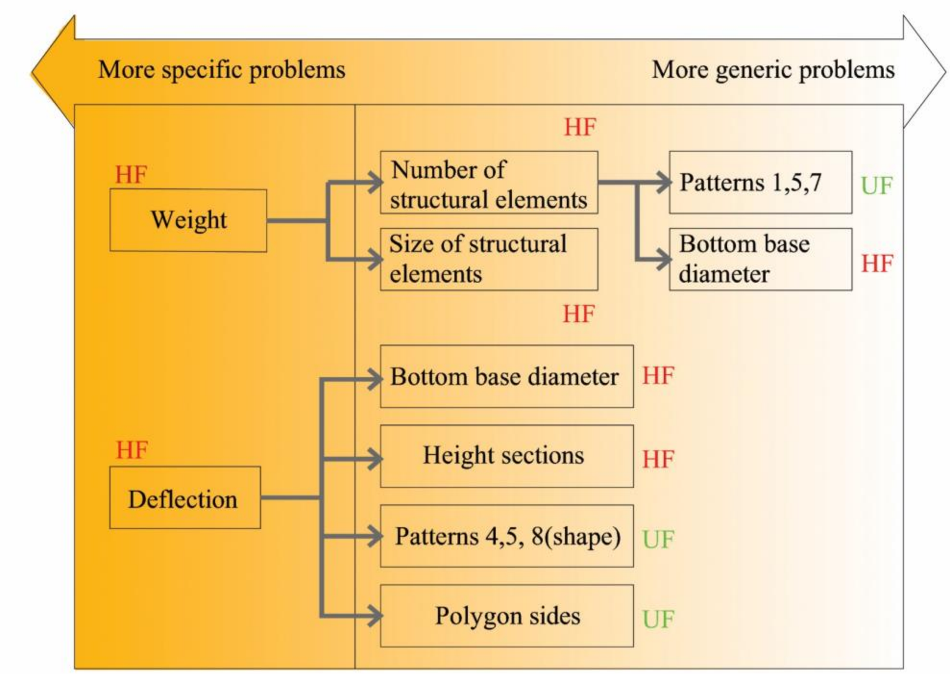


Figure 76: The relationship of the design parameters in the model of tapered lattice tower

In the third step, the matrix of contradiction (Table 11) offers some generic solutions such as taking *preliminary action* or considering the *local quality*. The designer may think of modification of towers' pattern (preliminary action) in a way that some structural elements contribute to the stability of the tower and some others transfer the vertical load to the foundation. The clustered column charts in Figure 74 shows that design alternatives with patterns 1, 5, 6, and 4 are the lightest ones. However, towers with patterns 1 and 6 have the worst deflection. Pattern 5 seems to yield appropriate stability and be enough lightness (Figure 75). Also, pattern number 4 which is similar to number 5 may be suitable but some horizontal elements should be added that relatively increases the total weight. Figures 77 and 78, which demonstrate the distribution of solutions based on the total weight versus the maximum deflection, validate the suitability of patterns 5 and 4. In this figure, lattice towers with the patterns 5 and 4 are marked. As a result, the designer may include the pattern type in the fitness function to explore further possible solutions.

Moreover, the diagram of parameters' relation in Figure 76 indicates that the height sections affects the maximum deflection of the towers. Hence, the designer may also consider this parameter while setting the fitness function.

Table 11: The matrix of contradictions of the tapered lattice tower project

Characteristics			Characteristic that is getting worse (HF)
			2
			Weight
Characteristic to be improved (UF)	12	Shape	15-Dynamism 10-Preliminary action 26-Copying 3-Local quality

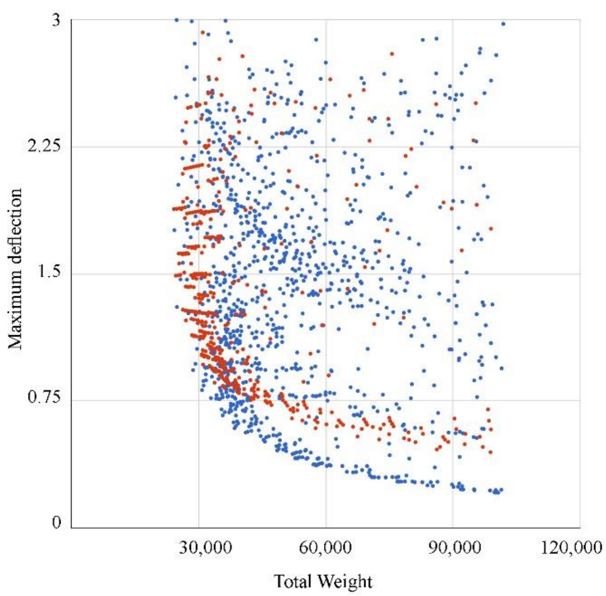


Figure 77: The distribution of solutions based on the maximum deflection vs. the total weight. Towers with pattern number 5 are marked in red.

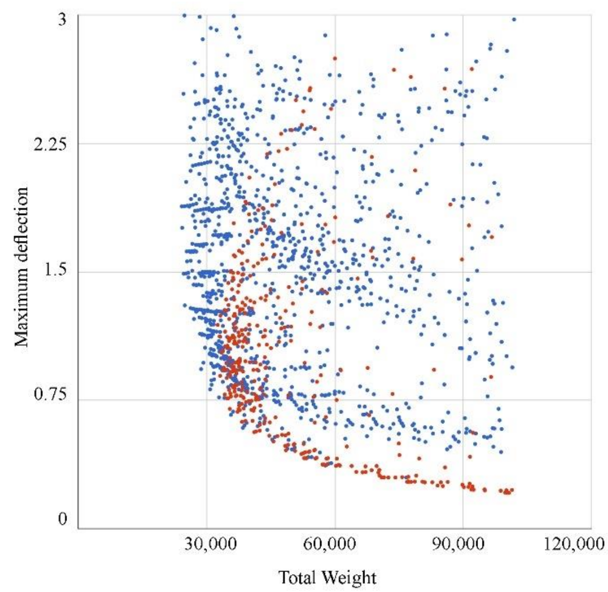


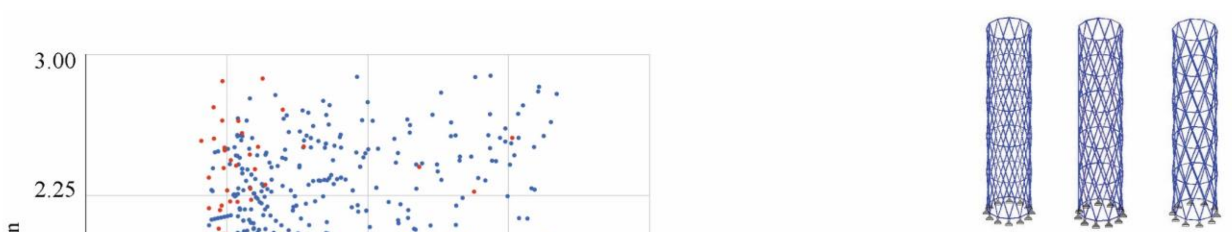
Figure 78: The distribution of solutions based on the maximum deflection vs. the total weight. Towers with pattern number 4 are marked in red.

3.6.4. Discussion

In this case, the mutual interaction between a GA-based exploration technique and TRIZ becomes clearer. The Theory of Inventive Problem Solving provides the designer with abstract ideas to overcome the design barriers (implicit search goals). The abstract nature of TRIZ principles may not direct the designer to a clear explicit solution. For instance, when the design objectives were defined in the case of lattice tapered towers, no contradiction came into our viewpoint. Later, when 200 random solutions were generated, the conflict between the total weight and maximum deflection was still difficult to recognize. Having generated further solutions systematically by setting the fitness function to minimize the two performative parameters, the contradiction between them emerged. Then, the TRIZ innovative principles came into play, and allowed a direct convergence around the towers with a certain type of pattern.

In this case study, similarity of the generated solutions to certain lattice towers are demanded. The employed patterns and the ratio of the bottom to the top diameter of the towers come into play to yield the preferred solutions. When the suitable patterns were recognized, TRIZ analysis along with the ParaGen form generator allowed a direct convergence to make a final decision.

In this case study, tower number 503 is chosen as a desirable design alternative. Tower number 503 with pattern number 7, has a maximum deflection of 0.59 cm and a total weight of 38504 kg. The diagram of relations shows that towers with pattern number 7 are relatively light weight solutions. In this example, the total weight of the chosen solution is minimized by decreasing the number of polygon sides at the base of the tower. At the same time, the diameter of the top and bottom of the tower is determined to remain 8 meters to minimized both the maximum deflection and total weight. With such understanding of the parameters dependencies, two cycles of form generation are carried out. Ultimately, tower number 3061 with a total weight of 32919 kg and a maximum deflection of 0.77, which is still within the acceptable interval, is generated to be the final solution.



id_tag	503	3060	3061
Height	37	37	37
Polygon_Sides	12	11	10
Height_Sections	5	5	5
Diameter_of_Base	8	8	8
Diameter_of_Top	8	8	8
Truss_Pattern	7	7	7
Number_of_Members	312	286	260
Number_of_Joints	132	121	110
Longest_Length_Member	3.842102	3.867808	3.901003
Total_Length_of_Members	1071.184	999.6714	928.528
Weight_Deflection	226789.7	237426.5	252490.1
Modal_Frequency	28.321	27.564	23.45
Total_Weight	38504.2	35703.24	32919.19
Max_Deflection	0.589	0.665	0.767
Tower_Type	0	0	0

Figure 79: Tower number 3061 is the final chosen solution with a total weight of 32919 kg and a maximum deflection of 0.77 cm.

3.7. Case study 4: Designing a mid-rise residential complex in Montreal

3.7.1. Overall description

In this case study, design alternatives of a mid-rise residential complex in Montreal are explored [102]. The configuration of the whole body of the residential complex is inspired by Habitat 67 (Figure 80) where the prefabricated modules seem to be stacked chaotically. In 1967, the Habitat residential complex gained worldwide admiration and turned out to be one of the major symbols of Expo 67 as it was an outstanding integration of architecture and structure. Fifty years later, Habitat 67 still seems a spectacular residential project. However, it may not be a state-of-the-art housing project according to the current consideration developments. In 1967, architects and engineers were exploring materials, and industrialization of building construction. Also, further prefabrication technologies were being established to confront the design barriers and reduce the construction duration and costs. Now, it is almost a decade that designers have been more concerned about the sustainable development of human-built environment and reduction of building construction impact on global warming, CO2 emission, ozone depletion, and consumption of natural resources. Therefore, if such an innovative project as Habitat 67 were to be built today, the design approach would be different.

Figure 80: Habitat 67, Montreal, Canada *[103]*

In this design exploration project, characteristics of Habitat 67 are considered to evaluate the performative characteristics of the generated solutions. In Section 3.7.2, a brief description of the structural system, construction techniques, costs and environmental performance of Habitat 67 is provided. Accordingly, the structural performance, the heating energy demand throughout November to March, the shell cost, the environmental and life cycle impact of the design alternatives are studied. The configuration processing of the design project and the process of form exploration using the GA+TRIZ method are explained in Sections 3.7.3 and 3.7.6 respectively.

3.7.2. Habitat 67

Moshe Safdie designed Habitat 67 as the Canadian Pavilion for Expo 1967. Some critics assert that Safdie has been influenced by the Brutalism and Metabolism trends for the creation of Habitat 67. However, other critics believe the dwellings of the Pueblo people in the Southwestern United States (Figure 81) were the main source of inspiration for Safdie's remarkable residential project [104]. The project is located on a strip of human-made land which was created as an ice breaker to protect the harbor of Montreal. Safdie's main design goals were creating high-quality affordable housing where tenants have their own garden despite the great density of apartment units. Thus, he employed prefabricated modular units to reduce the housing cost. However, practically, only three clusters of apartment units were constructed, and due to the reduction of the project's mass scale, Habitat failed to be a low-cost urban housing. In fact, the cost of 140,000 CAD per unit seems to be far from affordable housing [105]. Though Habitat could break the traditional form of orthogonal high rises and introduce a new housing topology.

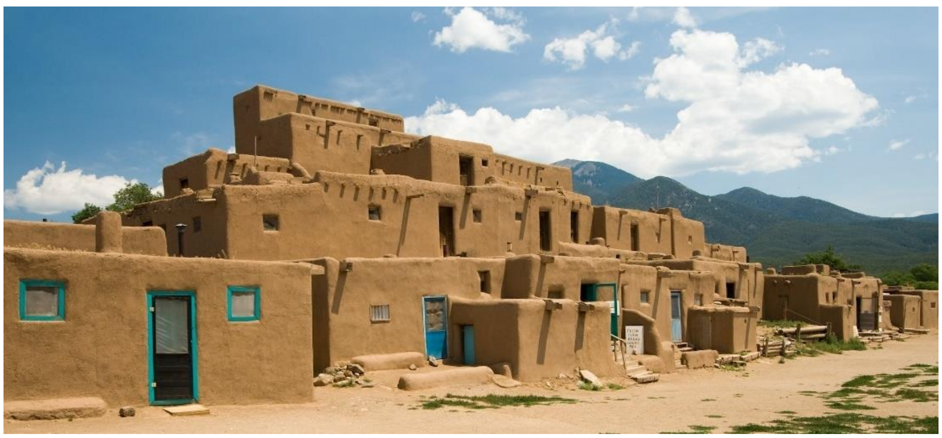


Figure 81: The dwellings of the Pueblo people in the Southwestern United States *[106]*

Habitat 67 is constructed from 354 identical prefabricated modules stacked in various geometrical configurations to provide 158 apartments. There are 15 models of apartment units including one to five modules. The units look similar, but each house differs from the others on the interior. You may enter at the top floor of an apartment where the living room is located and take the stairs down to the dining room and kitchen and finally find the master bedroom along with a small living room at the lowest floor (Figure 82). The apartments are soundproofed and heated by a central heating and air conditioning system. The geometrical and material properties of Habitat 67 along with the cost estimation are described in Table 12 [107].

Table 12: The design properties of Habitat 67

Geometrical properties
354 modules 38×17 ft^2 [108] (12.5×5.7×3.2 m^3 external measurement)
Total Height: 36.576 m (120 ft) | 12 stories
15 different modules with an area of 55 m^2 (624 ft^2)
Floor plans range from 1 to 4 bedroom apartments and 1 to 3 stories
Weight of each module = 70 to 90 tons
The area of terraces range from 20-90 m^2 (225 to 1000 ft^2)
Material
Exterior walls of the units: sand-blasted concrete
Window frames: brown anodized aluminum
Cost
140,000 CAD per unit
Total cost = 140,000 × 158 = 22,120,000 CAD
Heating/cooling cost for a one/two-bedroom apartment in Montreal = 200-300 CAD per month throughout the year
Heating/cooling cost for a one-bedroom apartment of Habitat = 400-600 CAD per month throughout the year [109].

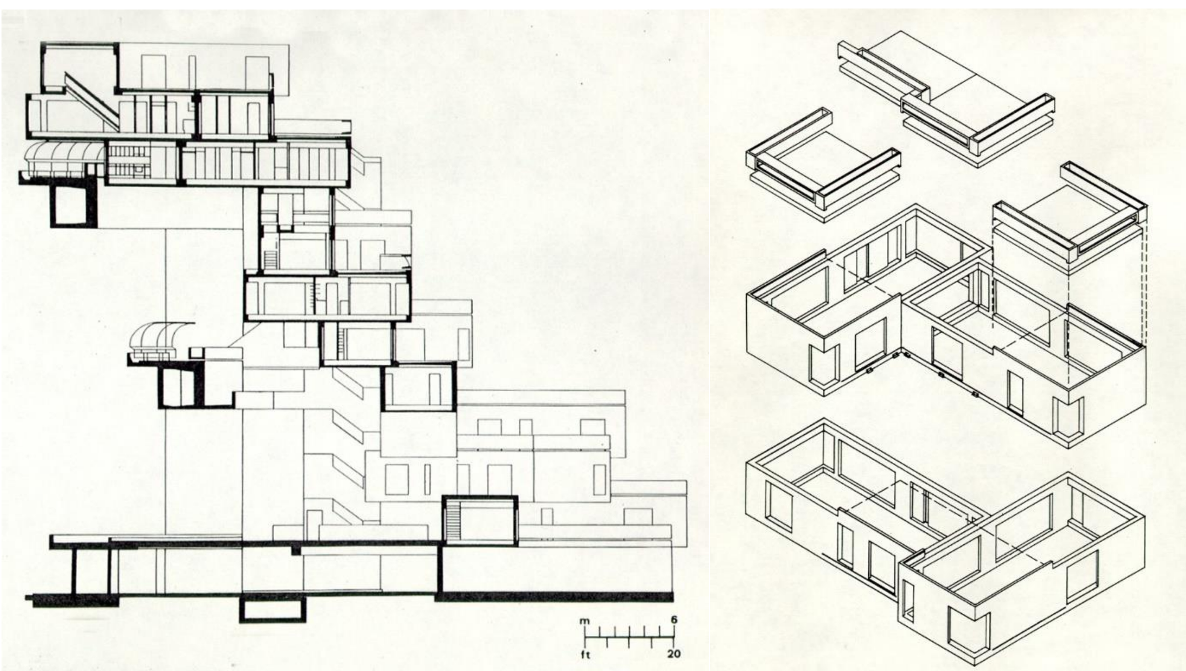


Figure 82: Constructional drawings of Habitat 67 *[110]*

The manufacturing site of Habitat 67 was located 300 m away from the site of implementation. First, the metal frames of each of the modules were assembled using a template. Then, the concrete was poured onto the frames which were enclosed in a steel mold. Then, the concrete was steamed to control its quality and color. Next, the modules were cleaned via a jet of sand, post longitudinally constrained, internally lined with insulating material and equipped with electrical and mechanical systems, windows, and water pipes. Then, on the ground, the modules were partially finished and, kitchen and prefabricated bathrooms were installed. Finally, the complete modules, whose weight varies between 70 and 90 tons, were hoisted by a giant crane, set up and secured to other units by means of post-tensioning cables. This last operation also included the installation of the concrete cover which closes the module and completion of the interior finish (Figures 83, 84, and 85) [107].

In the beginning, Habitat 67 belonged to the Canadian government. Then, Groupe Heafey bought it for 10 million CAD. Then, he sold 75% of the apartments for 11.4 million CAD and a monthly maintenance fee of 100 to 200 CAD. The rest of the 25% of the units have been rented for 500-1000 CAD per month. Despite the massive structure of the building and the heating insulation, it is reported that the heating cost of the apartments are twice of the usual building in Montreal because each module has several exposed walls [109].

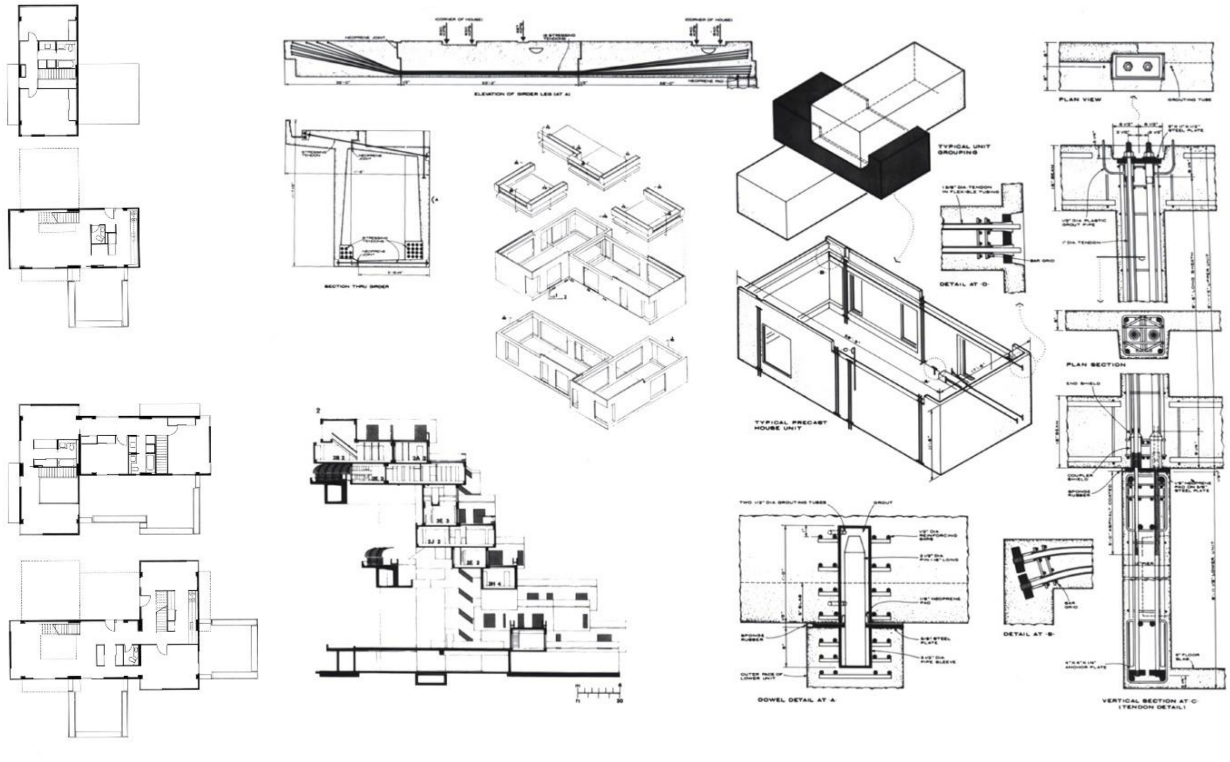


Figure 83: Floor plan of an apartment and constructional details *[103]*

Figure 84: Prefabrication of the apartment units in the manufacturer's site *[111]*

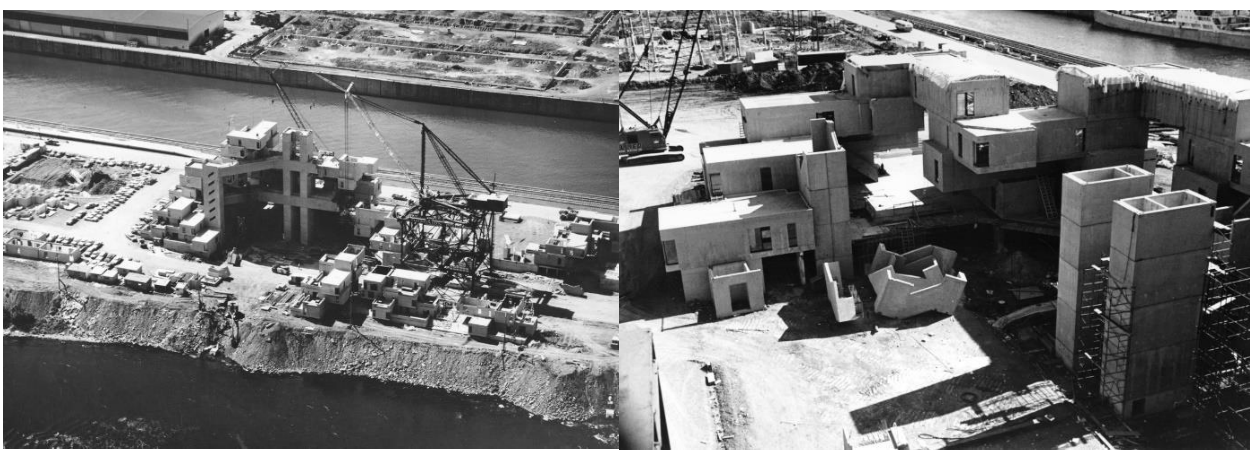


Figure 85: Construction of Habitat 67 *[112]*

3.7.3. Configuration processing of the CLT mid-rise residential tower

Habitat 67 includes three clusters of stacked modules. With the same fashion, the residential complex in this project is to be composed of three same clusters of apartment units (Figure 86). In order to reduce the simulation time in this project, only one of the clusters is parametrically modeled and analyzed. Therefore, performative characteristics such as the shell cost, thermal energy demand, weight of structures, and life cycle impact are compared to one-third of the corresponding values in Habitat 67. The configuration of each cluster of apartment units is defined by creating a stack of 12×16×11 (width×length×height) modules whose number of floors is reduced regarding the location of four attractor points on the XY plane (Figure 86). Then, 250 to 500 modules from this basic model are removed randomly to shape the roof gardens and private balconies (a seed value controls the reduction pattern). Each module is 5.8×5.8×3.4 m^3. Then, columns and required structural supports are added to the model where units are not supported by the walls of the lower floors. The geometrical properties of the residential complex are described in Table 13.

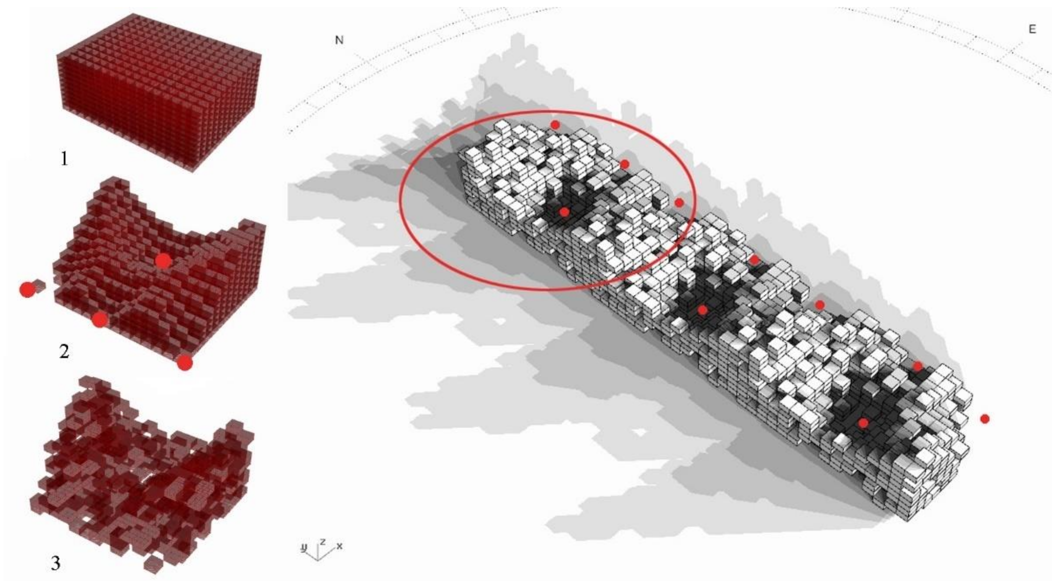


Figure 86: The configuration processing of mid-rise residential complex

Table 13: The geometrical properties of the mid-rise residential complex

Geometrical properties
Habitat module dimension = 12.5×5.7×3.2 = 228 m^3 Habitat maximum height = 36.576 m | 12 stories Assumption: Each residential unit includes two geometrical modules, floor to floor height = 3.4 (11 ft) ⇨ Geometrical dimension of each module = 5.8×5.8 m^2 Height of each apartment module = 3.4×11=37.4 m | 11 stories Area of each apartment module: 5.8×5.8 m^2 (19×19 ft^2) Height of each apartment module: 3.4 m (11 ft) Maximum number of floors: 11

3.7.4. Structural and thermal analyses

Walls, roofs and floor slabs are all to be made of structural panels. The roofs are expected to be used as roof gardens. Therefore, the appropriate combination of live load and snow load is considered in the structural analysis. Total weight of the structure, its natural frequency, and maximum displacement are obtained through the simulation carried out in Karamba a plugin for Grasshopper [113]. Also, a pilot structural analysis is carried out in STAAD. Pro version 2007.11.90 to verify the outputs. Application of Karamba in this form exploration project has two advantages. First, Karamba allows defining an orthotropic structural material while STAAD only includes isotropic material properties. Second, running both Karamba and ArchSIM engine for strcutural and environmental analyses [93] in Grasshopper makes the form exploration more convenient and saves time.

Thermal analysis is carried out for assessment of the Heating Ideal Zone Load for five months, from November 1st to March 31st. In Montreal, heating cost and maintaining the comfortable temperature within these five months are critical while cooling energy demand throughout the year is not that important. The thermal analysis is carried out using ArchSIM plugin for Grasshopper.

3.7.5. Life cycle impact assessment

Since the 1960s, several studies indicate that application of natural products is not environmentally optimal necessarily and designers cannot rely on their intuition to identify environmental impacts of certain products or services. Hence, a systematic approach is required to analyze and document the impacts of products throughout a cradle-to-grave or a cradle-to-cradle cycle. Accordingly, the International Organization for Standardization (ISO) defines Life Cycle Assessment (LCA) as "compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle" [114] [115] [116]. The scope of an LCA is defined by determination of some limits including, the process of production, disposal or recycling of products, delivery considerations, and transportation requirements, emissions and wastes of the product.

In this design case study, the LCA is carried out to evaluate the magnitude and significance of the potential impacts of the residential building complex on the environment. In this study, the same input data including, type of occupancy, location, and gross floor area can be truncated from the model for practical purposes and quick estimation.

A Life Cycle Impact Assessment heavily relies on data and software. A reliable database includes thousands of processes and their input and output flows. In this case study, the Product Declarations of the structural materials, provided by the suppliers, are used to compute the LCA. The provided information is also verified by the Athena Impact Estimator (version 5) software.

The LCA assessment in this design project includes global warming potential, acidification potential, ozone depletion potential, total used energy through the life cycle, non-hazardous waste, hazardous waste, non-renewable material consumption, renewable material consumption, and freshwater consumption.

3.7.6. Form exploration of the mid-rise residential complex using the GA+TRIZ method

In this project, the main design objectives are minimizing the environmental impact, reducing the heating energy demand in the cold season, providing a pleasant residential space for the tenants, and creating an iconic apartment complex in the city. According to the GA+TRIZ method, before creating the parametric model, the design objectives should be synthesized to their basic factors to study the existence of any contradiction among the design parameters.

Reducing the environmental impact such as global warming requires to decrease the consumption of material resources. As it is shown in Figure 87, reduction of environmental impacts of the residential complex conflicts the desire of providing more apartment units and greater floor area. In this regard, the matrix of contradiction suggests *changing the physical or chemical properties of employed substance* or employing *composite materials* (Table 14). The interpretation of the first generic suggestion can be the replacement of the building materials with high environmental impact by eco-friendly materials. This suggestion, derived from the TRIZ inventive principles supports, the idea of replacing the prefabricated reinforced concrete panels of Habitat 67 with Cross Laminated Timber panels.

There are five reasons for choosing CLT panels as a replacement of prefabricated reinforced concrete in this case study. The first reason is the renewability and low environmental impact of the wood, in particular, its low carbon footprint. Second, CLT panels can be employed in the prefabricated building industry where panels are cut to the required dimensions, engineered and treated to be thermal and fire resistant, and finally erected in-site relatively quickly. Third, the presence of wood can provide the occupants with a pleasant environment and improve the quality of interior space. Fourth, the reason for choosing CLT products and not, for example, light-frame wood construction is to keep the mass parameter consistent. This allows comparison of two massive constructions that have two different carbon footprints. Fifth, in Canada, in particular in Quebec, forestry is a huge part of the economy, and several companies supply the CLT products for the building industry. Accordingly, the required building codes are provided for architects and engineers to employ CLT products. There are successful examples of CLT buildings all over the world as well as in Canada. In Appendix 5, five mid-rise CLT residential towers are introduced that have pushed the boundaries of the CLT industry furthest.

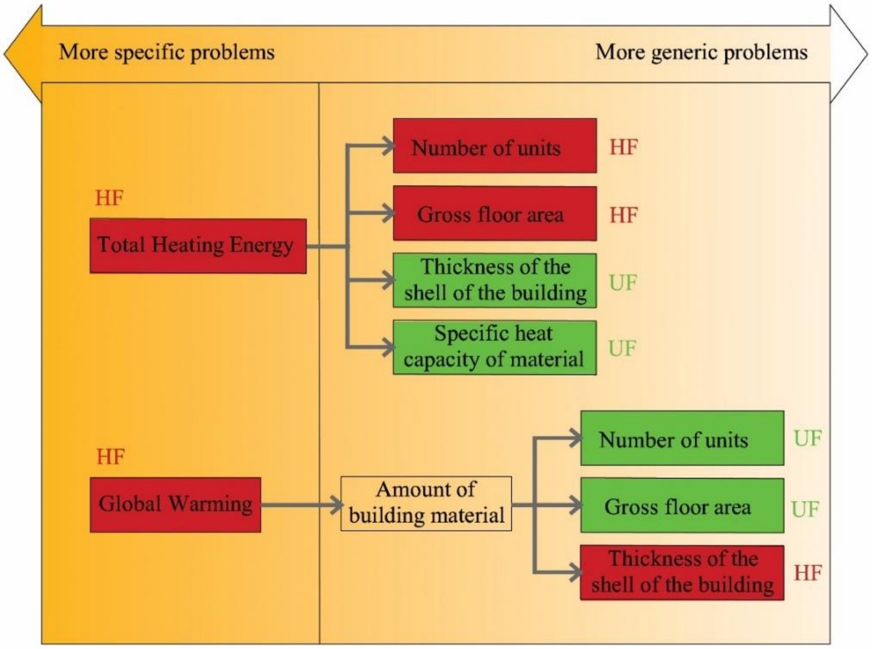


Figure 87: The relation of the parameters in designing the residential complex. The thickness of panels has both useful and harmful functions that indicate the existence of a physical contradiction.

Table 14: The matrix of contradictions of the mid-rise residential complex

Characteristics			Characteristic that is getting worse (HF)		
			31	22	4
			Harmful side effects developed by an object	Waste of energy	Length of a stationary object (thickness of the building shell)
Characteristic to be improved (UF)	26	Amount of substances	3- Local quality 35- Physical or chemical properties; 40- Composite materials 39- Inert environment		
	6	Area of a stationary object (Total floor area)		17-Moving to another dimension 7-Nesting dolls 30-flexible films or membranes	
	4	Length of a stationary object (thickness of the building shell)			All

Structural specifications of the CLT products that are to be used in this design project are provided by Nordic Structures Company in Montreal and are briefly presented in Table 15 and Figure 88. Further information about Nordic Structures Company can be found in [117].

Table 15: Properties of CLT panels produced by Nordic Structures, Montreal *[118]*

Uses: floor and roof slabs, wall panels, shear walls, and other applications Stress grade: E1 (L 1950Fb and T No. 3/Stud) Service condition: dry use Appearance grades: industrial and architectural Species: spruce-pine-fir, contains 90% black spruce Number of layers: 3, 5, 7 and 9 Thicknesses: from 89 to 267 mm (3-1/2 to 10-1/2 in.) Maximum width: 2.44 m (8 ft), Lengths: up to 19.5 m (64 ft) Warranty against manufacturer's defects: FSC-certified products available

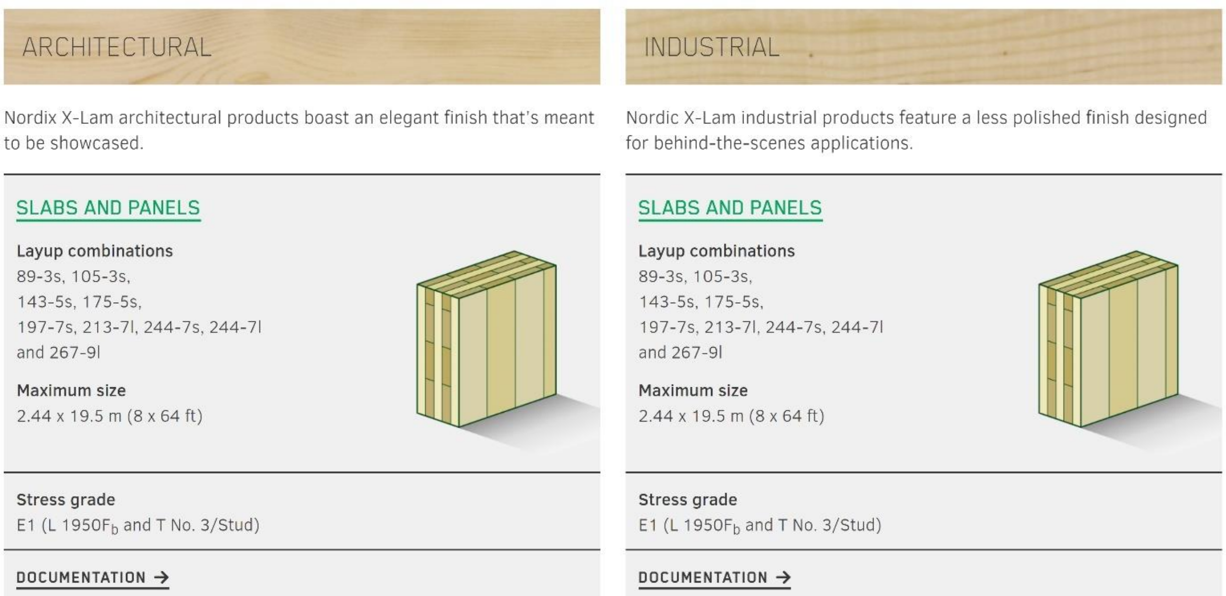


Figure 88: Appearance grades of CLT panels produced by Nordic Structures, Montreal *[118]*

Referring back to the diagram of parameters' relation, Figure 87 indicates the contradiction between the attempt to reduce the thermal energy demand and the desire to increase the total area of the residential projects. *Moving to another dimension*, brings the idea of modifying the volume of the interior space which does not seem to be agreeable for this project. Application of the *nesting doll* principle points out to thermal insulation of the building. Then, the insulation layer acts as a cover for our building (Table 14).

What is more, decreasing global warming by reducing the thickness of structural panels and decreasing the thermal energy demand by increasing the same thickness bring a physical contradiction into account (Figure 87). As explained in previous sections of this dissertation, the designer may primarily think of the implementation of some sorts of separation or study other TRIZ inventive principles to find a suitable generic solution. Separating the layers of the building shell for taking the different structural and thermal roles will be a good idea. It is also aligned with the idea of applying the nesting doll principle to resolve the contradiction which has been described above. Therefore, before creating the parametric model, two separate variables are considered that indicate the thickness of thermal insulation and the thickness of structural panels.

Table 16: The list of input variables with their acceptable intervals and outputs

Input variables	**Intervals**	**Output**
Y coordinate of Attractor Point 1	[0,12]	Maximum displacement of the roof
Y_Att_Point_2	[0,6]	Maximum displacement of the floor
Y_Att_Point_3	[0,12]	Weight of structure
Y_Att_Point_4	[6,12]	Natural frequency
Reduction	[250,500]	Model mass natural frequency
Seed reduction	[1,100]	Total cost
Roof CLT thickness	[0.09,0.20] m	Global warming potential
Floor CLT thickness	[0.09,0.20] m	Ozone depletion potential
Wall CLT thickness	[0.09,0.20] m	Acidification
Column width	[0.2,0.60] m	Total energy used for production, transfer and demolishing
Roof insulation thickness	[2,10] cm	Non-hazardous waste
Floor insulation thickness	[2,10] cm	Hazardous waste
Façade insulation thickness	[2,10] cm	Non-renewable material consumption
		Renewable material consumption
		Freshwater consumption
		Façade area
		Gross floor area
		Roof area
		Window area
		Ground floor area
		Total number of units
		CLT volume
		Number of units in 1st, 2nd, 3rd, 4th, …, 11th floor
		Ideal total heating energy
		November, December, January, February, and March ideal heating energy

It is notable that sometimes structural panels are employed in buildings without additional thermal insulation layer. In Habitat 67, prefabricated reinforced concrete panels were used without any thermal insulation. Therefore, in the preliminary phase of the design process, the designer may create the parametric model with only one parameter indicating the thickness of the building shell. Such a problem occurred in earlier project which involved the form exploration of a one-bedroom housing project (see [11]). Then, throughout the form exploration process, the geometry of the apartment units was modified to find the best trade-off between solutions with minimum thermal energy demand and greater gross floor area and total area of windows. Such preliminary analysis of relations among the design parameters could extend the search space and help to find more diverse suitable solutions.

Table 17: The environmental, and structural properties of the mid-rise residential complex

Material and thermal properties
CLT plates density = 500 kg/m^3 ,Conductivity = 0.13 W/mK ,Specific heat 1600 J/kgK Thermal emittance = 0.9 ,Solar absorptance = 0.7 , Visible absorptance = 0.7 Embodied energy =10 MJ/kg , Embodied carbon =0.71 kgCO2/kg
Material cost estimation
CLT structural system cost: Design + material supply +installation = 435-490 CAD/m^2 (40-45 CAD/ft^2) ≈ 450 CAD/m^2 (Exchange rate CAD to USC = 0.75) , Design + material supply +installation = 326 – 367 ≈ 350 USD/m^2
Material and load properties
CLT plates: Spruce-Pine-Fir Density = 400 kg/m^3 (25 lb/ft^3) Thickness = 8-20 cm (3 1/8 – 7 7/8 in) Load case 1 = self-weight + Roof load (promenade roof) of 2.8 kN/m^2 (58.5 psf) [119] Load case 2 = self-weight + residential live load of 1.92 kN/m^2 (40 psf) [119]
Load: 0.01 people/m^2 +11 equipment w/m^2 + 7 lighting w/m2, 150 lux, continuous dimming, AllOn schedule [120]. Conditioning: heating setpoint: 21C cooling setpoint 26 C Ventilation: Air change per hour = 0.5 ACH Hot water: On | peak flow 0.03 m^3/h/m^2 | 65 C supply temperature | All On
Construction
Roof = 95 mm CLT + 80mm Rigid foam EPS 035 insulation + 95 mm CLT + 20 mm Gypsum Fiber Board Partition = 20 mm Gypsum Fiber Board + 95 mm CLT + 20 mm Gypsum Fiber Board Ceiling = 95 mm CLT + 30 mm Impact sound insulation + 95 mm CLT + 20mm Gypsum Fiber Board External floor = 95 mm CLT + 80 mm Rigid foam EPS 035 insulation + 95 mm CLT + 30 mm Pine wood Façade = 30 mm Pine wood + 80 mm rigid foam pur no coating Insulation + 150 mm CLT + 20 mm Gypsum Fiber Board

In the next step of the design procedure, the parametric model of the apartment complex is built using the input variables listed in Table 16. Then, the database is set, separate models for structural and thermal simulations are created, and the GA-based breeding code is scripted. Details of inputs for structural and thermal analyses are provided in Table 17. The displacement and utilization diagrams of the generated solutions and, the bar charts that show their thermal energy demand from November to the end of March are to be stored in the database (Figures 89 and 90).

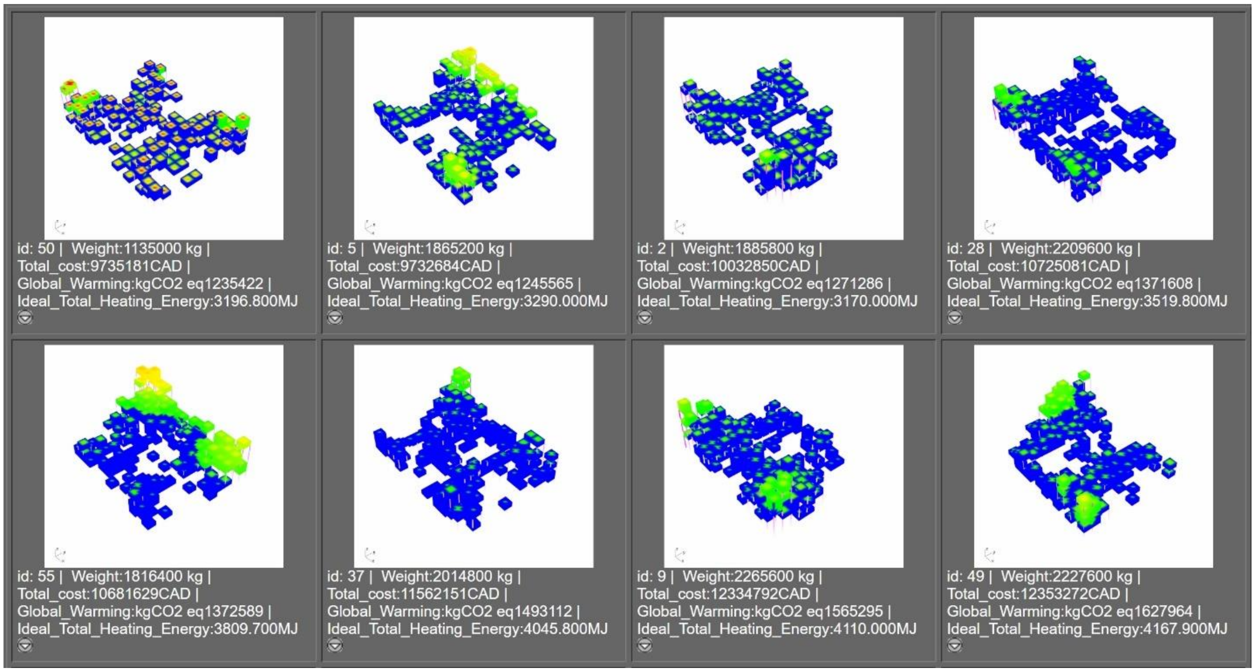


Figure 89: The display of displacement of solutions which have the minimum global warming potential and minimum cost of materials

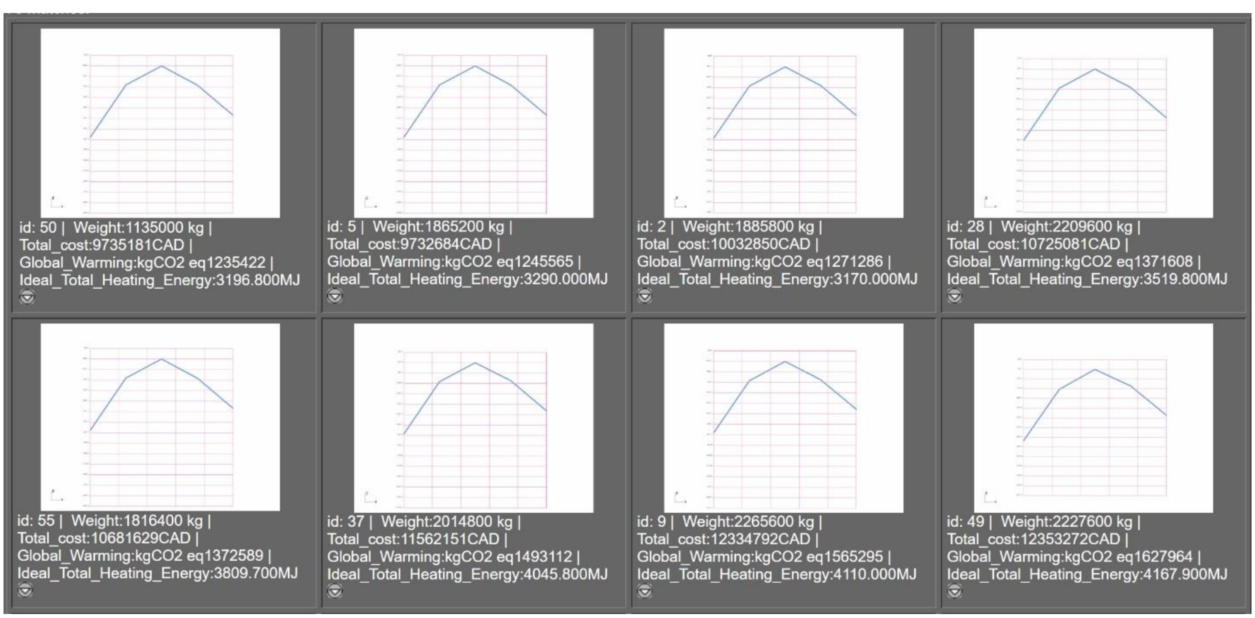


Figure 90: The array bar charts display the thermal energy demand of solutions which have the minimum global warming potential and minimum cost of materials

Studying the building shadow throughout the daytime, the designer may find certain design alternatives inappropriate. The solutions which have greater height at the southside versus the northside, are expected to have a shadow on the central courtyards and north apartment units (Figure 91). The designer may simply reduce the height of the building complex on the southside and increase the number of floors in the northside to gain the same total residential floor area. This solution can be verified by using the TRIZ matrix of contradiction. It suggests creating the shape *other way round* to resolve the conflict between the shape and the brightness of the building (see Figure 92 and Table 18). Applying *optical change* may be useful if it was possible to change the direction of the building in the site. But in this case study, the dimensions of the site do not allow for such modification.

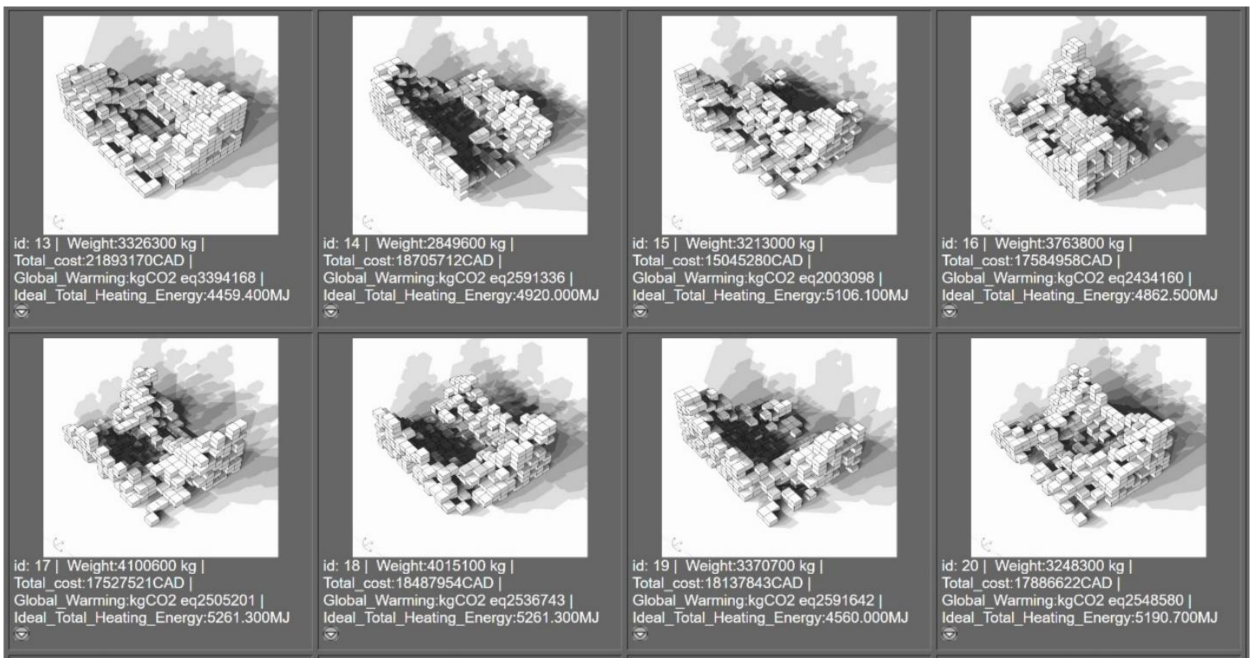


Figure 91: South-East view of the solutions demonstrating the quality of shadows

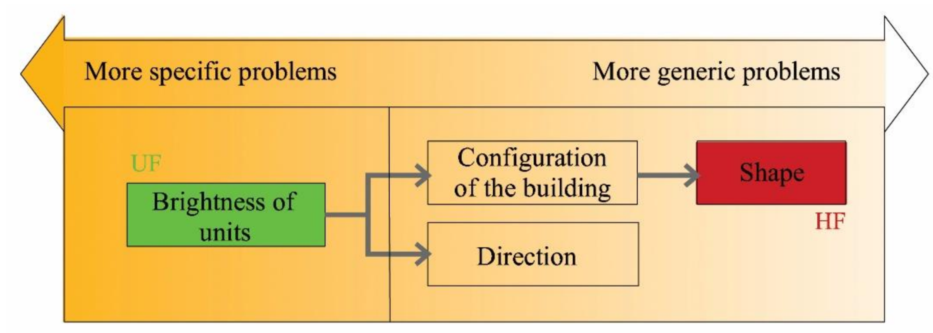


Figure 92: The conflict between the brightness of apartment units and the shape of the whole body of the complex

Table 18: The matrix of contradiction of the mid-rise residential complex for resolving the contradiction between the brightness of apartment units and the shape of the building complex

<table>
<tr><td colspan="3" rowspan="3">Characteristics</td><td>Characteristic that is getting worse (HF)</td></tr>
<tr><td>18</td></tr>
<tr><td>Brightness</td></tr>
<tr><td>Characteristic to be improved (UF)</td><td>12</td><td>Shape</td><td>13- Other way round
15- Dynamism
32- Optical change</td></tr>
</table>

3.7.7. Discussion

In this case study, the design objectives are synthesized into their basic factors and checked for probable conflicts. As a result, the contradiction between the life cycle impact of the building and the amount of structural material or the amount of floor area was revealed. Referring to the TRIZ inventive principles and the matrix of contradiction, first, made the designer opt for an eco-friendly material such as CLT panels instead of prefabricated reinforced concrete. Second, the analysis suggested insulating the building for better environmental performance. Third, it implies consideration of two separate variables to define the thickness of CLT panels and the thickness of thermal insulation. Taking these actions, allowed for the resolution of the explained conflict innovatively. Figure 93 demonstrates the distribution of solutions regarding their total gross floor area and global warming potential. The solutions lie on a line, and as it is discussed in Section 2.5.3, this form of distribution indicates a constant contrast between the two design objectives. The application of the GA+TRIZ methodology helped to obtain relatively more suitable solutions by directing the designer to choose better structural material and reducing the life cycle impact of all generated solutions. Using TRIZ in addition to the application of a genetic algorithm allowed for thinking outside the box to make a trade-off between the two objectives. In this case study, each generated solution made of CLT panels has significantly lower life cycle impact compared to its corresponding design alternative that is made of prefabricated reinforced concrete.

In this case study, application of the GA+TRIZ method helped to:

- increase the diversity of solutions by suggesting the consideration of thermal insulation in addition to the structural shell of the building

- save time by providing some hints at the beginning of the form exploration project to make a better parametric model
- provide implicit search goals to make a decision or to verify the suitability of the designer's ideas for solving a problem

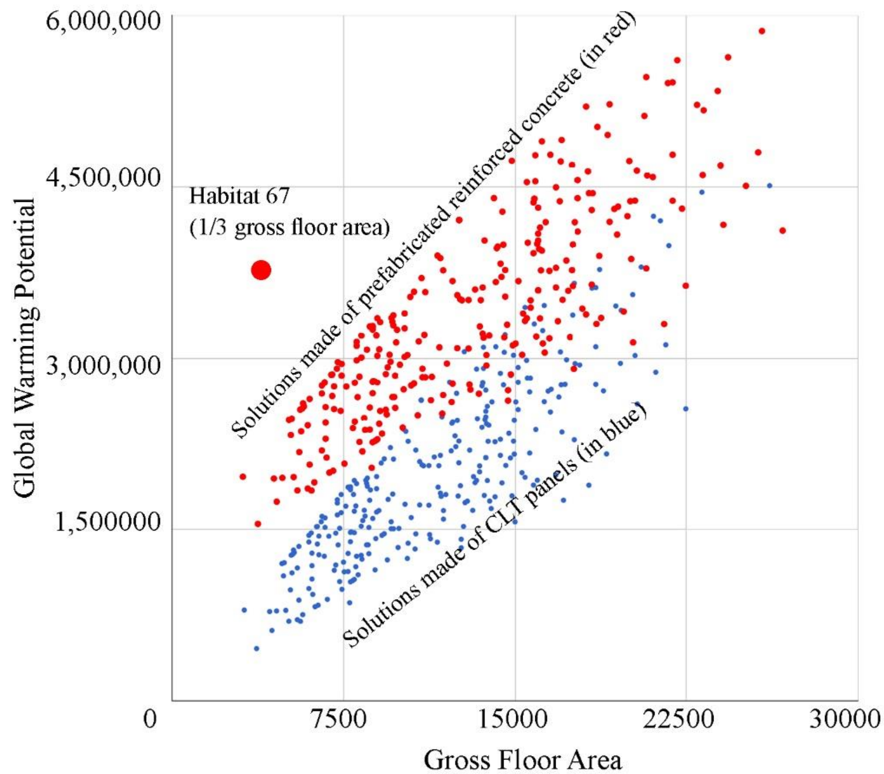


Figure 93: The plot displays the distribution of solutions regarding their gross floor area and global warming potential. Habitat 67 and a series of generated solutions made of prefabricated reinforced concrete are highlighted in red. The design alternatives made of CLT panels generated with the same configuration are highlighted in blue.

According to the described design objectives, a series of design alternatives is generated whose global warming potentials are less than 1,000,000 kg CO2 eq. Also, their ideal total heating energy from November to the end of March is less than 5000 MJ (Figure 94). Then, the generated solutions are explored to find a series of suitable design alternatives whose total floor area is greater than that of the Habitat 67. Figure 95 displays the distribution of solutions regarding their gross floor area and global warming potential. Figure 96 displays the distribution of solutions based on their gross floor area and ideal total heating energy from November to the end of March. In both graphs, solution number 228 has been chosen as a suitable solution. The performative characteristics of solution number 228 are displayed in Table 19.

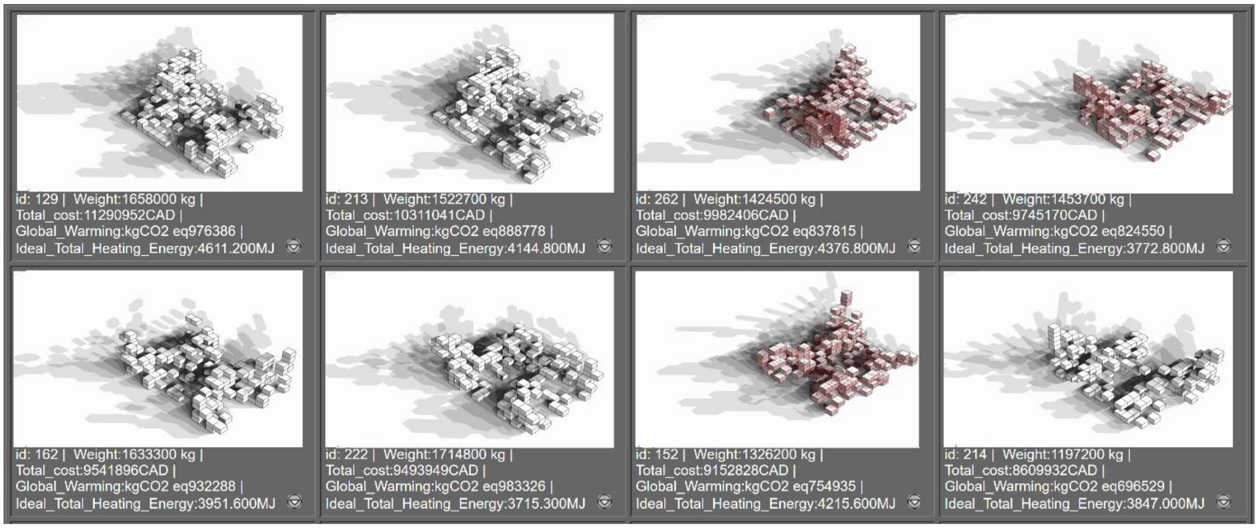


Figure 94: South-East view of the solutions whose global warming potential is less than 1,000,000 kg CO2 eq and ideal total heating energy from November to the end of March is less than 5000 MJ. The solutions are sorted based on their gross floor area in descending order.

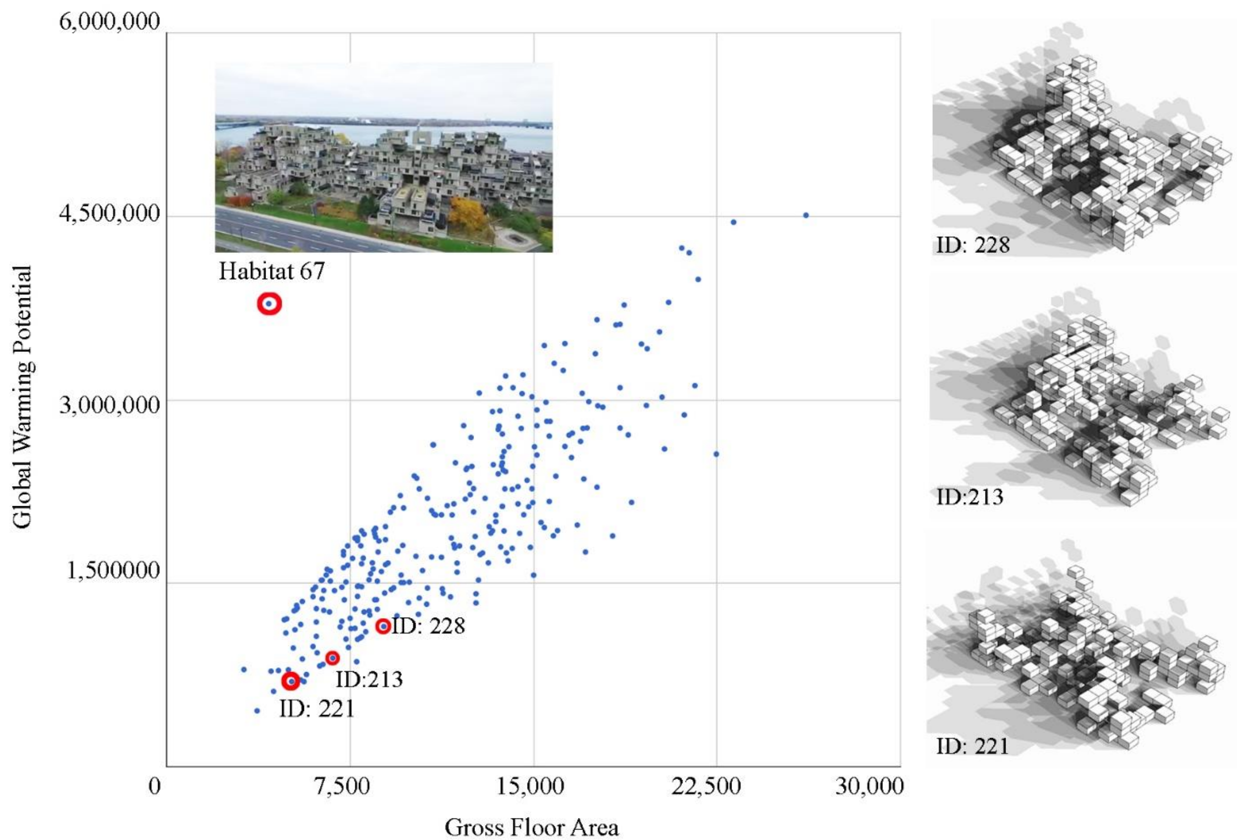


Figure 95: The plot displays the distribution of solutions regarding their gross floor area and global warming potential. Habitat 67 and some of the suitable solutions made of CLT panels are highlighted.

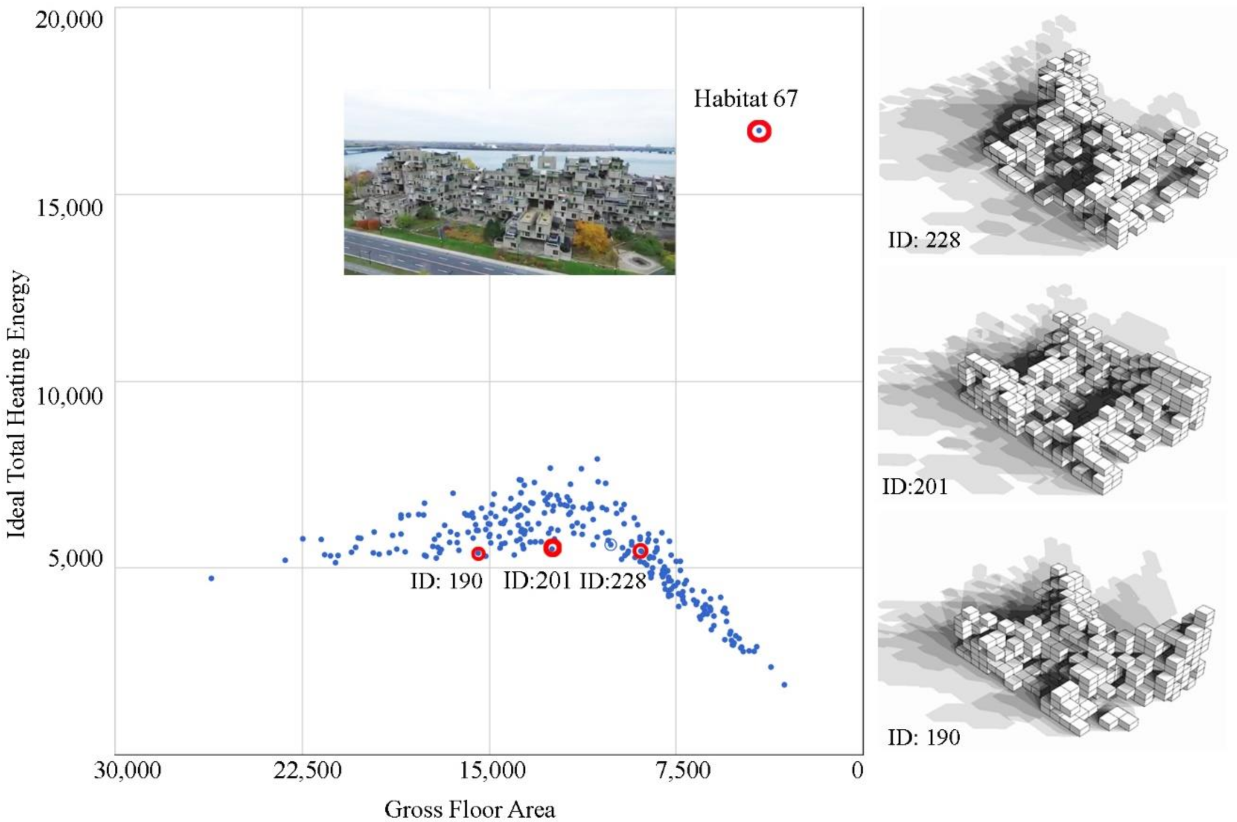


Figure 96: The plot displays the distribution of solutions regarding their gross floor area and ideal total heating energy from November to the end of March. Habitat 67 and some of the suitable solutions made of CLT panels are highlighted.

Table 19: The performative characteristics of solution number 228

Roof_CLT_Thickness	18	CLT_Volume	3866.35	Max_Displacement_Roof	0.516189
Floor_CLT_Thickness	9	Total_cost	13180851.9	Max_Displacement_Floor	0.950771
Wall_CLT_Thickness	9	Facade_Area	15105.52	Natural_Frequency	2.344068
Col_Width	49	Global_Warming	1146864	Mmass_Natural_Frequency	9225.546
Roof_Insulation_Thickness	7	Ozone_Depletion	0.01684	Ideal_Total_Heating_Energy	5437.8
Floor_Insulation_Thickness	6	Acidification	11196.72	Nov_Ideal_Heating_Energy	546.11
Facade_Insulation_Thickness	9	Non_hazardous_Waste	15327745	Dec_Ideal_Heating_Energy	1273.4
G_floor_Area	6627.08	Non_Renewable_Material_Consumption	365445.87	Jan_Ideal_Heating_Energy	1518
Total_Num_Units	264	Renewable_Material_Consumption	3820057.28	Feb_Ideal_Heating_Energy	1263.5
Weight	1913900	FreshWater_Consumption	2446.342	Mar_Ideal_Heating_Energy	836.81

Chapter 4: Conclusion and Suggestions for Future Research

1.6. Conclusion

The GA+TRIZ hybrid methodology is developed to improve the steps of problem structuring and decision making within the conceptual phase of design in the field of architecture. This computational search method provides the benefits of the application of a genetic algorithm and the Theory of Inventive Problem Solving (TRIZ) at the same time. On the one hand, the implementation of Non-Destructive Dynamic Population Genetic Algorithm (NDDP GA) used in the ParaGen method allows for the investigation of unexpected solutions and the adjustment of the search process. Then, the designer can dynamically regard any change in the design context or her personal preferences. On the other hand, the application of TRIZ provides some higher-level information to make a better decision when conflicting design objectives exist. TRIZ inventive principles can draw the designer’s attention in a completely different direction when she seems to be blocked within a certain trade-off set. The GA+TRIZ method helps the designer to build a better parametric model where pertinent variables, not all possible ones but those which will more probably be dominant, are included.

The GA+TRIZ methodology includes the following steps:

1. Defining the design objectives and finding probable conflicts
2. Synthesizing the design objectives into their basic factors and restating the specific design problem into a more generic and conceptual one
3. Using the TRIZ inventive principles and the associated matrix of contradiction to find a conceptual solution for the conceptual problem
4. Interpreting the conceptual solution into a specific solution to resolve the conflicts among the design objectives
5. Determining the design variables and creating the parametric model, and carrying out the preparatory setup

6. Generating and evaluating a series of solutions and making the primary adjustments
7. Studying the results and applying TRIZ tools to define the fitness function for the systematic solution generation
8. Generating further solutions systematically using the fitness function
9. Making the final decision and required post-processing using the TRIZ inventive principles.

In this dissertation, four design case studies are presented:

1. Form exploration of a folded plate dome for obtaining suitable solutions regarding the total weight of the dome, reverberation time, and quality of daylighting
2. Form exploration of a truss bridge for creating comparable, suitable solutions to the Foster Bridge, Ann Arbor, Michigan; The design goal was to minimize the total weight and the maximum deflection of the bridge.
3. Form exploration of a tapered lattice tower with less total weight and maximum deflection compared to the Shukhov Water Tower
4. Form exploration of a mid-rise apartment complex in Montreal with less environmental impact and minimum heating energy demand compared to Habitat 67

The results of these case studies demonstrate that application of the GA+TRIZ method allows to:

- work within a multi-objective setting
- include all the possible pertinent design parameters in the parametric model and reduce or even eliminate the need for re-doing the parametric modelling and preparatory setup
- re-consider maintaining some parameters as constant or variable
- check the conformity of the initial sketches with the design objectives as described in the first case study
- set the fitness function with a better understanding of parameters' dependencies
- overcome the conflicts among the design objectives using some innovative generic solutions and bring some other parameters into play to make a suitable final decision

- save time in the design process by preventing investment in generating an inappropriate solution at the very beginning
- keep the solution exploration relevantly time efficient by supporting the direct convergence around a specific solution
- maintain the interaction between the designer and the search engine

Application of TRIZ principles as a single design aid tool may have some challenges. First, the conflicts among the design objectives may not be obvious for the designer. While the combination of a GA-based form exploration and the TRIZ tool provides further information to recognize the conflicts. This benefit is explained in the third case study.

When the designer faces a physical contradiction, TRIZ matrix of contradiction suggests examining *all* of the 40 inventive principles to find the best generic solution. Such a non-specific suggestion may make it difficult for a novice designer to benefit from the TRIZ tool. Application of some sort of *separation* in time, place, scale, and condition may be helpful to some extent. Implementation of separation is explained in the second and fourth case study.

The outcome of this dissertation is the description of the GA+TRIZ search methodology along with examples of its application and all the required codes, scripts, and components. Besides, the attempt is made to investigate the extent to which the Theory of Inventive Problem Solving can be applied in architectural design. This dissertation contributes to multiple areas of design including computational design, multi-objective evolutionary form exploration, creative thinking in architecture, and interactive design search methods. Further contributions are possible when this method is employed in design pedagogy.

4.2. Suggestions for Future Research

There are several TRIZ tools whose contribution to the field of architecture can be studied in more detail. The focus of this dissertation is on the application of the 40 inventive principles and the matrix of contradiction during the conceptual phase of design. The contribution of other TRIZ tools to the field of design computation can be investigated in future works.

Also, the scope of this dissertation can be expanded, and not only the TRIZ tools and principles but also other innovative problem-solving methods can be combined with a genetic algorithm.

Although this dissertation research has been using a certain generative design framework (ParaGen) other generative design platforms can be employed to implement the coupling of an evolutionary algorithm and a TRIZ tool in the future.

Furthermore, the contribution of TRIZ tools to the field of architecture design pedagogy can be studied to help novice architecture students to learn the different strategies of problem-solving in their design projects.

APPENDICES

APPENDIX 1

TRIZ Matrix of Contradiction

Characteristics to be improved	CHARACTERISTICS	Characteristic that is getting worse: 1	2	3	4	5	6	7	8	9	10
1	Weight of a mobile object		–	15, 8 29, 34	–	29, 17 38, 34	–	29, 2 40, 28	–	2, 8 15, 38	8, 10 18, 37
2	Weight of a stationary object	–		–	10, 1 29, 35	–	35, 30 13, 2	–	5, 35 14, 2	–	8, 10 19, 35
3	Length of a mobile object	8, 15 29, 34	–		–	15, 17 4	–	7, 17 4, 35	–	13, 4 8	17, 10 4
4	Length of a stationary object	–	35, 28 40, 29	–		–	17, 7 10, 40	–	35, 8 2, 14	–	28, 10
5	Area of a mobile object	2, 17 29, 4	–	14, 15 18, 4	–		–	7, 14 17, 4	–	29, 30 4, 34	19, 30 35, 2
6	Area of a stationary object	–	30, 2 14, 18	–	26, 7 9, 39	–		–	–	–	1, 18 35, 36
7	Volume of mobile object	2, 26 29, 40	–	1, 7 4, 35	–	1, 7 4, 17	–		–	29, 4 38, 34	15, 35 36, 37
8	Volume of a stationary object	–	35, 10 19, 14	19, 14	35, 8 2, 14	–	–	–		–	2, 18 37
9	Speed	2, 28 13, 38	–	13, 14 8	–	29, 30 34	–	7, 29 34	–		13, 28 15, 19
10	Force	8, 1 37, 18	18, 13 1, 28	17, 19 9, 36	28, 10	19, 10 15	1, 18 36, 37	15, 9 12, 37	2, 36 18, 37	13, 28 15, 12	
11	Tension/Pressure	10, 36 37, 40	13, 29 10, 18	35, 10 36	35, 1 14, 16	10, 15 36, 28	10, 15 36, 37	6, 35 10	35, 24	6, 35 36	36, 35 21
12	Shape	8, 10 29, 40	15, 10 26, 3	29, 34 5, 4	13, 14 10, 7	5, 34 4, 10	–	14, 4 15, 22	7, 2 35	35, 15 34, 18	35, 10 37, 40
13	Stability of composition	21, 35 2, 39	26, 39 1, 40	13, 15 1, 28	37	2, 11 13	39	28, 10 19, 39	34, 28 35, 40	33, 15 28, 18	10, 35 21, 16
14	Strength	1, 8 40, 15	40, 26 27, 1	1, 15 8, 35	15, 14 28, 26	3, 34 40, 29	9, 40 28	10, 15 14, 7	9, 14 17, 15	8, 13 26, 14	10, 18 3, 14
15	Time of action of a moving object	19, 5 34, 31	–	2, 19 9	–	3, 17 19	–	10, 2 19, 30	–	3, 35 5	19, 2 16
16	Time of action of a stationary object	–	6, 27 19, 16	–	1, 40 35	–	–	–	35, 34 38	–	–
17	Temperature	36, 22 6, 38	22, 35 32	15, 19 9	15, 19 9	3, 35 39, 18	35, 38	34, 39 40, 18	35, 6 4	2, 28 36, 30	35, 10 3, 21
18	Brightness	19, 1 32	2, 35 32	19, 32 16	–	19, 32 26	–	2, 13 10	–	10, 13 19	26, 19 6
19	Energy spent by a moving object	12, 18 28, 31	–	12, 28	–	15, 19 25	–	35, 13 18	–	8, 35	16, 26 21, 2
20	Energy spent by a stationary object	–	19, 9 6, 27	–	–	–	–	–	–	–	36, 37
21	Power	8, 36 38, 31	19, 26 17, 27	1, 10 35, 37	–	19, 38	17, 32 13, 38	35, 6 38	30, 6 25	15, 35 2	26, 2 36, 35
22	Loss of energy	15, 6 19, 28	19, 6 18, 9	7, 2 6, 13	6, 38 7	15, 26 17, 30	17, 7 30, 18	7, 18 23	7	16, 35 38	36, 38
23	Loss of a substance	35, 6 23, 40	35, 6 22, 32	14, 29 10, 39	10, 28 24	35, 2 10, 31	10, 18 39, 31	1, 29 30, 36	3, 39 18, 31	10, 13 28, 38	14, 15 18, 40
24	Loss of an information	10, 24 35	10, 35 5	1, 26	26	30, 26	30, 16	–	2, 22	26, 32	–
25	Loss of time	10, 20 37, 35	10, 20 26, 5	15, 2 29	30, 24 14, 5	26, 4 5, 16	10, 35 17, 4	2, 5 34, 10	35, 16 32, 18	–	10, 37 36, 5
26	Amount of substance	35, 6 18, 31	27, 26 18, 35	29, 14 35, 18	–	15, 14 29	2, 18 40, 4	15, 20 29	–	35, 29 34, 28	35, 14 3
27	Reliability	3, 8 10, 40	3, 10 8, 28	15, 9 14, 4	15, 29 28, 11	17, 10 14, 16	32, 35 40, 4	3, 10 14, 24	2, 35 24	21, 35 11, 28	8, 28 10, 3
28	Accuracy of measurement	32, 35 26, 28	28, 35 25, 26	28, 26 5, 16	32, 28 3, 16	26, 28 32, 3	26, 28 32, 3	32, 13 6	–	28, 13 32, 24	32, 2
29	Accuracy of manufacturing	28, 32 13, 18	28, 35 27, 9	10, 28 29, 37	2, 32 10	28, 33 29, 32	2, 29 18, 36	32, 28 2	25, 10 35	10, 28 32	28, 19 34, 36
30	Harmful factors acting on an object from outside	22, 21 27, 39	2, 22 13, 24	17, 1 39, 4	1, 18	22, 1 33, 28	27, 2 39, 35	22, 23 37, 35	34, 39 19, 27	21, 22 35, 28	13, 35 39, 18
31	Harmful factors developed by an object	19, 22 15, 39	35, 22 1, 39	17, 15 16, 22	–	17, 2 18, 39	22, 1 40	17, 2 40	30, 18 35, 4	35, 28 3, 23	35, 28 1, 40
32	Manufacturability	28, 29 15, 16	1, 27 36, 13	1, 29 13, 17	15, 17 27	13, 1 26, 12	16, 40	13, 29 1, 40	35	35, 13 8, 1	35, 12
33	Convenience of use	25, 2 13, 15	6, 13 1, 25	1, 17 13, 12	–	1, 17 13, 16	18, 16 15, 39	1, 16 35, 15	4, 18 39, 31	18, 13 34	28, 13 35
34	Repairability	2, 27 35, 11	2, 27 35, 11	1, 28 10, 25	3, 18 31	15, 13 32	16, 25	25, 2 35, 11	1	34, 9	1, 11 10
35	Adaptability	1, 6 15, 8	19, 15 29, 16	35, 1 29, 2	1, 35 16	35, 30 29, 7	15, 16	15, 35 29	–	35, 10 14	15, 17 20
36	Complexity of a device	26, 30 34, 36	2, 26 35, 39	1, 19 26, 24	26	14, 1 13, 16	6, 36	34, 26 6	1, 16	34, 10 28	26, 16
37	Complexity of control	27, 26 28, 13	6, 13 28, 1	16, 17 26, 24	26	2, 13 18, 17	2, 39 30, 16	29, 1 4, 16	2, 18 26, 31	3, 4 16, 35	36, 28 40, 19
38	Level of automation	28, 26 18, 35	28, 26 35, 10	14, 13 17, 28	23	17, 14 13	–	35, 13 16	–	28, 10	2, 35
39	Capacity / Productivity	35, 26 24, 37	28, 27 15, 3	18, 4 28, 38	30, 7 14, 26	10, 26 34, 31	10, 35 17, 7	2, 6 34, 10	35, 37 10, 2	–	28, 15 10, 36

Characteristic that is getting worse

Characteristics to be improved	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	10, 36 37, 40	10, 14 35, 40	1, 35 19, 39	28, 27 18, 40	5, 34 31, 35	–	6, 29 4, 38	19, 1 32	35, 12 34, 31	–	12, 36 18, 31	6, 2 34, 19	5, 35 3, 31	10, 24 35
2	13, 29 10, 18	13, 10 29, 14	26, 39 1, 40	28, 2 10, 27	–	2, 27 19, 6	28, 19 32, 22	19, 32 35	–	18, 19 28, 1	15, 19 18, 22	18, 19 28, 15	5, 8 13, 30	10, 15 35
3	1, 8 35	1, 8 10, 29	1, 8 15, 34	8, 35 29, 34	19	–	10, 15 19	32	8, 35 24	–	1, 35	7, 2 35, 39	4, 29 23, 10	1, 24
4	1, 14 35	13, 14 15, 7	39, 37 35	15, 14 28, 26	–	1, 40 35	3, 35 38, 18	3, 25	–	–	12, 8	6, 28	10, 28 24, 35	24, 26
5	10, 15 36, 28	5, 34 29, 4	11, 2 13, 39	3, 15 40, 14	6, 3	–	2, 15 16	15, 32 19, 13	19, 32	–	19, 10 32, 18	15, 17 30, 26	10, 35 2, 39	30, 26
6	10, 15 36, 37	–	2, 38	40	–	2, 10 19, 30	35, 39 38	–	–	–	17, 32	17, 7 30	10, 14 18, 39	30, 16
7	6, 35 36, 37	1, 15 29, 4	28, 10 1, 39	9, 14 15, 7	6, 35 4	–	34, 39 10, 18	2, 13 10	35	–	35, 6 13, 18	7, 15 13, 16	36, 39 34, 10	2, 22
8	24, 35	7, 2 35	34, 28 35, 40	9, 14 17, 15	–	35, 34 38	35, 6 4	–	–	–	30, 6	–	10, 39 35, 34	–
9	6, 18 38, 40	35, 15 18, 34	28, 33 1, 18	8, 3 26, 14	3, 19 35, 5	–	28, 30 36, 2	10, 13 19	8, 15 35, 38	–	19, 35 38, 2	14, 20 19, 35	10, 13 28, 38	13, 26
10	18, 21 11	10, 35 40, 34	35, 10 21	35, 10 14, 27	19, 2	–	35, 10 21	–	19, 17 10	1, 16 36, 37	19, 35 18, 37	14, 15	8, 35 40, 5	–
11		35, 4 15, 10	35, 33 2, 40	9, 18 3, 40	19, 3 27	–	35, 39 19, 2	–	14, 24 10, 37	–	10, 35 14	2, 36 25	10, 36 3, 37	–
12	34, 15 10, 14		33, 1 18, 4	30, 14 10, 40	14, 26 9, 25	–	22, 14 19, 32	13, 15 32	2, 6 34, 14	–	4, 6 2	14	35, 29 3, 5	–
13	2, 35 40	22, 1 18, 4		17, 9 15	13, 27 10, 35	39, 3 35, 23	35, 1 32	32, 3 27, 15	13, 19	27, 4 29, 18	32, 35 27, 31	14, 2 39, 6	2, 14 30, 40	–
14	10, 3 18, 40	10, 30 35, 40	13, 17 35		27, 3 26	–	30, 10 40	35, 19	19, 35 10	35	10, 26 35, 28	35	35, 28 31, 40	–
15	19, 3 27	14, 26 28, 25	13, 3 35	27, 3 10		–	19, 35 39	2, 19 4, 35	28, 6 35, 18	–	19, 10 35, 38	–	28, 27 3, 18	10
16	–	–	39, 3 35, 23	–	–		19, 18 36, 40	–	–	–	16	–	27, 16 18, 38	10
17	35, 39 19, 2	14, 22 19, 32	1, 35 32	10, 30 22, 40	19, 13 39	19, 18 36, 40		32, 30 21, 16	19, 15 3, 17	–	2, 14 17, 25	21, 17 35, 38	21, 36 29, 31	–
18	–	32, 30	32, 3 27	35, 19	2, 19 6	–	32, 35 19		32, 1 19	32, 35 1, 15	32	13, 16 1, 6	13, 1	1, 6
19	23, 14 25	12, 2 29	19, 13 17, 24	5, 19 9, 35	28, 35 6, 18	–	19, 24 3, 14	2, 15 19		–	6, 19 37, 18	12, 22 15, 24	35, 24 18, 5	–
20	–	–	27, 4 29, 18	35	–	–	–	19, 2 35, 32	–		–	–	28, 27 18, 31	–
21	22, 10 35	29, 14 2, 40	35, 32 15, 31	26, 10 28	19, 35 10, 38	16	2, 14 17, 25	16, 6 19	16, 6 19, 37	–		10, 35 38	28, 27 18, 38	10, 19
22	–	–	14, 2 39, 6	26	–	–	19, 38 7	1, 13 32, 15	–	–	3, 38		35, 27 2, 37	19, 10
23	3, 36 37, 10	29, 35 3, 5	2, 14 30, 40	35, 28 31, 40	28, 27 3, 18	27, 16 18, 38	21, 36 39, 31	1, 6 13	35, 18 24, 5	28, 27 12, 31	28, 27 18, 38	35, 27 2, 31		–
24	–	–	–	–	10	10	–	19	–	–	10, 19	19, 10	–	
25	37, 36 4	4, 10 34, 17	35, 3 22, 5	29, 3 28, 18	20, 10 28, 18	28, 20 10, 16	35, 29 21, 18	1, 19 26, 17	35, 38 19, 18	1	35, 20 10, 6	10, 5 18, 32	35, 18 10, 39	24, 26 28, 32
26	10, 36 14, 3	35, 14	15, 2 17, 40	14, 35 34, 10	3, 35 10, 40	3, 35 31	3, 17 39	–	34, 29 16, 18	3, 35 31	35	7, 18 25	6, 3 10, 24	24, 28 35
27	10, 24 35, 19	35, 1 16, 11	–	11, 28	2, 35 3, 25	34, 27 6, 40	3, 35 10	11, 32 13	21, 11 27, 19	36, 23	21, 11 26, 31	10, 11 35	10, 35 29, 39	10, 28
28	6, 28 32	6, 28 32	32, 35 13	28, 6 32	28, 6 32	10, 26 24	6, 19 28, 24	6, 1 32	3, 6 32	–	3, 6 32	26, 32 27	10, 16 31, 28	–
29	3, 35	32, 30 40	30, 18	3, 27	3, 27 40	–	19, 26	3, 32	32, 2	–	32, 2	13, 32 2	35, 31 10, 24	–
30	22, 2 37	22, 1 3, 35	35, 24 30, 18	18, 35 37, 1	22, 15 33, 28	17, 1 40, 33	22, 33 35, 2	1, 19 32, 13	1, 24 6, 27	10, 2 22, 37	19, 22 31, 2	21, 22 35, 2	33, 22 19, 40	22, 10 2
31	2, 33 27, 18	35, 1	35, 40 27, 39	15, 35 22, 2	15, 22 33, 31	21, 39 16, 22	22, 35 2, 24	19, 24 39, 32	2, 35 6	19, 22 18	2, 35 18	21, 35 2, 22	10, 1 34	10, 21 29
32	35, 19 1, 37	1, 28 13, 27	11, 13 1	1, 3 10, 32	27, 1 4	35, 16	27, 26 18	28, 24 27, 1	28, 26 27, 1	1, 4	27, 1 12, 24	19, 35	15, 34 33	32, 24 18, 16
33	2, 32 12	15, 34 29, 28	32, 35 30	32, 40 3, 28	29, 3 8, 25	1, 16 25	26, 27 13	13, 17 1, 24	1, 13 24	–	35, 34 2, 10	2, 19 13	28, 32 2, 24	4, 10 27, 22
34	13	1, 13 2, 4	2, 35	11, 1 2, 9	11, 29 28, 27	1	4, 10	15, 1 13	15, 1 28, 16	–	15, 10 32, 2	15, 1 32, 19	2, 35 34, 27	–
35	35, 16	15, 37 1, 8	35, 30 14	35, 3 32, 6	13, 1 35	2, 16	27, 2 3, 35	6, 22 26, 1	19, 35 29, 13	–	19, 1 29	18, 15 1	15, 10 2, 13	–
36	19, 1 35	29, 13 28, 15	2, 22 17, 19	2, 13 28	10, 4 28, 15	–	2, 17 13	24, 17 13	27, 2 29, 28	–	20, 19 30, 34	10, 35 13, 2	35, 10 28, 29	–
37	35, 36 37, 32	27, 13 1, 39	11, 22 39, 30	27, 3 15, 28	19, 29 39, 25	25, 34 6, 35	3, 27 35, 16	2, 24 26	35, 38	19, 35 16	19, 1 16, 10	35, 3 15, 19	1, 18 10, 24	35, 33 27, 22
38	13, 35	15, 32 1, 13	18, 1	25, 13	6, 9	–	26, 2 19	8, 32 19	2, 32 13	–	28, 2 27	23, 28	35, 10 18, 5	35, 33
39	10, 37 14	14, 10 34, 40	35, 3 22, 39	29, 28 10, 18	35, 10 2, 18	20, 10 16, 38	35, 21 28, 10	26, 17 19, 1	35, 10 38, 19	1	35, 20 10	28, 10 29, 35	28, 10 35, 23	13, 15 23

#	CHARACTERISTICS (Characteristics to be improved)	Characteristic that is getting worse: 25	26	27	28	29	30	31	32	33	34
1	Weight of a mobile object	10, 35 20, 28	3, 26 18, 31	3, 11 1, 27	28, 27 35, 26	28, 35 26, 18	22, 21 18, 27	22, 35 31, 39	27, 28 1, 36	35, 3 2, 24	2, 27 28, 11
2	Weight of a stationary object	10, 20 35, 26	19, 6 18, 26	10, 28 8, 3	18, 26 28	10, 1 35, 17	2, 19 22, 37	35, 22 1, 39	28, 1 9	6, 13 1, 32	2, 27 28, 11
3	Length of a mobile object	15, 2 29	29, 35	10, 14 29, 40	28, 32 4	10, 28 29, 37	1, 15 17, 24	17, 15	1, 29 17	15, 29 35, 4	1, 28 10
4	Length of a stationary object	30, 29 14	–	15, 29 28	32, 28 3	2, 32 10	1, 18	–	15, 17 27	2, 25	3
5	Area of a mobile object	26, 4	29, 30 6, 13	29, 9	26, 28 32, 3	2, 32	22, 33 28, 1	17, 2 18, 39	13, 1 26, 24	15, 17 13, 16	15, 13 10, 1
6	Area of a stationary object	10, 35 4, 18	2, 18 40, 4	32, 35 40, 4	26, 28 32, 3	2, 29 18, 36	27, 2 39, 35	22, 1 40	40, 16	16, 4	16
7	Volume of mobile object	2, 6 34, 10	29, 30 7	14, 1 40, 11	26, 28	25, 28 2, 16	22, 21 27, 35	17, 2 40, 1	29, 1 40	15, 13 30, 12	10
8	Volume of a stationary object	35, 16 32, 18	35, 3	2, 35 16	–	35, 10 25	34, 39 19, 27	30, 18 35, 4	35	–	1
9	Speed	–	10, 19 29, 38	11, 35 27, 28	28, 32 1, 24	10, 28 32, 25	1, 28 35, 23	2, 24 35, 21	35, 13 8, 1	32, 28 13, 12	34, 2 28, 27
10	Force	10, 37 36	14, 29 18, 36	3, 35 13, 21	35, 10 23, 24	28, 29 37, 36	1, 35 40, 18	13, 3 36, 24	15, 37 18, 1	1, 28 3, 25	15, 1 11
11	Tension/Pressure	37, 36 4	10, 14 36	10, 13 19, 35	6, 28 25	3, 35	22, 2 37	2, 33 27, 18	1, 35 16	11	2
12	Shape	14, 10 34, 17	36, 22	10, 40 16	28, 32 1	32, 30 40	22, 1 2, 35	35, 1	1, 32 17, 28	32, 15 26	2, 13 1
13	Stability of composition	35, 27	15, 32 35	–	13	18	35, 24 30, 18	35, 40 27, 39	35, 19	32, 35 30	2, 35 10, 16
14	Strength	29, 3 28, 10	29, 10 27	11, 3	3, 27 16	3, 27	18, 35 37, 1	15, 35 22, 2	11, 3 10, 32	32, 40 28, 2	27, 11 3
15	Time of action of a moving object	20, 10 28, 18	3, 35 10, 40	11, 2 13	3	3, 27 16, 40	22, 15 33, 28	21, 39 16, 22	27, 1 4	12, 27	29, 10 27
16	Time of action of a stationary object	28, 20 10, 16	3, 35 31	34, 27 6, 40	10, 26 24	–	17, 1 40, 33	22	35, 10	1	1
17	Temperature	35, 28 21, 18	3, 17 30, 39	19, 35 3, 10	32, 19 24	24	22, 33 35, 2	22, 35 2, 24	26, 27	26, 27	4, 10 16
18	Brightness	19, 1 26, 17	1, 19	–	11, 15 32	3, 32	15, 19	35, 19 32, 39	19, 35 28, 26	28, 26 19	15, 17 13, 16
19	Energy spent by a moving object	35, 38 19, 18	34, 23 16, 18	19, 21 11, 27	3, 1 32	–	1, 35 6, 27	2, 35 6	28, 26 30	19, 35	1, 15 17, 28
20	Energy spent by a stationary object	–	3, 35 31	10, 36 23	–	–	10, 2 22, 37	19, 22 18	1, 4	–	–
21	Power	35, 20 10, 6	4, 34 19	19, 24 26, 31	32, 15 2	32, 2	19, 22 31, 2	2, 35 18	26, 10 34	26, 35 10	35, 2 10, 34
22	Loss of energy	10, 18 32, 7	7, 18 25	11, 10 35	32	–	21, 22 35, 2	21, 35 2, 22	–	35, 32 1	2, 19
23	Loss of a substance	15, 18 35, 10	6, 3 10, 24	10, 29 39, 35	16, 34 31, 28	35, 10 24, 31	33, 22 30, 40	10, 1 34, 29	15, 34 33	32, 28 2, 24	2, 35 34, 27
24	Loss of an information	24, 26 28, 32	24, 28 35	10, 28 23	–	–	22, 10 1	10, 21 22	32	27, 22	–
25	Loss of time		35, 38 18, 16	10, 30 4	24, 34 28, 32	24, 26 28, 18	35, 18 34	35, 22 18, 39	35, 28 34, 4	4, 28 10, 34	32, 1 10
26	Amount of substance	35, 38 18, 16		18, 3 28, 40	3, 2 28	33, 30	35, 33 29, 31	3, 35 40, 39	29, 1 35, 27	35, 29 25, 10	2, 32 10, 25
27	Reliability	10, 30 4	21, 28 40, 3		32, 3 11, 23	11, 32 1	27, 35 2, 40	35, 2 40, 26	–	27, 17 40	1, 11
28	Accuracy of measurement	24, 34 28, 32	2, 6 32	5, 11 1, 23		–	28, 24 22, 26	3, 33 39, 10	6, 35 25, 18	1, 13 17, 34	1, 32 13, 11
29	Accuracy of manufacturing	32, 26 28, 18	32, 30	11, 32 1	–		26, 28 10, 36	4, 17 34, 26	–	1, 32 35, 23	25, 10
30	Harmful factors acting on an object from outside	35, 18 34	35, 33 29, 31	27, 24 2, 40	28, 33 23, 26	26, 28 10, 18		–	24, 35 2	2, 25 28, 39	35, 10 2
31	Harmful factors developed by an object	1, 22	3, 24 39, 1	24, 2 40, 39	3, 33 26	4, 17 34, 26	–		–	–	–
32	Manufacturability	35, 28 34, 4	35, 23 1, 24	–	1, 35 12, 18	–	24, 2	–		2, 5 13, 16	35, 1 11, 9
33	Convenience of use	4, 28 10, 34	12, 35	17, 27 8, 40	25, 13 2, 34	1, 32 35, 23	2, 25 28, 39	–	2, 5 12		12, 26 1, 32
34	Repairability	32, 1 10, 25	2, 28 10, 25	11, 10 1, 16	10, 2 13	25, 10	35, 10 2, 16	–	1, 35 11, 10	1, 12 26, 15	
35	Adaptability	35, 28	3, 35 15	35, 13 8, 24	35, 5 1, 10	–	35, 11 32, 31	–	1, 13 31	15, 34 1, 16	1, 16 7, 4
36	Complexity of a device	6, 29	13, 3 27, 10	13, 35 1	2, 26 10, 34	26, 24 32	22, 19 29, 40	19, 1	27, 26 1, 13	27, 9 26, 24	1, 13
37	Complexity of control	18, 28 32, 9	3, 27 29, 18	27, 40 28, 8	26, 24 32, 28	–	22, 19 29, 28	2, 21	5, 28 11, 29	2, 5	12, 26
38	Level of automation	24, 28 35, 30	35, 13	11, 27 32	28, 26 10, 34	28, 26 18, 23	2, 33	2	1, 26 13	1, 12 34, 3	1, 35 13
39	Capacity / Productivity	–	35, 38	1, 35 10, 38	1, 10 34, 28	18, 10 32, 1	22, 35 13, 24	35, 22 18, 39	35, 28 2, 24	1, 28 7, 19	1, 32 10, 25

35	36	37	38	39	Characteristics to be improved
29, 5 15, 8	26, 30 36, 34	28, 29 26, 32	26, 35 18, 19	35, 3 24, 37	1
19, 15 29	1, 10 26, 39	25, 28 17, 15	2, 26 35	1, 28 15, 35	2
14, 15 1, 16	1, 19 26, 24	35, 1 26, 24	17, 24 26, 16	14, 4 28, 29	3
1, 35	1, 26	26	–	30, 14 7, 26	4
15, 30	14, 1 13	2, 36 26, 18	14, 30 28, 23	10, 26 34, 2	5
15, 16	1, 18 36	2, 35 30, 18	23	10, 15 17, 7	6
15, 29	26, 1	29, 26 4	35, 34 16, 24	10, 6 2, 34	7
–	1, 31	2, 17 26	–	35, 37 10, 2	8
15, 10 26	10, 28 4, 34	3, 34 27, 16	10, 18	–	9
15, 17 18, 20	26, 35 10, 18	36, 37 10, 19	2, 35	3, 28 35, 37	10
35	19, 1 35	2, 36 37	35, 24	10, 14 35, 37	11
1, 15 29	16, 29 1, 28	15, 13 39	15, 1 32	17, 26 34, 10	12
35, 30 34, 2	2, 35 22, 26	35, 22 39, 23	1, 8 35	23, 35 40, 3	13
15, 3 32	2, 13 28	27, 3 15, 40	15	29, 35 10, 14	14
1, 35 13	10, 4 29, 15	19, 29 39, 35	6, 10	35, 17 14, 19	15
2	–	25, 34 6, 35	1	20, 10 16, 38	16
2, 18 27	2, 17 16	3, 27 35, 31	26, 2 19, 16	15, 28 35	17
15, 1 19	6, 32 13	32, 15	2, 26 10	2, 25 16	18
15, 17 13, 16	2, 29 27, 28	35, 38	32, 2	12, 28 35	19
–	–	19, 35 16, 25	–	1, 6	20
19, 17 34	20, 19 30, 34	19, 35 16	28, 2 17	28, 35 34	21
–	7, 23	35, 3 15, 23	2	28, 10 29, 35	22
15, 10 2	35, 10 28, 24	35, 18 10, 13	35, 10 18	28, 35 10, 23	23
–	–	35, 33	35	13, 23 15	24
35, 28	6, 29	18, 28 32, 10	24, 28 35, 30	–	25
15, 3 29	3, 13 27, 10	3, 27 29, 18	8, 35	13, 29 3, 27	26
13, 35 8, 24	13, 35 1	27, 40 28	11, 13 27	1, 35 29, 38	27
13, 35 2	27, 35 10, 34	26, 24 32, 28	28, 2 10, 34	10, 34 28, 32	28
–	26, 2 18	–	26, 28 18, 23	10, 18 32, 39	29
35, 11 22, 31	22, 19 29, 40	22, 19 29, 40	33, 3 34	22, 35 13, 24	30
–	19, 1 31	2, 21 27, 1	2	22, 35 18, 39	31
2, 13 15	27, 26 1	6, 28 11, 1	8, 28 1	35, 1 10, 28	32
15, 34 1, 16	32, 26 12, 17	–	1, 34 12, 3	15, 1 28	33
7, 1 4, 16	35, 1 13, 11	–	34, 35 7, 13	1, 32 10	34
	15, 29 37, 28	1	27, 34 35	35, 28 6, 37	35
29, 15 28, 37		15, 10 37, 28	15, 1 24	12, 17 28	36
1, 15	15, 10 37, 28		34, 21	35, 18	37
27, 4 1, 35	15, 24 10	34, 27 25		5, 12 35, 26	38
1, 35 28, 37	12, 17 28, 24	35, 18 27, 2	5, 12 35, 26		39

APPENDIX 2

40 TRIZ Inventive Principles

1	**Segmentation**	a. Divide an object into independent parts. b. Make an object sectional (for easy assembly or disassembly). c. Increase the degree of an object's segmentation.
2	**Extraction** (Extracting, Retrieving, Removing)	a. Extract the *disturbing* part or property from an object. b. Extract only the necessary part or property from an object.
3	**Local Quality**	a. Transition from homogeneous to heterogeneous structure of an object or outside environment (action). b. Different parts of an object should carry out different functions. c. Each part of an object should be placed under conditions that are most favorable for its operation.
4	**Asymmetry**	a. Replace symmetrical form(s) with asymmetrical form(s). b. If an object is already asymmetrical, increase its degree of asymmetry.
5	**Consolidation**	a. Consolidate in space homogeneous objects, or objects destined for contiguous operations. b. Consolidate in time homogeneous or contiguous operations.
6	**Universality**	An object can perform several different functions; therefore, other elements can be removed.
7	**Nesting** (Matrioshka)	a. One object is placed inside another. That object is placed inside a third one. And so on … b. An object passes through a cavity in another object.
8	**Counterweight**	a. Compensate for the weight of an object by combining it with another object that provides a lifting force. b. Compensate for the weight of an object with aerodynamic or hydrodynamic forces influenced by the outside environment.
9	**Prior Counteraction**	Preload countertension to an object to compensate excessive and undesirable stress.
10	**Prior Action**	a. Perform required changes to an object completely or partially in advance.

		b. Place objects in advance so that they can go into action immediately from the most convenient location.
11	**Cushion in Advance**	Compensate for the relatively low reliability of an object with emergency measures prepared in advance.
12	**Equipotentiality**	Change the condition of the work in such a way that it will not require lifting or lowering an object.
13	**Do It in Reverse**	a. Instead of the direct action dictated by a problem, implement an opposite action (i.e., cooling instead of heating). b. Make the movable part of an object, or outside environment, stationary — and stationary part moveable. c. Turn an object upside-down.
14	**Spheroidality**	a. Replace linear parts with curved parts, flat surfaces with spherical surfaces, and cube shapes with ball shapes. b. Use rollers, balls, spirals. c. Replace linear motion with rotational motion; utilize centrifugal force.
15	**Dynamicity**	a. Characteristics of an object or outside environment, must be altered to provide optimal performance at each stage of an operation. b. If an object is immobile, make it mobile. Make it interchangeable. c. Divide an object into elements capable of changing their position relative to each other.
16	**Partial or Excessive Action**	If it is difficult to obtain 100% of a desired effect, achieve more or less of the desired effect.
17	**Transition into a New Dimension**	a. Transition one-dimensional movement, or placement, of objects into two-dimensional; two-dimensional to three-dimensional, etc. b. Utilize multi-level composition of objects. c. Incline an object, or place it on its side. d. Utilize the opposite side of a given surface. e. Project optical lines onto neighboring areas, or onto the reverse side, of an object.
18	**Mechanical Vibration**	a. Utilize oscillation. b. If oscillation exists, increase its frequency to ultrasonic. c. Use the frequency of resonance. d. Replace mechanical vibrations with piezo-vibrations. e. Use ultrasonic vibrations in conjunction with an electromagnetic field.
19	**Periodic Action**	a. Replace a continuous action with a periodic one (impulse). b. If the action is already periodic, change its frequency. c. Use pauses between impulses to provide additional action.
20	**Continuity of Useful Action**	a. Carry out an action without a break. All parts of the object should constantly operate at full capacity. b. Remove idle and intermediate motion.

		c. Replace *back-and-forth* motion with a rotating one.
21	**Rushing Through**	Perform harmful and hazardous operations at a very high speed.
22	**Convert Harm Into Benefit**	a. Utilize harmful factors — especially environmental — to obtain a positive effect. b. Remove one harmful factor by combining it with another harmful factor. c. Increase the degree of harmful action to such an extent that it ceases to be harmful.
23	**Feedback**	a. Introduce feedback. b. If feedback already exists, change it.
24	**Mediator**	a. Use an intermediary object to transfer or carry out an action. b. Temporarily connect the original object to one that is easily removed.
25	**Self-service**	a. An object must service itself and carry-out supplementary and repair operations. b. Make use of waste material and energy.
26	**Copying**	c. A simplified and inexpensive copy should be used in place of a fragile original or an object that is inconvenient to operate. d. If a visible optical copy is used, replace it with an infrared or ultraviolet copies. e. Replace an object (or system of objects) with their optical image. The image can then be reduced or enlarged.
27	**Dispose**	Replace an expensive object with a cheap one, compromising other properties (i.e., longevity).
28	**Replacement of Mechanical System**	a. Replace a mechanical system with an optical, acoustical, thermal or olfactory system. b. Use an electric, magnetic or electromagnetic field to interact with an object. c. Replace fields that are: 1. Stationary with mobile. 2. Fixed with changing in time. 3. Random with structured. d. Use fields in conjunction with ferromagnetic particles.
29	**Pneumatic or Hydraulic Constructions**	Replace solid parts of an object with a gas or liquid. These parts can now use air or water for inflation, or use pneumatic or hydrostatic cushions.
30	**Flexible Membranes or Thin Films**	a. Replace customary constructions with flexible membranes or thin film. b. Isolate an object from its outside environment with flexible membranes or thin films.
31	**Porous Material**	a. Make an object porous, or use supplementary porous elements (inserts, covers, etc.).

		b. If an object is already porous, fill pores in advance with some substance.
32	**Changing the Color**	a. Change the color of an object or its environment. b. Change the degree of translucency of an object or its environment. c. Use color additives to observe an object or process which is difficult to see. d. If such additives are already used, employ luminescent traces or trace atoms.
33	**Homogeneity**	Objects interacting with the main object should be made out of the same material (or material with similar properties) as the main object.
34	**Rejecting and Regenerating Parts**	a. After completing its function, or becoming useless, an element of an object is rejected (discarded, dissolved, evaporated, etc.) or modified during its work process. b. Used-up parts of an object should be restored during its work.
35	**Transformation of Properties**	a. Change the physical state of the system. b. Change the concentration or density. c. Change the degree of flexibility. d. Change the temperature or volume.
36	**Phase Transition**	Using the phenomena of phase change (i.e., a change in volume, the liberation or absorption of heat, etc.).
37	**Thermal Expansion**	a. Use expansion or contraction of material by changing its temperature. b. Use various materials with different coefficients of thermal expansion.
38	**Accelerated Oxidation**	c. Make transition from one level of oxidation to the next higher level: 1. Ambient air to oxygenated. 2. Oxygenated to oxygen. 3. Oxygen to ionized oxygen. 4. Ionized oxygen to ozoned oxygen. 5. Ozoned oxygen to ozone. 6. Ozone to singlet oxygen.
39	**Inert Environment**	a. Replace a normal environment with an inert one. b. Introduce a neutral substance or additives into an object. c. Carry out the process in a vacuum.
40	**Composite Materials**	Replace homogeneous materials with composite ones.

APPENDIX 3

Index.php

```
<html>
<?php
include "../library/includes.php";
$TRIZ_db = new database($dbhost, $dbuser, $dbpass, "TRIZ");
#$con = new mysqli("127.0.0.1", "root", "sql", "mydb");
$res = "";
if($_POST["row"] && $_POST[column]){
	$principleids = array();
	if($query = $TRIZ_db->query("SELECT `@TRIZ_40_Inventive_Principle` as principleid from matrice WHERE `@TRIZ_39_Parameters_col`=$_POST[column] AND `@TRIZ_39_Parameters_row`=$_POST[row]")){
		$i = 0;
		while($qrow = $query->fetch_assoc()){
			#echo("$qrow[principleid]");
			$principleids[$i] = $qrow[principleid];
			$i++;
			#echo("query result:");
			#echo("$qrow[principleid]");
		}
		#echo("in query");
	}
	#echo("<br>");
	$principleid_str="";
	foreach($principleids as $p){
		#echo("$p");
```

```
        if($principleid_str){
            $principleid_str = $principleid_str. "," .$p;
        }else{
            $principleid_str = "" . $p;
        }
    }
    #echo("principle id str is:  $principleid_str");
    if($query = $TRIZ_db->query("SELECT Principles from TRIZ_40_Inventive_Principles
where id in ($principleid_str)")){
        #echo("query ran!");
        while($qrow = $query->fetch_assoc()){
            #echo("$qrow[description]");
            if($res){
                $res = $res .", " . $qrow[Principles];
            }else
            {
                $res = $qrow[Principles];
            }
        }
    }
}
?>

<body>

<form action="<?php $_PHP_SELF ?>" method="POST">

<!-- ?php
$con = new mysqli("127.0.0.1","root","sql","mydb");
? -->
```

```
<!-- ================================ -->
<!-- column -->
<!-- ================================ -->
<p>
Characteristic that is getting worse
<select name="column">
<option value="">Select...</option><br>

<?php
if($query = $TRIZ_db->query("SELECT * from TRIZ_39_Parameters")){
	while($row = $query->fetch_assoc()){
		$selected = $_POST[column] == $row[ID] ? "selected" : "";
	echo "<option value=\"$row[ID]\" $selected >$row[Parameters]</option><br>";
      }
}
?>
</select></p>

<!-- ============================== -->
<!-- row -->
<!-- ============================== -->
<p>
Characteristic to be improved
<select name="row">
<option value="">Select...</option><br>
<?php
if($query = $TRIZ_db->query("SELECT * from TRIZ_39_Parameters")){
	while($row = $query->fetch_assoc()){
		$selected = $_POST[row] == $row[ID] ? "selected" : "";
		echo "<option value=\"$row[ID]\" $selected >$row[Parameters]</option><br>  ";
```

```
        }
}
?>
</select>
</p>

<?php
$TRIZ_db->close();
?>
<input type="submit"/>
</form>
<p>

<?php
if($res){
        echo("The innovative principle(s) you may consider is/are: $res.");
}else{
        echo("Please select both the characteristic to be improved and the one that is getting
worse.");
}
?>
</p>
</body></html>
```

APPENDIX 4

Config.php

```
<?php
$page_title = 'TRIZ';        // Name displayed in the title bar (should use this in nav.js)
$path = 'gcga30';            // This tells nav.js which page we are on
```

APPENDIX 5

CLT Mid-rise Residential Towers

Forté, Melbourne

Forté is a 10-story apartment with a rise of 32.2m built in 2012. It was the first Australian building made from CLT panels (Figure 97). The ground and first floor slabs are constructed from geopolymer concrete because of the larger span that is required in the retail spaces. Moreover, such a choice of material for the first two floors allows keeping the timber away from the ground and protect it from issues caused by termites and weather. 759 CLT panels of European spruce, weighing a total of 485 tonnes shape the stair, lift core, slabs, internal and external walls.

The Life Cycle Impact analysis yields that the replacement of steel and concrete by CLT panels in this project will reduce the CO_2 equivalent emissions by 1400 tonnes [121]. It is estimated that using timber has saved 7.7 million liters of water.

Figure 97: Forté (image by Victoria Harbour)

Figure 98: The Cube, London (image by Jack Hobhouse)

The cube, London

A pair of 10-story residential towers that both stand 33m tall was designed by Hawkins-Brown and built in 2015 [121]. The Cube is designed with a twisted cruciform plan and comprises a CLT and steel hybrid structure built around a reinforced concrete core (Figures 98, 99, and 100).

The cube has a total floor area of 6750 m^2 and includes1200 m^2 of commercial space on the ground floor and 50 apartments.

Figure 99: The cube, first-floor plan

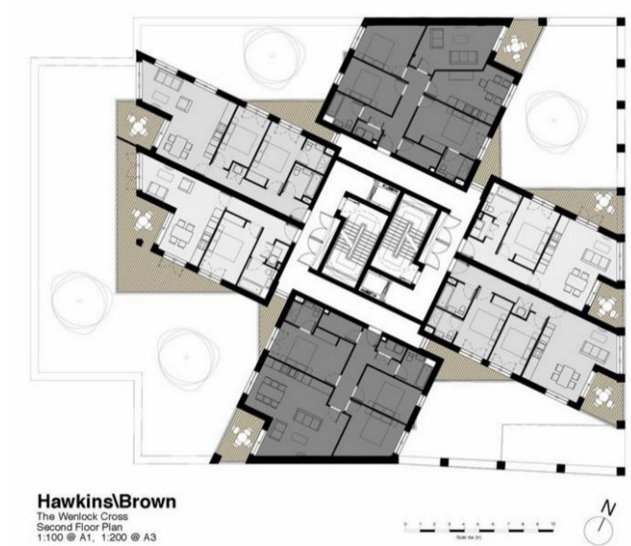


Figure 100: The cube, second-floor plan

Figure 101: Dalston Lane, London (photo by Waugh Thistleton) *[122]*

Dalston Lane, London

Dalston Lane with 121 residential units, 1500 m^2 restaurant and retail space, 3500m^2 flexible workspace hub, in 10 stories, and 33 meters height is one of the largest residential projects design by Waugh Thistleton in London. The external walls are clad with brick, but the frames, walls, floors, ceiling, stairs and a lift core are all made from CLT products (Figures 101 and 102).

It weighs a fifth of a concrete building of its equivalent size and, locks in 2,600 tonnes of CO_2, and requires less number of deliveries to the site by 80% [123] [121]. To avoid disruption to the local area, Dalston Lane project was carefully designed as a prefabricated frame to be constructed off-site. The assembling process took 374 days which is relatively short for constructing such a building in Dalston's scale.

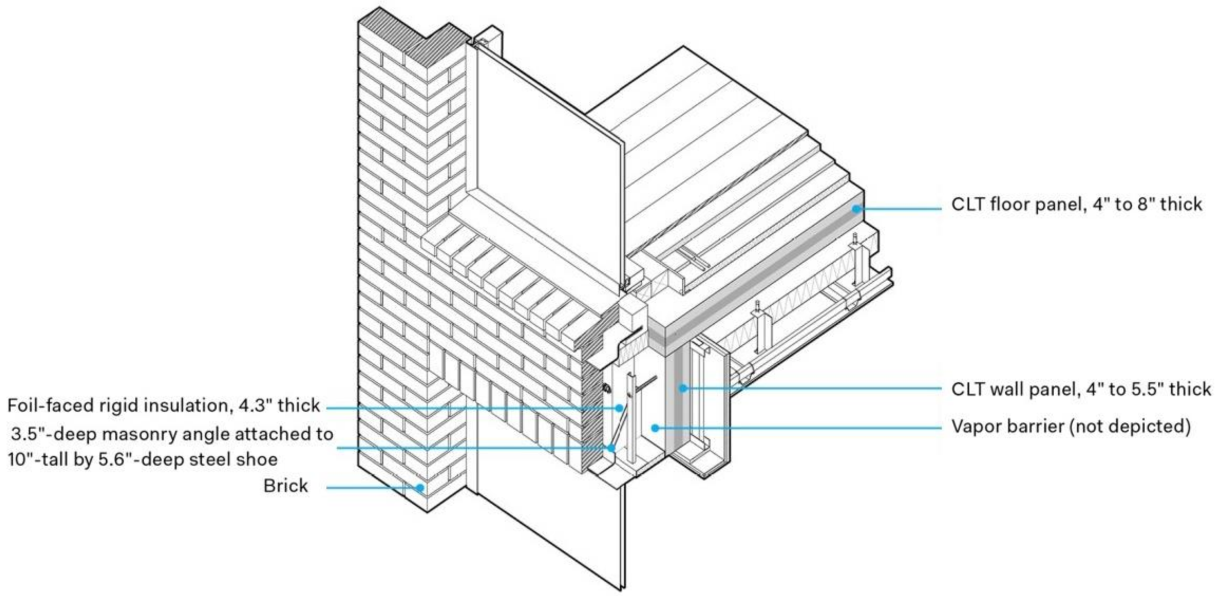


Figure 102: Dalston Lane, London *[122]*

Arbora, Montreal, Canada

Nordic Structures and Lemay+CHA architecture firm designed Arbora project in Montreal with a total area of 55515 m^2 (597560ft^2). Arbora is one of the residential building complexes that is claimed to be the largest complex in the world built from CLT structures. The project is made up of 434 residential units, in three 8-story buildings, including 273 condominiums, 30 townhouses, and 130 rental units (Figure 103).

Origin, Quebec City, Canada

Origin is a 13-story residential tower with a height of 40.9m in Quebec city (Figure 104). Origin consists of 92 housing units, ranging from a studio apartment to three-bedroom units, and has a total area of 890 m^2. The basement and the ground floor of the building are made from reinforced concrete. The CLT panels are used from the first floor all the way up to the thirteenth. The lateral load resisting system and the gravity resisting system are all made from the CLT components which stand on a one-meter-thick floating concrete foundation. Glulam timber posts and beams round and embrace the CLT structural system. The CLT panels are manufactured from FSC-certified black spruce. The 3111m^3 of wood that is used to shape the Origin's structure capture 2295 tons of CO_2 [124].

Figure 103: Arbora project, Montreal *[117]*

Figure 104: Origin, Quebec City, Canada *[124]*

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