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Method to Build a Generalized Table of Parameters in Engineering Design of Technical Systems: Lattice Structure as a Case Study

Design parameters are a crucial element of the product design process. However, design parameter models are often used to solve specific design problems. Generalizing design parameters is an approach to tackle more design problems. This study contributes to resolving certain limitations associated with modeling and representing the design parameters. This paper presents a generalized table of parameters (GTP) for modeling system parameters. This table is linked to a contextual database based on data and information collected from scientific databases, experts' interviews, and Computer-Aided Design (CAD) and Finite Element Modeling (FEM) software analysis and usage. The proposed representative table shows the robustness of integrating multiple sources of information to present a holistic and generalized view of the design system. The quality of the provided data in the table is assessed by applying certain evaluating dimensions and indicators. A case study will be presented on the lattice structure within a specific context in the mechanical field.

Keywords: *Design parameters, Generalized Table of Parameters, Contextual database, Modeling, Mechanics, Lattice structure.*

1. INTRODUCTION

The process of developing a new product often involves improving or modifying existing systems, and the use of design parameters is essential in many processes and approaches to modeling the design system. This paper presents a method for modeling and representing design system parameters. Parameters are the main elements of many design methods [1]. In [2], a systematic approach to integrating TRIZ/QFD into a single system for the optimization of Engineering requirements. Other contri–butions have attempted to integrate both approaches, such as[3]and [4]. However, these proposals suffer from certain limitations. The main limitation of these methods is that the requirements and driven design para–meters need to be more specific to a product-related design problem and a targeted customer slice. Consequently, the design process cannot be generalized to multiple design problems.

Design parameters and their representation are essential in other methods, such as Root Cause Analysis (RCA), which is a process aimed at finding the cause-effect relationships of the problem in order to identify its causes. [5]. Nevertheless, a set of research contri-butions have been dedicated to obtaining the benefits of integrating TRIZ with RCA approaches, such as the Functional Why-Why approach [6], which reformulates the problem in the initial situation into the so-called Why-Why contradictions. Another approach is deve-loped based on the CECA method [7]. Lastly, the most advanced approach is Root Conflict Analysis (RCA+) [8]. These proposals are interesting in that they model the design system in the form of parameters.

On the other hand, one cannot ignore the basic TRIZ-based developed method, ARIZ (ARIZ is an acronym for the Russian expression "Algorithm for Inventive Problem Solving) [9], and especially ARIZ 85-C, which is a generic method for analyzing problems and searching for relevant solutions. In [10], the authors argue that the Classical TRIZ corpus lacks the means to carry out an extensive survey during the initial situation analysis, implying the inability of TRIZ methods to collect necessary knowledge, e.g., context and literature data, or expert feedback, related to the design problem addressed during the analysis of the initial situation. Inventive Design Methodology (IDM) [11]–[14], as a systematic approach, was developed to overcome this limitation. However, it can be seen that one of the main limitations of IDM is the heavy reliance on experts' opinions and interviews. In the same direction, [15] developed an approach to enable design problem selection, based on qualitative information, through interviews with problem experts.

One of the main limitations of many expertise-based design methods is that the robustness of the manipulated data depends on the experience level of the working team, which can lead to varying results, such as design parameters. These limitations hinder the expansion of the problem space and the discovery of further para–meters contributing to the comprehension of the design problem. Moreover, they can be a limiting factor in terms of accuracy and completeness.

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Design of Experiments (DoE) [16] is a very com–mon and robust approach to modeling and representing the design parameters. Nevertheless, it still suffers from certain limitations. The first limitation is that the building model of the design parameters using DoE is limited by the selected set of variables, owing to the high cost of the experimental approach (for many case studies). As a result, this list of variables must be very limited to certain values to reduce the number of runs. The second limitation is that DOE can be run for a specific case study under very specific conditions. Thus, it is quite difficult to generalize a set of experimental runs for a wide range of design problems. Generali–zation is an urge to use the same…

In the methods cited, more attention should be paid to integrating multiple sources of information to build a unified model that accurately represents the system's parameters. This can lead to a lack of consistency between different models or a loss of important infor–mation. Less attention has been paid to the genera–lization of the modeled parameters. This generalization could help to address more design problems on two levels: the quantity and the complexity of design problems. At the level of graphical representation, the network representation of design parameters, such as that used in [15] and [8], is not very effective in the case of a large number of parameters. This is because, as the number of parameters increases, reading such networks becomes more difficult and fuzzier.

To address these challenges, a new approach has been proposed to collect data and information from various sources and build a contextual database containing the collected data and information. Based on this dataset, and by transforming and manipulating this data, a generalized table of parameters (GTP) would be built to organize, represent, and model the parameters of the product system. This approach involves collecting data and information from multiple sources, such as existing documentation from scientific databases, interviews with experts, and experimentation. Additi–onally, this information is used to build a more comprehensive model of the system. The resulting table of parameters can be used to support the design, improvement, and modification of the product system.

To validate the applicability and feasibility of the proposed method, lattice structures were chosen as a case study. The interest in a lattice structure lies in its unique characteristics, which can meet a wide range of industrial needs. Lattice structures occupy an interesting niche in manufacturing. These structures can be used further for promising properties such as acoustic and vibrational damping, energy absorption [17,18], high strength-to-weight ratios, and thermal management capabilities [19,20]. Moreover, these properties have been tested on some real applications like vehicular crashing and collision [21,22], airfoils [19], and Blast resistance [23]. Their characteristics determine the wide range of applications for lattice structures. Lattice structures are frequently used in many fields and applications [24]:

- The structural design of aircraft, rockets, etc.
- The automotive industry is due to their lightweight and high strength. Moreover, their great capacity to absorb mechanical energy (crashworthiness), such as the energy absorbers in car bumpers.
- The biomechanical field as they can be molded into the shape of human tissues and bones to replace diseased organs, thanks to their high strength and biocompatibility.
- Thanks to its adaptable mechanical and struc–tural qualities, the medical industry can meet unique requirements, such as medical implants.
- Aerospace applications, such as the manu–facture of thermal control systems, have de–monstrated a 50% reduction in weight and a 60% increase in thermal capacity compared with traditionally manufactured structures.
- Military applications, such as the use of zero or negative Poisson’s ratio structures in protective and blast-resistant armor.
- Chemical applications, such as catalytic sup–port, thanks to highly porous structures offe–ring a large surface area.
- Thermal fields, such as the heat exchangers
- Packaging, thanks to their high capacity to absorb shock energy.

Several other applications can be added daily to integrate fabricated lattice structures into industrial applications in different scientific fields, such as mechanical, chemical, thermal, electromagnetic, etc.

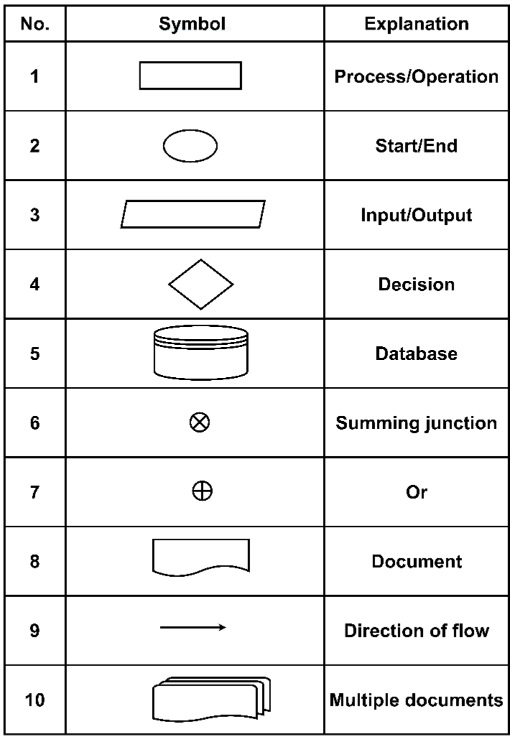

Figure 1. Symbols of process flowchart

This paper aims to propose a method for establishing a generalized table of parameters, which can be used as a tool to facilitate the understanding of inventive design problems. The table is linked to a contextual database based on the extraction of data and information from various sources of information, including scientific databases, expert perceptions, and available options in Computer-Aided Design (CAD) and Finite Element

Modeling (FEM) software. The use of this table should contribute to an overall understanding of the problematic situation and the development of a resolution strategy based on the extracted data.

The paper is organized as follows: Section 1.1 presents a review of some previous studies and methods whose findings and results will be used to develop the method proposed in this paper. It also highlights the limitations of these studies, as well as the practical problem of modeling and representing the design parameters. Section 1.2 presents the proposed method for constructing the generalized table of parameters. Section 1.3 presents the topology of the developed table. This section defines the global structure of the table and different inherent definitions. Section 1.4 illustrates the proposed method for modeling the design parameters. To this end, we present a case study, namely the lattice structure, as an application of the proposed method. Section 1.5 is dedicated to feedback on the proposed methods, their potential uses and limitations, as well as a brief conclusion.

2. THE PROPOSED APPROACH TO COMBINE DIFFERENT SOURCES OF INFORMATION

In [25-27], some of the knowledge and information collection techniques were mentioned. A list of these techniques and methods is as follows: Searching through achieved documents in scientific databases, doing Interviews with experts, doing Surveys, performing experiments, interviewing focus groups, and performing case studies.

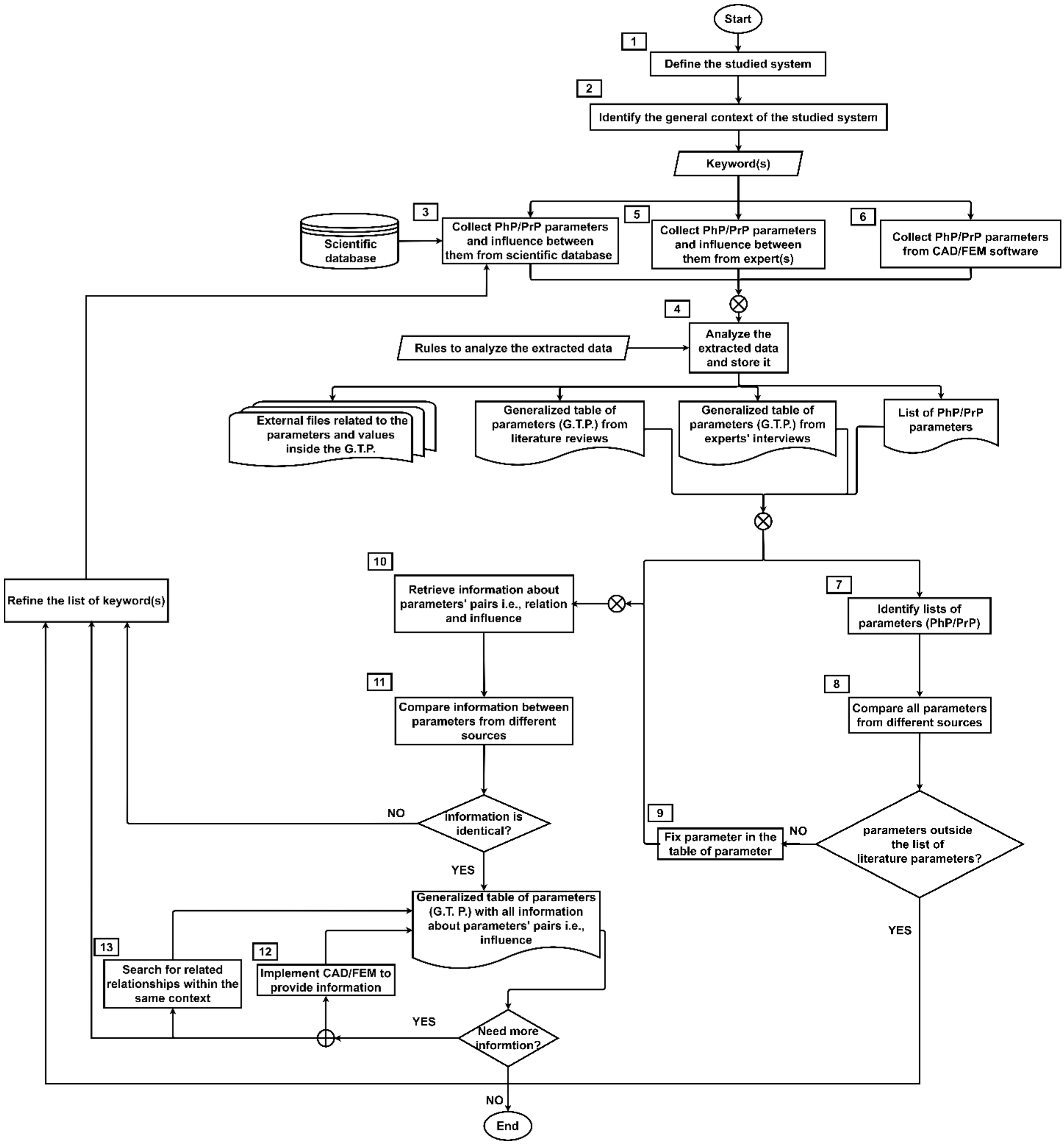

Figure 2. The proposed unified approach to fill the generalized table of parameters based on the integration between three methods of collecting information

The authors chose three techniques to collect information. These techniques are: (1) Collecting information from scientific databases, (2) Collecting information from experts' opinions, and (3) collecting information from the experimental approach. After selecting these techniques, an approach was proposed to integrate them, as shown in Figure 2, to build a contextual database and then model the analyzed data and represent it using a generalized table of parameters. Figure 1 refers to the symbols used in the process flowchart and their explanation. The method illustrated in Figure 2 comes in thirteen sequential steps.

The steps of the unified method indicated in Figure 2 are explained as follows:

Step 1: this step defines the studied system, whether it is a product or a process.

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

•The technology used for manufacturing, e.g., injection molding, additive manufacturing

•The material used for manufacturing, e.g., polymer, metal

•The composition of the expected developed product, e.g., composite, specific material

•The expected applied deformation to this product, e.g., Quasi-static, dynamic

•The concerned field, e.g., mechanical, thermal

•The potential design problem(s) linked to the concerned field, i.e., specific table

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

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

•Use the keywords as input to search for relevant scientific articles/books from scientific databases (e.g., science direct)

•Try compositing different keywords together to widen the search process

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

1. Parameters extracted:

•PhP: physical parameter, i.e., the linked parameter to the global form of the lattice structure, material, and experimental control parameters.

•PrP: performance parameter, i.e., the linked parameters to solve the potential problem(s).

2. The influence between each pair of these parameters.

Step 6: One or more interviewing informative sessions can be held with one or more experts. A set of questions related to the system and general context were asked to the expert(s) to determine the following data and information.

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

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

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

•If a parameter in List 1 is similar in functionality to a parameter in List 2, then the two parameters are identical. In this case, we fix one parameter to put in the G.T.P.

•If a parameter exists in List 1, but does not exist in List 2, then the two parameters are non-identical. In this case, we put both of them in the G.T.P.

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

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

Step 10: in this step, it is time to retrieve information about parameters' pairs from different sources, i.e., influence. Once all parameters are listed in the GTP, we retrieve information related to each cell individually from each table of parameters/list of parameters produced previously (the table/list of each source).

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

•The information, e.g., relation or influence, of a specific cell is said the same in all tables?

•The information, e.g., relation or influence, of a specific cell is different at least in one table.

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

Step 12: At this stage, it is supposed that the work of filling the GTP is finished. However, in reality, there needs to be more information about the influence of some pairs of parameters. To overcome this obstacle and increase the performance of the data inside the table, complete as much information as possible inside the GTP. For this reason, we propose steps 12 and 13.
In step 12, in case there is missing information between parameters in the table. One option is to implement a customized FEM model to provide information. An alternative option is to add keywords about the coupling parameters, then search again for relevant scientific articles through scientific databases.

Step 13: in this step, we propose exploiting the collected relationships, e.g., mathematical, graphs, and experts' feedback, to find missing information. We give an example for a better explanation.
If we have three parameters, A, B, and C (mentioning that (→)means the influence between parameters)

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

3. TOPOLOGY OF THE GTP

The topology of the G.T.P. refers to the structure or layout of the table and how the different parameters are organized within it. The G.T.P. is designed to be a comprehensive and unified model of the product system parameters, and as such, its topology is carefully planned to ensure that it can capture all relevant data/ information, provide flexibility in inserting and/or extracting data/information, represent the data/infor–mation with high performance. Figure 3 shows a capture from the GTP, which shows the organization of information and data inside.

Indices: The GTP is provided with two indices (Alphabet on the vertical axe and numbers on the horizontal axe) to facilitate reaching out information inside. The cells inside the table are named by using these indices by following the format ("vertical index" + "-" + "horizontal index"). For example, the four cells in Figure 3 are A-1, A-2, B-1, and B-2.

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

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

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

Parameter Family: each one or more of the parameters can be grouped in a family which can be used for a specific context, e.g., cell, structure, energy. The family can help non-specialists with choosing the system parameters.

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

Parameter name: each parameter should have an identical name that is simple and expressive such as Young's modulus of the lattice structure.

Value: it represents the influence (effect) that describes the direction of a relationship between two parameters. The influence has five scenarios, which will be explained. Supposing that we have two parameters in tables A and B, then, as indicated by red arrows, the reader has to start from parameter A; when parameter A changes, then parameter B changes, consequently.

index							1	2	…………………					
	Parameter type													
		Source of parameter												
			Parameter unit											
				Parameter family										
					Parameter category									
						Parameter name	PhP1	PhP2	….	PhP(i)	PrP1	PrP2	……	PrP(j)
A						PhP1		……	……	…..	……	……	…..	
B						PhP2	*Cell (PhP2-PhP1)* **+ Value**							
….						…..								
						PhP(i)								

Figure 3. An indicative image to illustrate the topology of the Generalized Table of Parameters (GTP)

	Parameter (B)
Parameter (A)	Value

At this level, the value could be:

+1 → When Parameter A increases, then Parameter B increases, as well.

-1 → When Parameter A increases, then Parameter B decreases.

0 → No influence of parameter A on parameter B.

X→ No information about the relation between Parameters (A) and Parameter (B)

Other → It means one or more than one scenario:

- There is extra information extracted from a data source that may enrich this cell's information.
- The cell links a qualitative parameter with another qualitative parameter or a qualitative parameter with a quantitative parameter.

4. ILLUSTRATION OF THE METHOD FOR LATTICE STRUCTURE DESIGN PROBLEMS

The purpose of this section is to illustrate the unified method for building the generalized table of parameters. This method is based on extracting the information from three sources; first, the available scientific databases; second, one or more experts in the same field of the treated problem [17]; and the third source is the FEM and CAD modeling software. This collected information is used to build a Generalized Table of Parameters GTP.

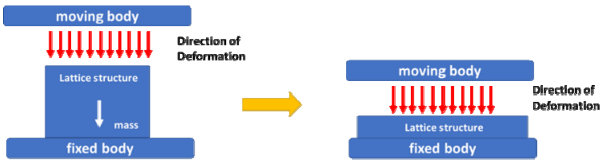

Figure 4. Schematic image of the applied deformation to lattice structure (case study)

4.1 Introduction to the case study

The case study is to build a generalized table of parameters about lattice structure, and this case study is global and generalized to cover more than one problem in the same general context. The established table will undergo a general context to frame the types of problems for which this table can be used. The case study is expected to cover lattice structures subjected to deformation, as shown in Figure 4.

4.2 Getting the table of parameters

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

Step 1: The system is a lattice structure that is used as a part of protective tools to absorb mechanical energy.

Step 2: the general context is determined in detail in section 1.4.1. which states that the generalized table of parameters covers the following concerns:

- The structure should be fabricated by additive manufacturing technology [28]
- It should be made of polymeric materials
- The structure is made of a specific material, not a composite
- This structure might be subject to different applied deformation
- The concerned field is the mechanical field
- The potential design problem(s) linked to the concerned field are:
  - ➢ Energy
  - ➢ Structure strength
  - ➢ Light weighting
  - ➢ Deformation
  - ➢ Cost

Step 3: This step is devoted to searching for information from the available literature reviews. This search process is implemented based on keywords that will help search relevant scientific sources such as scientific articles, books, or websites. The set of keywords is listed in Table 1.

Table 1: The set of keywords used to search for literature reviews related to the specific design problem

The keyword
Lattice structure
Additive manufacturing
Polymeric lattice structure
Cellular materials
Material Mechanics
Material of 3D printing technology
Rigidity
Light weighted lattice structure
Energy absorption
Deformation
Additive manufacturing defects

Consequently, a list of references (e.g., scientific articles, books) was extracted and analyzed.

Since this step is devoted to searching for relevant articles through scientific databases, about 66 articles and 4 books were collected and numbered. The collec–ted articles and books are listed in

Table 2: the resulting statistics about the collected literature reviews

	Literature review articles	Books
Quantity	66	4
Reference	[29]–[94]	[95]–[98]

Step 4: Parameters extracted from scientific databases are classified as follows: PhP = 25 parameters and PrP = 16 parameters.

The extracted data are stored in three documents:

1. The first document is to store extracted parameters from each source of information, such as scientific databases.

2. The second document is the table of parameters itself. The template of this document is illustrated previously in Figure 3.

3. The third document is a set of external files. Each file is linked to a specific cell in the generalized table of parameters GTP. These files are divided into two templated; the first template is built to organize all necessary information about each parameter in the GTP, which is indicated in Figure 5.

The second template is built to organize all necessary information about each intersecting cell between each pair of parameters in the GTP. This template is indicated in Figure 6. Quantifying the levels of each parameter and representing the solving technique could help in optimizing the design system by choosing the most relevant parameter to the design problem.

This choice is performed at a specific objective target of design. We argue that this kind of information is the potential for further integration into the design process.

Step 5: Four meeting sessions were held with experts in the field of lattice structures and materials, besides one TRIZ expert. Sessions' durations varied from 20 to 120 minutes. After presenting the case study lattice structure and providing the necessary information about the general context of the GTP, certain questions were asked to the experts, such as:

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

The experts provided a list of design parameters composed of 24 design parameters. These parameters are divided up into 13 physical parameters and 10 performance parameters. The expert(s) provided relations and influences between each pair of parameters, as well. These pieces of data and information are stored in a table-form document (output document).

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

Parameter name.doc — The file name in header

Parameter name
The name of the parameter
Graphical representation
Definitions and graphical representations
Parameter category
Qualitative or Quantitative
Parameter family
The family to which the parameter belongs
Parameter unit
Units in SI standard units
Source of parameter
Source 1, Source 2, or Source 3
Type of parameter
PhP or PrP
Levels of parameter
The limits and extents of values of this parameter in one or more sources e.g., maximum and minimum values for quantitative parameters

Date — The date in footer

Figure 5. The template of the file where the data and information about each parameter are stored

Cell name.doc ← The file name in header

The information in this file concerns the influence between (Parameter 1 from row) and (Parameter 2 from column)				
Parameter 1	**Parameter 2**	**Value**	**Definition**	**Solution**
Levels of Parameter 1	Levels of Parameter 2	Value of the cell	Definition of value	Solving technique e.g., influence
Scientific article/book				
All information from scientific databases e.g., Graphs, equations, etc.				
Experts' opinions				
All information based on the experts' feedback				
CAD/FEM software				
All information from CAD or FEM software e.g., CAD models and simulation results				
Conflict(s)				
If there is a conflicting information between the one or more sources of information				
Remarks/References				
Cited references and remarks				

Date ← The date in footer

Figure 6. The first table of the template in the file where pieces of data and information about each intersecting cell between each pair of parameters are stored

Step 7: in this step, it was supposed to prepare one file containing all parameters from different documents for further comparison. This step resulted in collecting the following quantities of parameters, as indicated in Taable 3.

Table 3: Quantity of parameters collected from different sources of data

Source	Type of Parameter	Quantity
Scientific datasets	PhP	25
	PrP	16
Experts' opinions	PhP	13
	PrP	10
CAD software	PhP	13
FEM software	PrP	18

Step 8: in this step, all parameters from different sources are compared to distinguish identical from non-identical ones. All parameters are collected and listed in one file to be comparable. The number of PhP = 32 parameters and the number of PrP = 23 parameters.

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

Parameter type	Quantity	
PhP	11	identical
PhP	21	non-identical
PrP	5	identical
PrP	17	non-identical

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

Step 10: in this step, we list all parameters in the template on the GTP to start filling the table with transformed data and information. The template is illustrated in Figure 3.

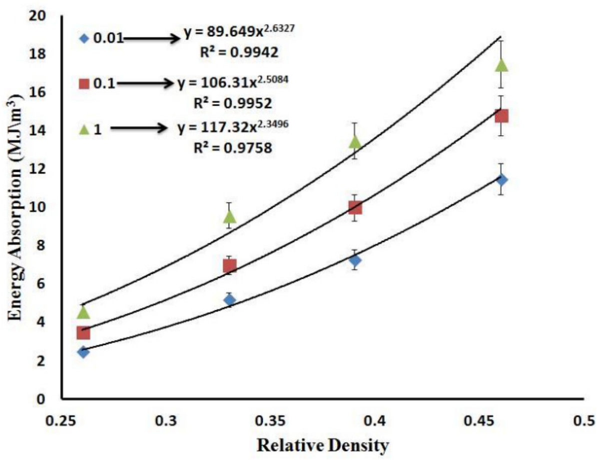

Figure 7. A graph to illustrate the relation between the relative density of lattice structure and the absorbed energy under changing the strain rate (from [37])

Step 11: in this step, the data and information concerning each pair of parameters from different sources are retrieved. The data is analyzed, and the influence between each pair is identified. To clarify this step, a real example from the GTP will be explained. In the GTP the relative density of the lattice structure is a physical parameter PhP, and the energy absorption per unit volume of the lattice structure is a performance parameter PrP. Some references, such as [44], confirmed the increase in the quantity of the absorbed energy with the increase in the relative density of the lattice structure Figure 7. For this reason, the influence between this pair of parameters is (+1).

Another reference [34] emphasized the same fact, as illustrated in Figure 8.

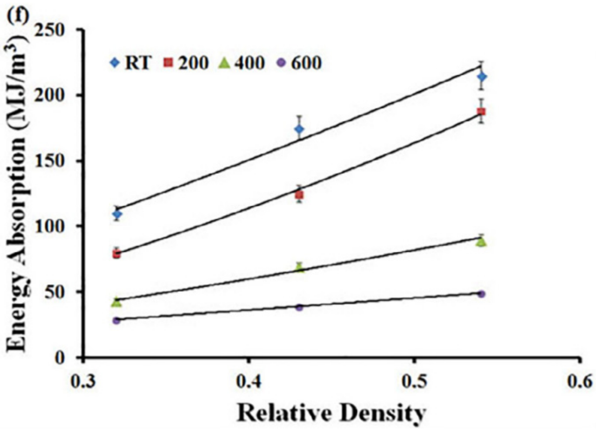

Figure 8: A graph to illustrate the relation between the relative density of lattice structure and the absorbed energy under changing the temperature(from [47])

However, the expert's feedback was on the contrary with references, as he mentioned the absence of the influence between the two parameters. That means the influence value is 0 in this case. At this stage, the two sources conflict about this information. Therefore, we proposed updating the list of keywords to search further scientific articles/books. The keyword added was (relative density and energy absorption of lattice structure). The search process was carried out one more time by adding new keywords, starting from step 3. References [35] and [73] were added to the list of articles. The reference [35] confirmed the increase of the value of the absorbed energy with the increase of the relative density of the lattice structure, as shown in Figure 9.

Another reference [73] confirmed the same infor–mation as indicated in Table 5. As the table shows a monotonic increase in the absorbed energy W with the density.

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

Step 12: as mentioned before, this step is activated in case there is missing information between pairs of parameters in the table. To illustrate this step better, a real cell value was picked from the GTP. The infor–mation between the parameters, Global dimen–sions, and energy absorption per unit volume was missing. For this reason, two CAD models were built to extract the information by using numerical simulation. We fixed the values of all other parameters and created two models with two different values of global dimensions (mm), as illustrated in Figure 10. The first CAD model was a structure composed of 2*2 Kelvin cells. The global dimensions of this model were 50*50*50 mm. The second CAD model was 3*3 Kelvin cells. The global dimensions of this model were 75*75*75 mm. FEM model was built, and numerical simulation runs were carried out by using ABAQUS® 2019.

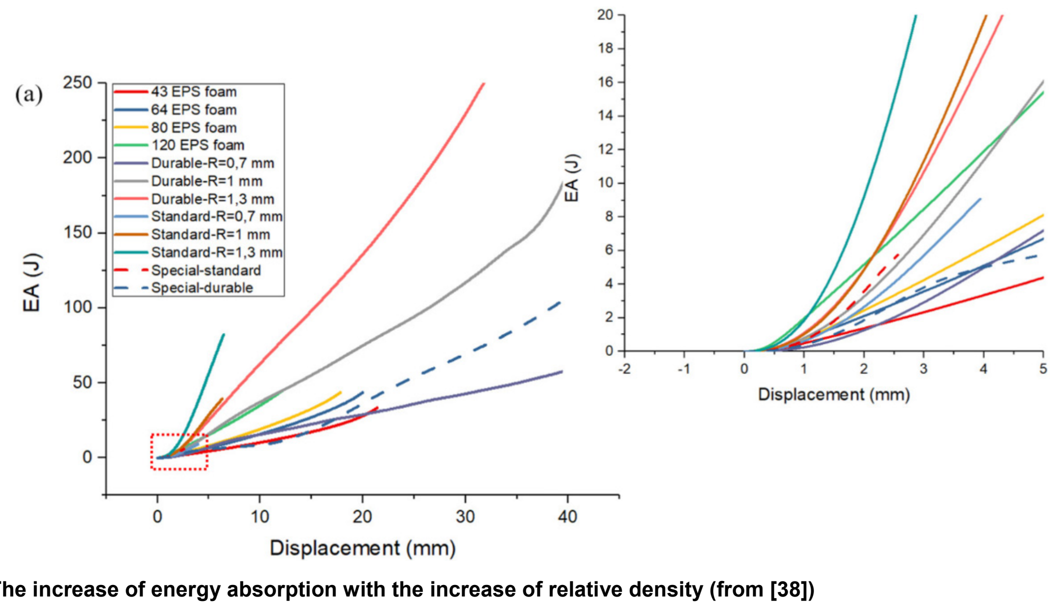

Figure 9: The increase of energy absorption with the increase of relative density (from [38])

Table 4: The increase of energy absorption with the increase of relative density (from [73])

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

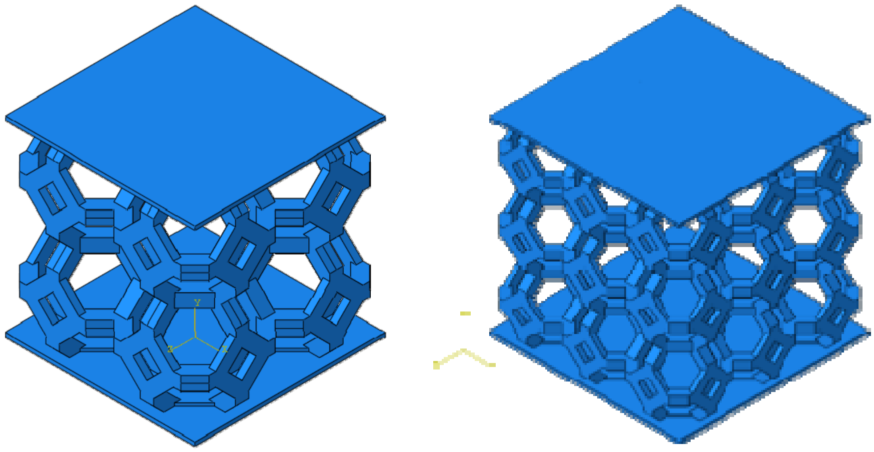

Figure 10: on the left is the CAD model of size 2*2*2 cell, whereas, on the right, the CAD model 3*3*3 cell

Table 5: The numerical simulation results of the two FEM models, 2*2*2 and 3*3*3

	size (3*3*3)	size (2*2*2)
Young's modulus of lattice structure (MPa)	51.00082818	46.53642231
Densification strain	0.624019368	0.655998154
Plateau stress (MPa)	2.934877778	3.259124927
Absorbed energy (MJ/m^3)	1.409002758	1.504290065
Global Dimensions (mm)	75*75*75	50*50*50
Strain (%)	Until 80%	Until 80%

From the results of the FEM models, one can conclude that Young's modulus of lattice structure increases when the global dimensions are increasing homogeneously. Therefore, the influence of the dimension change parameter and Young's modulus of lattice structure is +1 in the GTP. However, all of the densification strain, plateau stress, and absorbed energy per unit volume decrease. Therefore, the influence of the dimension change parameter and mentioned parameters are -1 in the table of parameters. The change in the absorbed energy and plateau stress from one model to another is rather small; hence, the influence of the change in global dimensions on the two parameters could be either 0 or -1. Figure 11 indicates the comparison between the two-resulting stress-strain curves. The hashed area between the two curves represents the quantified difference in energy absorption between the two models 2*2*2 cells and 3*3*3 cells.

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

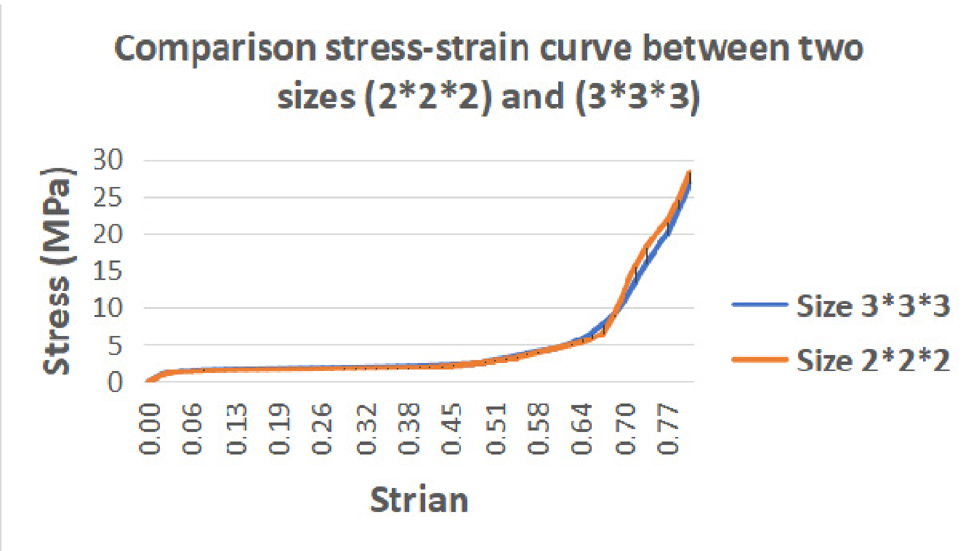

Figure 11: Stress-Strain curve of the two models, 2*2*2 cells and 3*3*3 cells

If the relative density of the lattice structure is denoted by (1):

$$\rho_{relative} = \frac{\rho_{lattice}}{\rho_{base}} \quad (1)$$

where $\rho_{relative}$ is the relative density of the lattice structure, $\rho_{lattice}$ is the density of the lattice structure. In contrast, ρ_{base} is the density of the base material from which the lattice is made.

And fracture toughness of the lattice structure is denoted by (2) [30]:

$$K_{IC} = \alpha \rho_{relative} \sigma_{fs} \sqrt{l} \quad (2)$$

where K_{IC} is the fracture toughness of the lattice structure, and σ_{fs} is the fracture strength of the lattice structure. Hence, the increase in the relative density of the lattice structure causes a decrease in the fracture strength of the lattice structure. Therefore, the influence value of cell A-34 is -1, and cell A-30 is +1.

4.3 Measuring the quality of collected data and information

Data quality, precision, and accuracy are generally thought of as having a major impact on the information that may be inferred from this data [99,100]. In the article [101], the authors developed a measurement framework to quantitatively assess the quality of Open Government Data (OGD) based on intrinsic quality characteristics.

The report from UNICEF [102] worked on elaborating the definition of statistical product qua–lity in terms of various quality aspects or dimensions. In the field of big data, the authors of [103] proposed establishing a hierarchical structure of a data quality framework, which involves a dynamic big data quality assessment process with a feedback mechanism. Further data quality criteria and dimensions were presented in the article [104]. In a general context, authors of [105] provided examples of metrics that can be used to measure data quality, such as accuracy, completeness, consistency, and time-related dimensions. Based on the previous literature articles, we propose the dashboard indicated in Table 6 to measure the quality of the data and information provided in the GTP.

Table 6: Dashboard to measure the data quality of the entire GTP

Dimension	Explain of dimension	Indicator	Measure of indicator	Limits of measurement
Accessibility	• Data can be easily made public or easy to obtain?	• open access sources of literature • possibility of getting a version of the software	• The type of journal (open access/free book/paid book/paid article) • Availability of a trial version of the software	• Paid articles (however, the university email was used to get access to these articles) • 3 free books and one paid book • There is a trial version of PTC Creo and ABAQUS
Timeliness	• Within a given time, whether the data arrive on time? • Whether data are regularly updated?	• The time between the interview with the expert and updating the table with information • How many versions between the last version of the software and the downloaded version	• On the recent day- The day of the first interview • The number of the last version released – The studied version number	• 179 days • 3
Credibility	• Data is extracted from trustworthy scientific sources? • Do data come from specialized experts? • Experts regularly audit and check the correctness of the data content?	• The scientific source is in the predatory journals list • The domain of work of the expert • How many times the data is revised per month by an expert	• Existence of journal name in the list • The name of the domain of expertise of expert(s) • Number of revision times per month	• No • Cellular structures and foams • Randomly revised and not periodically (around 4 times per month)
Consistency	• The conflict about the same piece of data/information between one/more sources of data	• Existence of conflict	• Number of conflicts' cells with a dotted hash/total number of all informative cells in the table	• (31cell /1612 cell) * 100 = 1.92 %
Completeness	• Deficiency of a component that will impact the use of the data for inventive design	• Missing pieces of data/information •	• Number of cells with (X) sign / total number of all informative cells in the table	• (295 cell /1612 cell) * 100 =18.3%

Readability	• Data (content, format, etc.) are clear and understandable? • The data provided can be easily accessible	• The format of provided files is known as formats • Readability and clearness of provided data in each cell • Cells are indexed/hyperlinked to access them easily	• Format of the table file • Format of linked external files • Indicators for values inside cells are provided • Indices, e.g., referring numbers/letters to cells • External files are linked to cells	• Xlsx extension • Docx and Doc extensions • Provided • Provided • Linked (each cell is hyperlinked with an external file)

5. FEEDBACK DISCUSSION

The feedback discussion of the method used revolves around three main questions: firstly, what positive feed–back has been observed about this method? Secondly, can this table be integrated into the inventive problem-solving method? Thirdly, what are the potential limi–tations resulting from applying the proposed method?

The preceding questions are answered in the following discussion points:

- Many design parameters make it possible to deal with different design problems in one or more fields using a holistic representation of these para-meters and their influences, e.g., mechanical field or coupling-field problems, thermo-mechanical problems, etc.
- Generalization can effectively help to deal with more design problems on two levels, the quantity level and the complexity level of design problems.
- Each cell is hyperlinked to an external file containing high-performance data and information. This file contains solving techniques, e.g., influence, which could be used for phases of the design process, such as optimization. For example, we are quantifying the levels of each parameter.
- The completeness of some missing information in the GTP is thanks to the collected mathematical models concerning the relationship between various parameters, e.g., equations (1) and (2), attributed. This confirms the argument of [15] that the law governing the parameters could help complete the information in such a table. On the other hand, it is thanks to the ease of computer modeling software such as PTC Creo and ABAQUS. These tools facilitated the completion of some information in the proposed table. However, modeling lattice structures based on the variation of some parameters is challenging and time-consuming for some parameters. For this reason, the proposed method offers the possibility of updating the keyword list with new keywords relevant to the missing information and repeating the search cycle for relevant scientific articles/books.
- The design parameters provided by scientific data–bases are far more numerous than those provided by experts and software Table 3. We assert that the greater the number of scientific articles/books collected, the greater the quantity of parameters.
- The percentage of conflicts is considered a significantly low ratio to the amount of provided information. This fact highlights the robustness of the proposed approach. Moreover, the proposed method suggests a means of resolving information conflicts.
- In this study, the transformation and analysis of data collected from several data sources and their integration into a tool such as the GTP, demonstrated the power of multiplying data and information sources.
- In the proposed GTP, each source of data provided unique information and data, i.e., non-identical parameters, in step 9, section 1.4.2. On the other hand, some parameters were common to several sources, i.e., identical parameters. This integration between data sources showed the risk of dependence on a single data source to achieve coherent information about the design system. This risk was not revealed when conflicts between data sources arose.
- The values provided in the table are cleansed of duplications, and cells can be easily accessed using the horizontal and vertical indices.
- The table is integrated with external files to ensure better readability of the data provided and greater flexibility in accessing each piece of information individually.
- The method used in this paper has contributed to modeling the system and its performance by determining system parameters such as physical and performance parameters. The generalized table of parameters could be a good practice to show to what extent such a modeling approach can successfully integrate with inventive design problem-solving methods. In addition, the generalized table and its relevant documents can function as an instant dataset in a specific field to solve a set of problems. Any researcher or user needing to solve one or more design problems in the same field can do so without having to refer to a long list of references and repeat a lengthy process of analyzing these scientific sources.
- However, some limitations are still inherent to the proposed method. Although the generalized table of parameters is a powerful tool for modeling the designed system, obtaining all the data in this table is a considerably time-consuming process. Indeed, this table depends on manually collecting all

relevant information/data concerning each pair in the tables PhP/PhP and PhP/PrP. The second limitation is that the data collection and analysis process highly depends on the individual skills and competencies of the person entrusted with this task (i.e., the researcher). Another limitation is the limited number of scientific sources extracted, given that this process is human-based. This limitation can be addressed by developing an automated tool to extract excessive scientific sources, e.g., literature reviews, patents, and so on. Therefore, this tool can follow the data analysis rules presented in this paper.

Another limitation concerns the availability of human experts. Part of this study is conducted with the help of two experts, one being a TRIZ expert and the other an expert in cellular materials. However, the authors attempted to gain access to four other experts to enrich the expert space in the GTP, but unfortunately, one expert had schedule conflicts, and the other three did not respond to the invitation. This raises the difficulty of massive reliance on experts alone to conduct studies, as in [15] and [106]. This limitation justifies the robustness of the proposedmethod.

6. CONCLUSION

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

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ACRONYMS AND ABBREVIATIONS

GTP	Generalized Table of Parameters
FEM	Finite Element Modeling
CAD	Computer-Aided Design
TRIZ	A Russian acronym, translated into English as “Theory of Inventive Problem Solving”
DoE	Design of Experiments
CDB	Contextual Data Base
PhP	Physical Parameter
PrP	Performance Parameter
Source 1	Refers to a scientific database, e.g., articles, books patents
Source 2	Refers to the experts’ opinion
Source 3	Refers to the analysis of computer-aided design software CAD and finite element modeling software FEM, as a source of knowledge

Greek symbols

$\rho_{relative}$	Relative density of the lattice structure
$\rho_{Lattice}$	Density of the lattice structure
ρ_{base}	Density of the base material from which the lattice is made
K_{IC}	Fracture toughness of lattice structure
σ_{fs}	Facture strength of the lattice structure
l	Cell size of the lattice structure

МЕТОДА ЗА ИЗГРАДЊУ ГЕНЕРАЛИЗОВАНЕ ТАБЕЛЕ ПАРАМЕТАРА У ИНЖЕЊЕРСКОМ ПРОЈЕКТОВАЊУ ТЕХНИЧКИХ СИСТЕМА: СТРУКТУРА РЕШЕТКЕ КАО СТУДИЈА СЛУЧАЈА

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Параметри дизајна су кључни елемент процеса дизајна производа. Међутим, модели параметара дизајна се често користе за решавање специфичних проблема дизајна. Уопштавање параметара дизајна је приступ за решавање више проблема дизајна. Ова студија доприноси решавању одређених ограничења везаних за моделовање и представљање параметара дизајна. Овај рад представља генерализовану табелу параметара (ГТП) за моделовање параметара сис–тема. Ова табела је повезана са контекстуалном базом података заснованом на подацима и инфор–мацијама прикупљеним из научних база података, интервјуа стручњака и анализе и употребе софтвера за пројектовање помоћу рачунара (ЦАД) и модели–рање коначних елемената (ФЕМ). Предложена репрезентативна табела показује робусност интег–рације више извора информација како би се представио холистички и генерализовани поглед на систем дизајна. Квалитет датих података у табели се процењује применом одређених евалуационих димензија и индикатора. Биће представљена студија случаја о структури решетке у оквиру специфичног контекста у механичком пољу.