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Mechanical Engineering Design Theory Framework for Solar Desalination Processes: A Review and Meta - Analysis

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A B S T R A C T

The aim of the present study is to assess theoretical and practical analysis of scientific publications on solar desalination. This analysis is proposed within mechanical design theory framework. For this, inductive and statistical methods were used in analysis of the scientific publications of different specialties that deal with the design process of solar desalination. With the use of the mentioned methods a tendency was obtained that justifies applying the study results to this type of devices of the approaches of the theory of the mechanical design analyzed. Statistical analysis is conducted for the above assessment not only analytically but quantitatively. This gives responses to problems currently posed by different authors related to the possibility of linking several disciplines used today in isolation for the application of mechanical design theory to this type of solar desalination.

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NOMENCLATURE

F	Frequency
TF	Refers to the Frequency respect to the population
XOi	Occurrence of the event (1 or 0)
RF	Relative Frequencies (%)
TRF	Relative Frequencies respect to the population (%)
PC	Partial Cases
C	Cases

Subscripts

i	Event sampled number

INTRODUCTION

The development of solar desalination is given to replace the energy sources traditionally used by most of the current desalination systems. When a source, such as solar, makes it possible to use seawater to counteract the scarcity of another type of water in major regions of the world. The importance of solar desalination grows based on the impact of the use of solar energy on cost and sustainability of processes is discussed by Pared et al. [1]. However, there are technical issues to be resolved in order to have this type of device attractive commercially. This is reflected in publications of authors of this topic as in the case of Farid and Al-Hajaj [2], where it is argued that although the device is known, a limited number of companies have commercialized solar Desalination with a Humidification-Dehumidification cycle (DHD) and it is still required to improve their performance. In this sense, they have proposed to remodel, simulated and optimized its design. To do this, three of its main components must be changed: the humidifier, the condenser, and the solar collector area. So the improvement of them is crucial to facilitate the marketing of the device. Other authors such as Al-Hallaj et al. [3] addressed the issue of these types of solar desalinations when expressing a similar problem with proposed solutions. Moumouh et al. [4] proposed the use of new materials in the construction of these devices, which they see as one of the variants of solution of the raised problem to make solar DHD more effective.

In the course of this research, it was consulted and analyzed works on design of solar energy systems that included proposals of steps to follow in this process and their relation with the practical implementation of the system [5]. Likewise, a trend assessment will be carried out to assess other authors [6]; in this case for other types of devices. Therefore, these approaches have proved to be adequate to develop research into the problems addressed in this article. In this paper, the possibility of

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applying the mechanical engineering design theory in the Process of development and continuous improvement of solar desalination units has been valuated. From the solar DHD models similar to those described in literature [1] and also by Veza and Ruiz [7].

In methodologies of mechanical engineering design the relations existing between the descriptive functional taxonomy defined by Kirschman and Fadel [8] with similar variables found in literature [9], theory of inventive problem solving (TRIZ) by Altshuller are emphasized. In addition, it is required to develop elements of mechanical engineering design to solar desalination units. It is therefore feasible to assess analytically and quantitatively the possibility of applying the design theory of mechanical engineering to give answers to the practical and theoretical needs that surround the solar DHD units. Thus, a statistical study is set up inductively from the literature representative of this theme to evaluate the state of the art through a group of variables of convenient form. Among the main groups within literature, divided by topic are: mechanical engineering design methodology (MIDM), the specifics on solar desalination DHDT, finite element method (FEM) to represent it as kind of document and those of the implementation of innovations of TRIZ. In all of the above, it is planned to observe: the design in function of materials, the use of Computer Aided Design/Computer Aided Engineering / Computer Aided Process Planning/ Computer Aided Manufacturing (CAD/CAE/CAPP/CAM) and similar, among other techniques and methodologies.

MATERIAL AND METHODS

In the present article, inductive methods were used to extract the representative variables of the study from a first logical analysis of the bibliography. The variables are then processed using statistical methods. The relative frequency is calculated according to equations (1-4) and a cluster analysis is applied. Each document was evaluated and analyzed according to its theme, giving the value corresponding to each variable. If the subject related to the variable appears in the document it receives the value 1 otherwise the value is 0. They represent binary data. The calculations of the cluster analysis were done in a professional software of statistical analysis [10], taken into account only the columns in the dendrogram. That is, only the dendrogram that generates the proposed variables is taken. The cluster analysis of the professional statistical analysis software was configured for this study with: Euclidean Distance, Use of Serializations, Multiple Heuristic Fragmentation and the Ward Method [11].

From the analysis emanated by the data in Table 1, there would be a current trend of the different approaches of the sample. The graphs of the relative frequency (Figures 2 and 4) were obtained using a spreadsheet.

$$F = \sum_{i=0}^{PC} \mathrm{XO} \tag{1}$$

$$RF = \frac{F}{PC} 100 \tag{2}$$

$$TF = \sum_{\mathrm{i}=0}^{\mathrm{C}} \mathrm{XO} \tag{3}$$

$$TRF = \frac{TF}{C} 100 \tag{4}$$

Statistical analysis variables

In the sample there are authors whose works answer the questions raised above. These responses can be expressed in variables that are proposed inductively as follows:

Design Process (DP) should be based on: Descriptive models of the design process, i.e., pre-designed models, process-oriented models with computational tools, languages, representations, design process environment, analysis and decision making in the process of design, linking the design process with the fabricability of the product and other aspects of the product life cycle, such as maintainability and operations costs [12, 13].

Functional Taxonomy (FT) what it must contain is based on the fact that: The functional taxonomy proposed by Finger and Dixon [12, 13]. It consists of four broad categories, each of which contains different types in which it is presented. These are: Motion (linear, rotary, transmit, dissipate, rigid, flexible, and others); Control (power, movement, information, internal feedback, user - supplied, modify); Power / Matter (store, intake, expel, transmit, dissipate, electrical, mechanical, and others); Enclose (cover, view, protect, removable, permanent, guide) discussed by Kirschman and Fadel [8].

Innovation Methodologies (IM) what it must contain is based on the fact that: It is the incorporation of principles according to innovation methodologies. In the sample the TRIZ methodology was favored. The TRIZ methodology developed by Altshuller [9] is a method to generate innovations. In fact, there are examples of the use of the premises of the TRIZ method in several design processes such as Fey and Vertkin [14], Song-Kyoo [15] and Cavallucci [16].

Functional Design (FD) what it must contain is based on the fact that: It must be seen as the definition of geometric parameters strongly related to the principle of operation of the system according to its nature. As the function required for this sample is related to the (Humidification-Dehumidification cycle (HD) solar desalination devices are observed in documents describing implementations of this type of devices. The details on functional design were discussed by Veza and Ruiz [7], Ashrafizadeh [17], Mistry [18, 19], Narayan et al. [20], Jubran et al. [21] Jaluria [22].

SC(Social Characteristics) must be based on: Established relationships between decision-making in the design process regarding the characteristics of the institution where the steps will be executed until the output of the product and also with market conditions. Krishnan and Ulrich [23] and Finger and Dixon [12, 13].

Numerical Simulation (NS) what it must contain is based on that, this type of variable is applied to the sample evaluation because in some documents on the design of HD solar desalination systems cases of application of numerical calculations in the design of the same are observed. Knowing the importance to simulate a prototype prior to its manufacture, document samples are added on calculations using the FEM. Numerical simulations on conceptual mechanical design discussed by Anjos et al. [24], Hughes et al. [25-34] and Razzaqa et al. [35]. Materials are significant percentage of the total cost of an object, so it is important to know if they meet the required functionality. That is why it is included in the sample.

RESULTS AND DISCUSSION

Cluster analysis

The dendrogram of Figure 1 shows two groups from the dataset of Table 1. The first one has the variables FD and SC, since many authors in the desalination works of the HD cycle, comment on their relationship with the economic and social environment. The second group reveals a strong relationship of the variable DP with the design process mentioned in the documents consulted with FT and IM variables sampled. This should be interpreted as: when characterizing and describing the functionality of an element, these characteristics can be used to organize a taxonomic tree, or to follow a process of improvement through innovation.

Hence, in order to design an artifact by elemental logic, it is essential to know the principle of operation of all its parts. When used in the sample texts about classical FEM with a tendency to applied mathematics content, the NS variable appears alone in a group. In this sense, it should not be overlooked that these texts have been proposed as ways to improve the simulation of solar DHD and it is important to have a record of their behavior for the course of this research.

Relative frequency analysis

Figure 2 is a graph based on the values of the relative frequencies of Table 1. The value of each variable is shown by the type of text in which the sample was separated and its value with respect to the total sample. Figure 2 is organized so that the value of the variable can be seen with respect to the total sample. For example, for the DP variable the texts on design methodology of MIDM and TRIZ show relative frequency values above the total sample. The texts on design of solar desalination show an occurrence below, while the texts on the method of finite elements used in the study do not make important references to the theory of design, so it appears without values. What happens for the other variables should also be seen.

TABLE 1. Evaluation of the texts consulted in each subgroup of literature as in the total sample

Texts by group	DP	FT	IM	FD	SC	NS
MIDM						
[12]	1	1	0	0	1	1
[13]	1	1	0	0	1	1
[36]	1	1	0	0	1	0
[8]	1	1	0	1	0	0
[23]	1	1	1	1	1	0
[37]	1	1	0	1	1	0
[38]	1	1	1	1	1	0
[39]	1	1	0	1	1	0
[40]	1	1	1	1	1	0
[22]	1	1	1	1	1	1
[41]	1	1	0	1	1	0
F/11 PC	11	11	4	8	10	3
RF	100.0	100.0	36.36	72.73	90.91	27.27
DHDT						
[7]	0	1	0	1	1	0
[2]	0	0	0	1	1	0
[42]	0	0	0	1	0	1
[43]	0	0	0	1	0	0
[3]	1	0	0	1	1	0
[21]	0	0	0	1	1	1
[44]	0	0	0	1	1	1
[45]	1	0	0	1	1	0
[1]	1	0	1	1	1	1
[46]	1	1	0	1	1	0
[47]	0	0	0	1	1	0
[53]	0	0	0	1	1	1
[52]	1	0	0	1	1	1
[48]	0	0	0	1	0	1
[49]	0	0	0	1	0	1
[18]	1	0	0	1	0	1
[19]	1	0	0	1	0	1
[50]	1	0	0	1	0	1
[17]	1	0	0	1	0	0
[51]	1	0	0	1	0	0
[20]	0	0	0	1	0	0
[4]	0	0	0	1	0	0
F/22 PC	10	2	1	22	11	11
RF	45.45	9.09	4.55	100.0	50.0	50.0

TABLE 1. Continuation

Texts by group	DP	FT	IM	FD	SC	NS
TRIZ						
[14]	1	1	1	1	0	0
[9]	1	1	1	1	0	0
[16]	1	0	1	0	0	0
[15]	1	0	1	0	0	0
F/4 PC	4	2	4	2	0	0
RF	100.0	50.0	100.0	50.0	0.0	0.0
FEM						
[24]	0	0	0	0	0	1
[25-34]	0	0	0	0	0	1
[35]	0	0	0	0	0	1
F/3 PC	0	0	0	0	0	3
RF	0.0	0.0	0.0	0.0	0.0	100.0
TF/ 40 C	25	15	9	32	21	17
TRF	62.5	37.5	22.5	80.0	52.5	42.5

When the comparison explained in the previous paragraph is made, that facilitates the graph of Figure 2 and evaluates the groups generated in the dendrogram of Figure 1, which gives an idea of the current state in this theoretical framework.

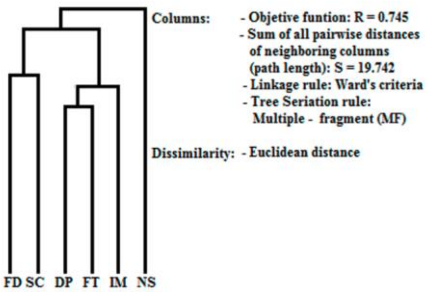

Figure 1. Dendrogram generated in ERMUTMATRIX, where the groups are shown in the cluster analysis

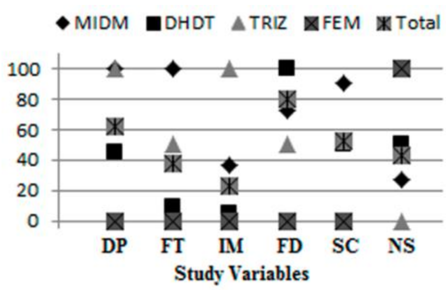

Figure 2. Graph of relative frequencies obtained from Table 1

Not only from the point of view analytical but also quantitative; it is observed that the texts on DHDT count on a treatment of these processes and use of the methodology of design DP in a relative frequency value of 45.45 against 62.50 of total samples. That is, a difference of 17.05 points. It suggests that new approaches should be generated to further apply the design of these types of devices based on practice that regularly establishes the theory of design in mechanical engineering. By itself, the dendrogram in Figure 1 generates in groups separated the variables DP and FD which by logic, should be closer. The DHDT text group is extremely low compared to the total sample in FT and IM variables. Based on this, it raises the question of whether to best apply mechanical design theory, assuming the most up-to-date tools mentioned above, which means better solar DHD. From this combination of approaches the characteristics of each of them should be suitably taken according to the practice of the design to generate form features with which to give output to the stages of: design, simulation, manufacture and others of the process that are wanted to be treated by means of CAD / CAE/ CAPP / CAM system.

Overlap Operation as a new trend analysis

Therefore, following the similar logic of some documents that were analyzed in the previous paragraphs and trying to visualize how to improve the theoretical framework, the information in Table 1 can be regrouped using the Boolean OR operation. That is, 1 if at least one operand is 1 and 0 if both operands are 0. This is called overlap operation. After this overlap operation the effect of the theoretical framework analyzed on the state of the art can be evaluated.

Overlap by Documents (rows)

Using the logic of common points between documents it is possible to predict a new methodology (or at least know the trend) for the mechanical design of solar DHD by means of a superposition operation and filling voids (zeros) in the state of the art according to this analysis. Therefore, the overlap of rows of scientific articles is proposed as follows:

Text References Function-Based (TRFB): New subgroup no longer formed by specific texts but under the assumption of seeing what would happen if the texts on design, whose works emphasize the principle of operation of the devices if they are enriched with the simulation of them by the FEM method. In the interest of this, the texts selected to be superimposed (the entire row is superimposed) are:

TRFB = [7] **OR** [8] **OR** [14] **OR** [9] **OR** [16] **OR** [15] **OR** [24] **OR** [25-34] **OR** [36] (5)

Texts with design of solar dhd joined with methodology of design (tdmd)

New subgroup, following the same logic as for TRFB, in this case in the interest of overlapping design cases of HD solar desalination and mechanical design theory, which does not specify types of devices, the selected texts are:

TDMD = [53] **OR** [47] **OR** [12] **OR** [13] **OR** [23] (6)

Theory of materials with design of desalination systems (TMDD)

To see the behavior on the theoretical trend, if the Materials Theory is used to design solar DHD units, a new subgroup is created by superimposing the documents:

TMDD = [42] **OR** [4] (7)

For all new subgroups above, it is done as for **TRFB**, the entire row is superimposed, influencing the new values that the variables take.

By variables (columns)

It is also possible to use the combination of some columns to obtain a new variable, also following the logic of filling the voids (zeros) in the state of the art and predicting the new trend of the same. The overlapping variables are the containers of the treatment of the functionality in different approaches to the treatment of the devices; the new variable would be Variable of a possible New Methodology (VNM):

VNM = FT **OR** IM **OR** FD (8)

Results of overlap

Once the selected rows have been superimposed first and then the variables as explained in the previous paragraph, Table 2 is obtained. Where the non-overlapping documents of the MIDM type and the resulting data of the virtual improvement appear, after combining the solar DHD design text with other disciplines in Table 2 DHDT+. In the dendrogram of Figure 3 NS also appears alone. While the other variables are combined in a group as a result of overlap, group that is not far away SC. Variable of the characteristics of the social environment around where the design and the future exploitation of the device are made.

The case of NS is further removed. It was used in the sample of documents on finite elements of general type and that is reflected in both dendrograms. In the graph of Figure 4 it is observed that after the overlap the variable improves some points with respect to the original state. Figure 4 compares the relative frequency values of the new variables of Table 2 with respect to the same or similar values of the total sample that appear in Table 1. Here it can be seen that VNM has TRF better than the rest of the variables before their mutual combination. All variables after the overlap have better values than the original sample. This fact quantitatively shows the trend indicating the improvement of the state of the art after the virtual combination of the different mentioned tools.

TABLE 2. Sample after overlap

Texts by group	**DP**	**VNM**	**SC**	**NS**
MIDM				
[36]	1	1	1	0
[37]	1	1	1	0
[38]	1	1	1	0
[39]	1	1	1	0
[40]	1	1	1	0
[22]	1	1	1	1
DHDT+				
TRFB	1	1	1	1
[2]	0	1	1	0
[42]	0	1	0	1
[43]	0	1	0	0
[3]	1	1	1	0
[21]	0	1	1	1
[44]	0	1	1	1
[45]	1	1	1	0
[1]	1	1	1	1
[46]	1	1	1	0
TDMD	1	1	1	1
[52]	1	1	1	1
[48]	0	1	0	1
[49]	0	1	0	1
[18]	1	1	0	1
[19]	1	1	0	1
[50]	1	1	0	1
[17]	1	1	0	0
[51]	1	1	0	0
[20]	0	1	0	0
TMDD	1	1	1	0
TF/27 C	19	27	17	13
TRF	70.37	100.0	62.96	48.15

At the beginning of this article, the authors of the referred articles [1-4] mentioned practical problems that required the search for new theoretical approaches to design and manufacture HD solar desalination devices that are much more efficient and more attractive to the market. It should be clarified that works on the design of thermal systems that use the sun as an energy source continue to develop, as is the case reported literature [54]; as well as what is related to emphasizing the importance of this energy source [55]. These theoretical proposals come from the combination analyzed here in a statistical way; which in practice, induces a specific methodology for the conception of this type of desalination, with steps established in Figure 5. Then, the geometric design of the artifact begins with a first proposal that can be perfectly a design template. Applying a CAD/CAE system goes into a stage of proposal design, simulation and redesign.

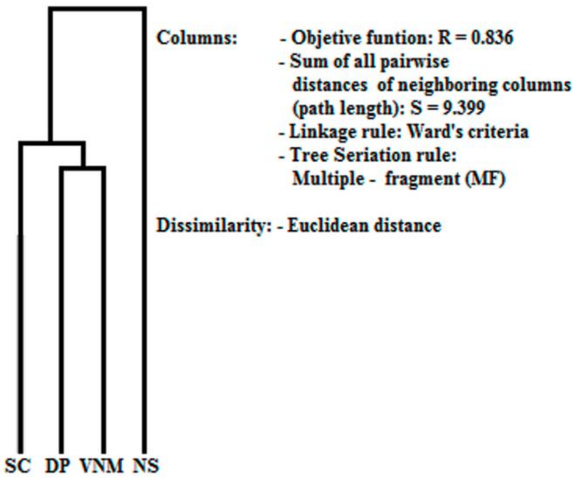

Figure 3. Dendrogram obtained after overlapping the variables, according to equations (5-8).

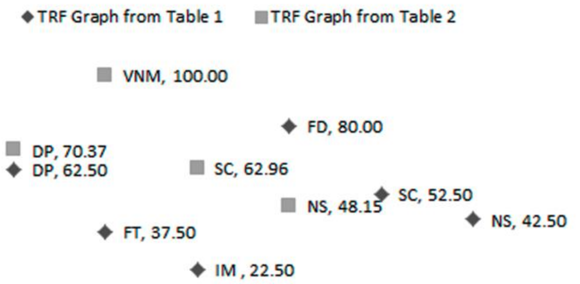

Figure 4. Graph of the Relative Frequency of the variables of the data after the overlays.

Note in Figure 5 the CAD / CAE system strongly supported by FEM calculation modeling. The design proposal can be protected by an innovative process if its realization is determined and thus each version can be simulated to evaluate its behavior. The design proposal obtained from this step is evaluated in terms of manufacturability, maintainability, functionality and economic behavior, both of manufacturing costs and operation. After passing the test, proceed with the manufacture, the cycle is repeated from the geometric modeling. Therefore, in the steps proposed in Figure 5, a process of designing HD solar desalination units through the use of computational tools and other benefits offered and derived from applying the theory of design in mechanical engineering. The application of all these tools according to Figure 5 is a reflection in practice of the implementation of the results of the present study of the state of the art in a methodology of the HD solar desalination design process.

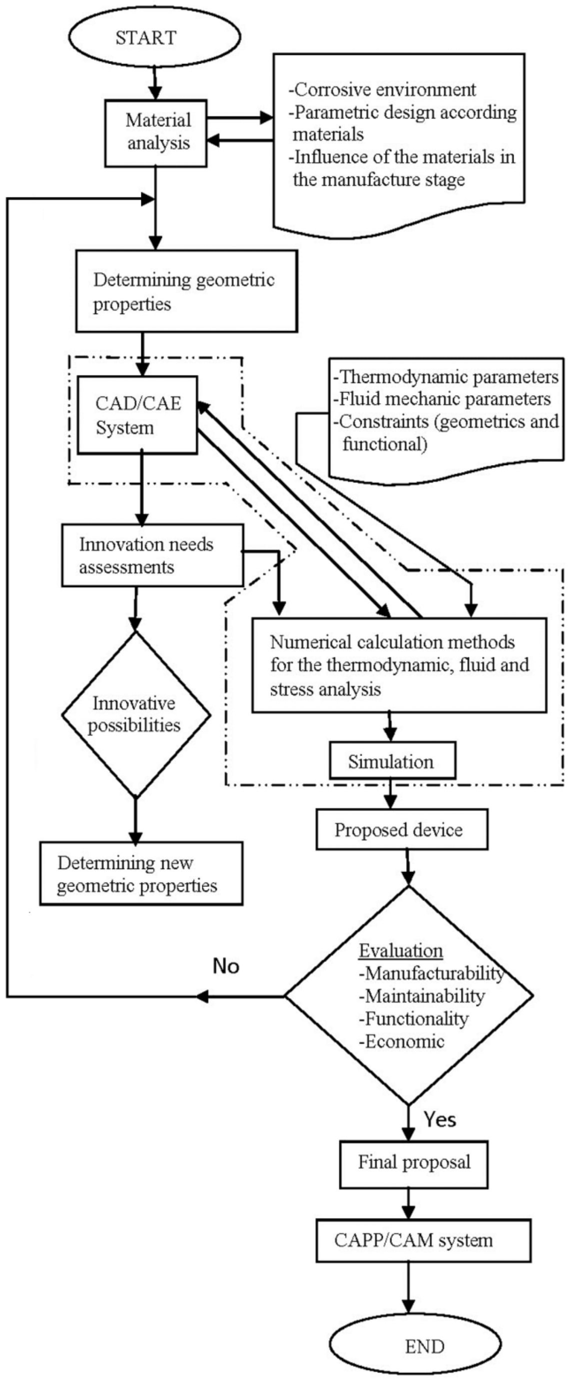

Figure 5. Flowchart of steps for HD solar desalination units design process.

CONCLUSIONS

In the present work, a solution proposal related to the need to improve the performance of HD solar desalination units was evaluated. Although these devices use this convenient source of energy in their work process, they need more development to achieve superior performance. Extending the range of possibilities to cover and be commercially beneficial for manufacturers and users. Therefore, it was proposed to evaluate the combined use of its design process with other methodologies or theoretical approaches. In this case the mechanical engineering design theory that includes material selection, TRIZ innovation implementation methodology and FEM simulation. The above combination is a proposed way to reach the solution of the problem.

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Persian Abstract

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چکیده

هدف از پژوهش حاضر ارزیابی نظری و عملی در تحقیقات انتشارات علمی در زمینه آب شیرینی خورشیدی است. این تجزیه و تحلیل در چارچوب نظریه طراحی مکانیکی ارائه شده است. برای این منظور، روش های القایی و آماری در تجزیه و تحلیل انتشارات علمی تخصص های مختلف مورد استفاده قرار گرفته است که با فرایند طراحی مشروب خورشیدی مواجه است. با استفاده از روش های ذکر شده، تمایل به استفاده از نتایج مطالعه به این نوع دستگاه های رویکردهای تئوری طراحی مکانیکی مورد بررسی قرار گرفته است. تجزیه و تحلیل آماری برای ارزیابی فوق نه تنها از نظر تحلیلی، بلکه کمی سنجیده می شود. این مسئله پاسخ به مشکلات در حال حاضر مطرح شده توسط نویسندگان مختلف مربوط به امکان پیوند چندین رشته امروزه در انزوا برای استفاده از تئوری طراحی مکانیکی به این نوع از نمک زدایی خورشیدی است.