Universidad Continental

FACULTAD DE INGENIERÍA

Escuela Académico Profesional de Ingeniería Mecatrónica

Tesis

Design and Structural Analysis of a Maca Freeze-Dryer for the Peruvian High Andean Zones Using VDI 2221

Beyker Jesús Quispe Aguirre
Karolina Vilma Solorzano Pomachagua
Marvin Luis Blancas Diego
Deybi Maycol Huamanchahua Canchanya

Para optar el Título Profesional de
Ingeniero Mecatrónico

Huancayo, 2024

INFORME DE CONFORMIDAD DE ORIGINALIDAD DE TESIS: EN FORMATO ARTÍCULO CIENTÍFICO

A	**:**	Decano de la Facultad de Ingeniería
DE	**:**	Manuel Michael Beraún Espíritu Asesor de tesis en formato artículo científico
ASUNTO	**:**	Remito resultado de evaluación de originalidad de tesis en formato artículo científico
FECHA	**:**	28 de Febrero de 2024

Con sumo agrado me dirijo a vuestro despacho para saludarlo y en vista de haber sido designado asesor de la tesis en formato artículo científico titulada: "Design and Structural Analysis of a Maca Freeze-Dryer for the Peruvian High Andean Zones Using VDI 2221", perteneciente al/la/los/las estudiante(s) Beyker Jesus Quispe Aguirre, Karolina Vilma Solorzano Pomachagua y Marvin Luis Blancas Diego, de la E.A.P. de Ingeniería Mecatrónica; se procedió con la carga del documento a la plataforma "Turnitin" y se realizó la verificación completa de las coincidencias resaltadas por el software dando por resultado 10 % de similitud (informe adjunto) sin encontrarse hallazgos relacionados a plagio. Se utilizaron los siguientes filtros:

• Filtro de exclusión de bibliografía	SI	x	NO	
• Filtro de exclusión de grupos de palabras menores (Nº de palabras excluidas:)	SI		NO	x
• Exclusión de fuente por trabajo anterior del mismo estudiante	SI	x	NO	

En consecuencia, se determina que la tesis en formato artículo científico constituye un documento original al presentar similitud de otros autores (citas) por debajo del porcentaje establecido por la universidad.

Recae toda responsabilidad del contenido la tesis en formato artículo científico sobre el autor y asesor, en concordancia a los principios de legalidad, presunción de veracidad y simplicidad, expresados en el Reglamento del Registro Nacional de Trabajos de Investigación para optar grados académicos y títulos profesionales – RENATI y en la normative de la universidad.

Atentamente,

La firma del asesor obra en el archivo original

(No se muestra en este documento por estar expuesto a publicación)

DECLARACIÓN JURADA DE AUTORÍA

El presente documento tiene por finalidad declarar adecuada y explícitamente el aporte de cada estudiante en la elaboración del trabajo de investigación a ser utilizado para la sustentación de tesis: formato de artículo científico.

Título:
Design and Structural Analysis of a Maca Freeze-Dryer for the Peruvian High Andean Zones Using VDI 2221

URL / DOI:
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85156178214&doi=10.1109%2fICMEE56406.2022.10093296&partnerID=40&md5=e48385adc92a569125058b61804fc3d6 / 10.1109/ICMEE56406.2022.10093296

Yo: Beyker Jesús Quispe Aguirre, con Documento nacional de identidad (DNI) N° 70990875, teléfono 986197274, estudiante de la Escuela Académico Profesional de Ingeniería Mecatrónica.

Yo: Karolina Vilma Solorzano Pomachagua, con Documento nacional de identidad (DNI) N° 71999405, teléfono 960571348, estudiante de la Escuela Académico Profesional de Ingeniería Mecatrónica.

Yo: Marvin Luis Blancas Diego, con Documento nacional de identidad (DNI) N° 73007158, teléfono 957236441, estudiante de la Escuela Académico Profesional de Ingeniería Mecatrónica.

Yo: Deyby Maycol Huamanchahua Canchanya, con Documento nacional de identidad (DNI) N° 44878371, teléfono 992339449, exdocente de la Escuela Académico Profesional de Ingeniería Mecatrónica.

Ante Usted, con el debido respeto me presento y expongo:

Declaramos que hemos participado en la ideación del problema, recolección de datos, elaboración y aprobación final del artículo científico.

La firma del autor y del asesor obra en el archivo original
(No se muestra en este documento por estar expuesto a publicación)

REVISION PARA TESIS

ORIGINALITY REPORT

10%	6%	8%	1%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	pubs.rsc.org Internet Source	2%
2	Brajhan Tabra-Verastegui, Luis Casas-Dionisio, Deyby Huamanchahua. "Automated System of Pre-hispanic Camellones to Reduce Crop Damage Due to the Extreme Weather Event of Frost", 2022 International Conference on Mechanical Engineering and Power Engineering (MEPE), 2022 Publication	1%
3	repositorioinstitucional.uabc.mx Internet Source	1%
4	Sumiati, Eugenia Audrey, Agung Triayudi, Lia Kamelia. "Application of Certainty Factor Method to Diagnose Venereal Diseases Using Confusion Matrix for Multi-Class Classification", 2022 16th International Conference on Telecommunication Systems, Services, and Applications (TSSA), 2022 Publication	1%

www.science.gov

5	Internet Source	1%
6	A. Reyes, A. Mahn, P. Huenulaf. "Drying of Apple Slices in Atmospheric and Vacuum Freeze Dryer", Drying Technology, 2011 Publication	1%
7	mdpi.com Internet Source	1%
8	Sario Angel Chamorro Quijano, Jhon Stalin Figueroa Bados, Dominick Marco Cruz Esteban, Carlos Alberto Coaquira Rojo et al. "Design of an Automated Machine that Projects Ultraviolet Rays for the Safety of Food Products for Supermarkets", 2021 10th International Conference on Industrial Technology and Management (ICITM), 2021 Publication	<1%
9	Fijalkowska, Aleksandra, Małgorzata Nowacka, Artur Wiktor, Magdalena Sledz, and Dorota Witrowa-Rajchert. "Ultrasound as a Pretreatment Method to Improve Drying Kinetics and Sensory Properties of Dried Apple : Ultrasound Treatment before Drying", Journal of Food Process Engineering, 2015. Publication	<1%
10	Shiwei Zhang, Jun Liu. "Distribution of Vapor Pressure in the Vacuum Freeze-Drying	<1%

	Equipment", Mathematical Problems in Engineering, 2012 Publication	
11	ebin.pub Internet Source	<1 %
12	www.usfreeads.com Internet Source	<1 %
13	"Chapter 303248 Photography", Springer Science and Business Media LLC, 2023 Publication	<1 %
14	www.e3s-conferences.org Internet Source	<1 %
15	www.renrendoc.com Internet Source	<1 %

Exclude quotes On
Exclude bibliography On
Exclude matches Off

Design and Structural Analysis of a Maca Freeze-dryer for the Peruvian High Andean Zones using VDI 2221

Beyker Quispe
Faculty of Mechatronics Engineering
Universidad Continental
Huancayo, Peru
70990875@continental.edu.pe

Karolina Solorzano
Faculty of Mechatronics Engineering
Universidad Continental
Huancayo, Peru
71999405@continental.edu.pe

Marvin Blancas
Faculty of Mechatronics Engineering
Universidad Continental
Huancayo, Peru
73007158@continental.edu.pe

Deyby Huamanchahua
Faculty of Mechatronics Engineering
Universidad Continental
Huancayo, Peru
dhuamanchahua@continental.edu.pe

***Abstract*— In recent decades, the interest and demand for maca (Lepidium meyenii) have grown worldwide, establishing the tuber as one of Peru's flagship products, so adding value to it without losing its nutritional properties is a viable option to further increase its production and sale. Therefore, the most efficient process to consider is freeze-drying, which allows for preserving most of the organoleptic and nutritional properties of the food over time. The objective of this work is to design a compact and easy-to-use machine, which allows generating an added value to maca through freeze-drying. For this purpose, the VDI 2221 methodology was used, where a list of requirements was considered according to the structure of the freeze-dryer, a black box, and a white box, which led to making the morphological matrix from which the optimal 3D prototype was obtained. The result of this design showed that the machine provides 1 kg/batch of production and that the structure supported the size of the freeze dryer with a maximum deformation of 0.004491 mm, on the other hand, the part of the structure that supported the vacuum pump was prone to breakage. This research concludes that the use of the VDI 2221 methodology has the potential to structure the important functions and components for machine design, but another methodology is needed to help organize the processes systematically.**

Keywords*— *freeze-drying, VDI 2221, vacuum freeze drying, lyophilization, mechatronic design methodology, Lepidium meyenii

INTRODUCTION

Freeze drying is considered one of the best drying methods that largely preserves the organoleptic and nutritional properties of biological products. Freeze-dried foods are characterized by low water activity and high porosity [1], [2]; their advantages are that it reduces storage space, facilitate packaging and transport, and mainly increase shelf life [3].

Over the past few decades, interest and demand for maca have grown worldwide through aggressive commercial promotion of the plant [4]. This interest has established maca as one of Peru's flagship products. Peruvian maca (*Lepidium meyenii*) is rich in fiber and nutrients, including vitamin C, copper, and iron. In addition to these essential nutrients, this root contains bioactive compounds that are responsible for providing benefits to people seeking a healthy diet [5].

The agronomic management of the vegetative stage of maca consists of preparing the land, analyzing the soil characteristics, sowing, maintenance of the crop with cultural work, harvesting, and natural drying of the hypocotyls. Traditionally, the maca hypocotyls are consumed after cooking, and the active fraction is the aqueous phase, which causes a substantial loss of the above-mentioned benefits [5].

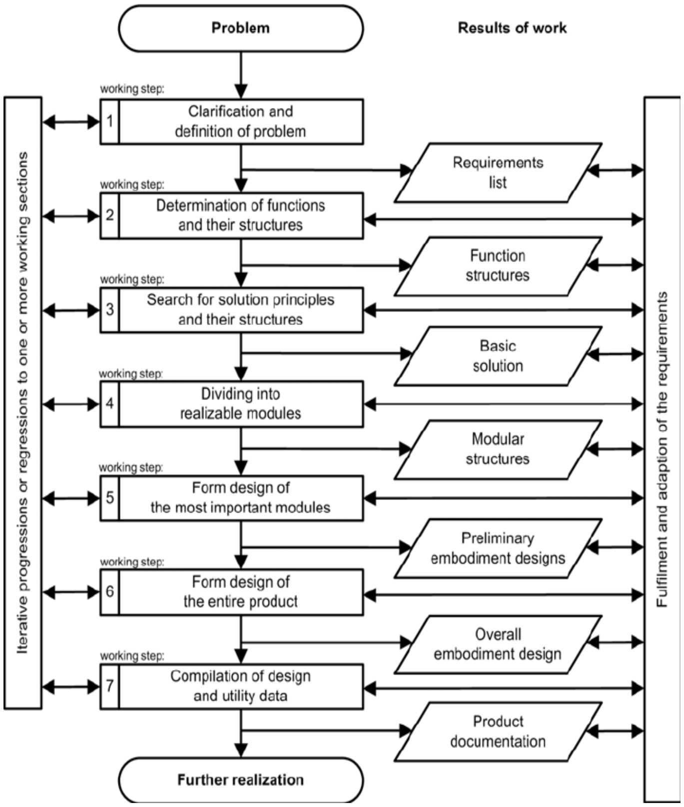
Some research talks about the design of freeze-drying machines that use vacuum systems to obtain better quality products and when reconstituted with water they recover their freshness [6], [7]. Other projects use ultrasound pretreatment of foods before going through the freeze-drying process, all these researches share similar ideas with this project [8]–[12].

On the contrary, there are also notorious differences with most of the mentioned works, among the main ones we can mention: the type of research methodology, the simulation of the prototype using software, and the drying technique, where the final result in moisture content is affected by the time of the drying process [13]. Likewise, it is shown that this process can damage the product due to the high use of temperature, the effects are visualized in the discoloration and the structure of the food [14].

The objective of this research is to present a conceptual design of a freeze-drying machine for maca slices, for which we will use the VDI 2221 methodology, which will help us to present a design according to the needs of the high Andean zones of Peru. On the other hand, to simulate the best design of the freeze-drying machine, Inventor software will be used in this investigation, which will provide us with a structural analysis of the prototype and stress analysis to reinforce the design.

METHODOLOGY

The VDI 2221 methodology is a design model for machine development, which follows a series of guidelines that lead to the generation of a product that meets specific requirements [15]. The stages of this methodology are shown in Fig. 1.



Research methodology VD1 2221

This German design model is based on the search for solutions that allow the development of a product that satisfies the needs required by society. [15]. Therefore, the conceptual design for this research will be developed following these procedures:

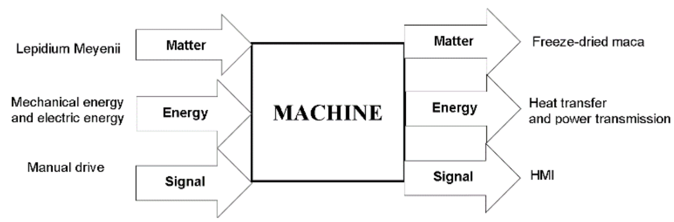
- Determination of the subject matter.
- Development of a list of requirements for the machine.
- Functional structure of the freeze dryer.
- The operation of the machine is represented in a Black Box and White Box.
- Realization of the morphological matrix.
- Optimal prototype choice.
- Description of the chosen prototype
- Creation of the 3D design.

To make the list of requirements of the freeze dryer, it is necessary to make a description of the tasks that allow the best operation according to a need. For this purpose, a table with three columns is developed. The first column is a series of parameters to describe the machine in detail. The second column presents the specifications of the parameters to describe the function of the machine. The last column stands for two options: desire (W) and requirement (R), which classify the parameters and specifications to obtain a specific design. Table I presents the list of requirements to develop the design for this proof of concept.

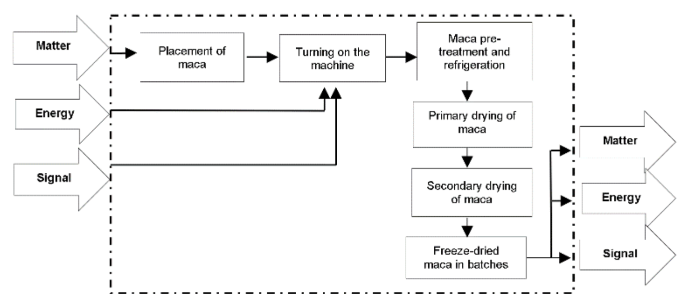
LIST OF REQUIREMENTS

Parameter	Specification	W/R
Function	Freeze-dry the maca in the shortest possible time and with the greatest possible dehydration.	R
Geometry	Total weight not more than 100 Kg	R
	The ability not less than 4 Kg/batch	W
	The largest dimension of 60x80x90 cm3	R
Material	Stainless steel	R
Assembly and fabrication	Easy to assemble and support machine	R
	Easy-to-understand part assembly system	R
Operation	The freeze dryer is easy to use.	W
	The machine is operated by a single operator	R
	Safe to use machine	R
Kinematics	Power requirement of 1000 W	W
Price	Total cost for the lower middle class	W
Security	Affordable repair	R
	Emergency system in case of failure	R
Ergonomics	Adequate machine height to avoid operator fatigue	W

The function structure allows one to know both in a general and specific way the procedure performed by the machine from the first stage to the final stage. Thus, a viable option to represent the machine processes is to generate a Black Box and a White Box [16] which are represented in Fig. 2.



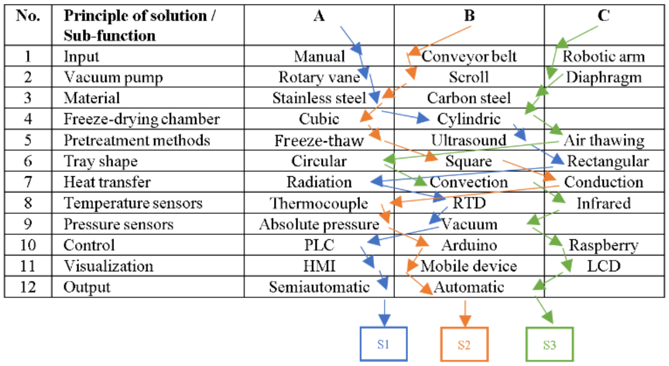
a)



b)

Black Box(a) and White Box(b)

The morphological matrix supplies the workable solutions to obtain the design that best fits a need, therefore, a set of functions that describe the machine as specifically as possible is organized. Finally, routes are drawn by choosing the most practical options, as shown in Table II.



No.	Principle of solution / Sub-function	A	B	C
1	Input	Manual	Conveyor belt	Robotic arm
2	Vacuum pump	Rotary vane	Scroll	Diaphragm
3	Material	Stainless steel	Carbon steel	
4	Freeze-drying chamber	Cubic	Cylindric	
5	Pretreatment methods	Freeze-thaw	Ultrasound	Air thawing
6	Tray shape	Circular	Square	Rectangular
7	Heat transfer	Radiation	Convection	Conduction
8	Temperature sensors	Thermocouple	RTD	Infrared
9	Pressure sensors	Absolute pressure	Vacuum	
10	Control	PLC	Arduino	Raspberry
11	Visualization	HMI	Mobile device	LCD
12	Output	Semiautomatic	Automatic	

Morphological Matrix

As a result of the morphological matrix, 3 possible solutions are obtained:

S1 or Solution 1: A1-A2-A3-B4-B5-C6-A7-B8-B9-A10-A11-A12

S2 or Solution 2: B1-B2-A3-A4-A5-B6-C7-A8-A9-B10-B11-B12

S3 or Solution 3: C1-C2-B3-B4-C5-A6-B7-C8-B9- C10-C11-B12

These 3 alternatives are subjected to a technical and economic evaluation process, represented in Table II and Table III respectively, to obtain the design of an optimal prototype.

TECHNICAL EVALUATION

List of workable solutions			Solution 1		Solution 2		Solution 3		Ideal solution	
No	*Evaluation criteria*	*g*	*p*	*gp*	*p*	*gp*	*p*	*gp*	*p*	*gp*
1	Function	8	3	24	4	32	2	16	4	32
2	Geometry	7	2	14	3	21	3	21	4	28
3	Design	8	3	24	3	24	3	24	4	32
4	Efficiency	9	2	18	3	27	2	18	4	36
5	Assembly	7	3	21	3	21	3	21	4	28
6	Stability	9	3	27	3	27	2	18	4	36
7	Operation	8	2	16	2	16	2	16	4	32
8	Maintenance	7	2	14	2	14	2	14	4	28
9	Ergonomics	8	3	24	3	24	3	24	4	32
10	Safety	9	2	18	3	27	2	18	4	36
∑gp			200		233		190		320	
x (%)			82.81%		8.,00%		73.44%		100%	

The data in Table II follow the evaluation criteria considering local issues. We have the variable p, which refers to an integer numerical value between 0 and 5, where the highest value is the level of satisfaction generated by the solution in the criterion associated with the variable p. The variable g stands for an integer numerical value between 0 and 10, where the higher the score, the greater the importance of the criterion related to that variable. The values of the variables are assigned according to the designer's criteria. Finally, there is the variable x, which is obtained by comparing the solutions with the ideal solution; these percentage values are found on the horizontal axis of Fig 4.

ECONOMIC EVALUATION

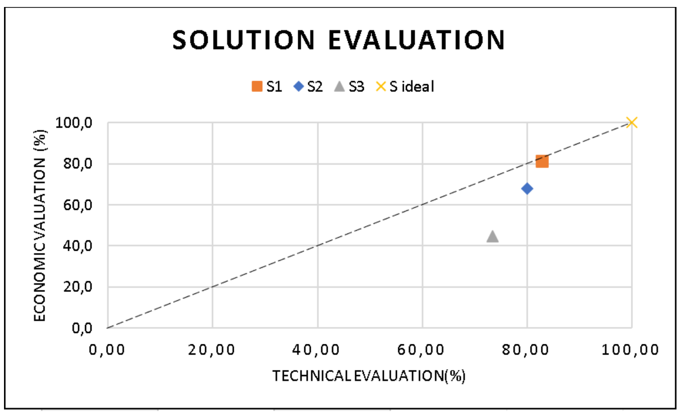
List of workable solutions			Solution 1		Solution 2		Solution 3		Ideal solution	
No.	*Evaluation criteria*	*g*	*p*	*gp*	*p*	*gp*	*p*	*gp*	*p*	*gp*
1	Manufacturing costs	8	3	24	4	32	2	16	4	32
2	Material costs	7	2	14	3	21	3	21	4	28
3	Assembly costs	8	3	24	3	24	3	24	4	32
4	Maintenance costs	10	2	20	3	30	2	20	4	40
∑gp			195		228		185		312	
y (%)			81.25%		67.97%		44.53%		100%	

The data in Table III follow the following evaluation criteria considering the local economy. The variables p and g follow the standards of Table II. Then, we have variable y, which is obtained by comparing the solutions with the ideal solution, these percentage values are found on the vertical axis of Fig. 4.

COMPARISON OF RATINGS

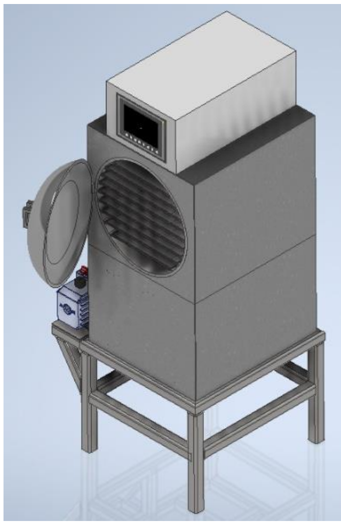
	The horizontal axis (x)	**The vertical axis (y)**
	Technical evaluation	*Economic evaluation*
Solution 1	82.81%	81.25%
Solution 2	80.00%	67.97%
Solution 3	73.44%	44.53%
Ideal solution	100%	100%

Table IV shows the comparison of the data obtained from the economic and technical evaluation tables, to obtain the best selection represented in the following figure.



Evaluation of solutions

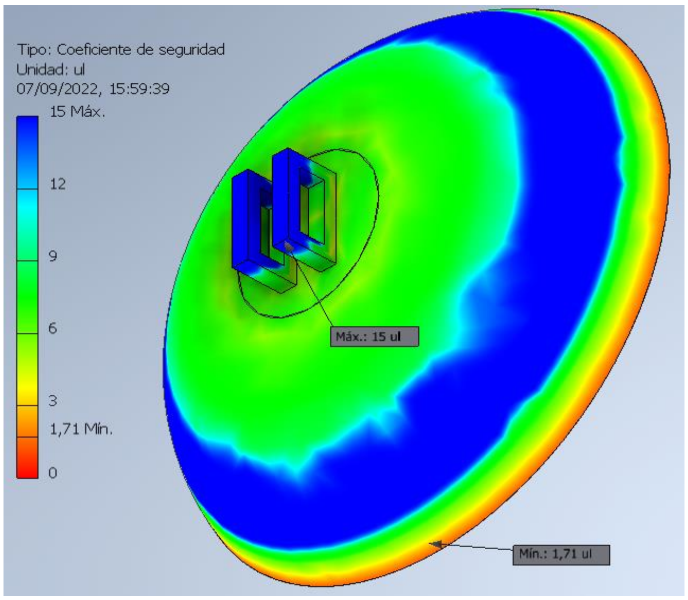
The results in Fig. 4 show that the optimal selection is solution 1, this design has a rectangular shape, which according to the list of requirements has the following dimensions: 600x800x900 mm3, the material that the freeze drying chamber has to have is stainless steel, the freeze-drying chamber has an ultrasonic pre-treatment, the vacuum system has a rotary vane pump, the shape of the trays for the maca slices are rectangular, the tray system has at its base direct contact resistors for the primary and secondary drying process, the machine will use temperature and pressure sensors, the control system is commanded by a PLC, the visualization of the operation will be shown in an HMI located in the upper part of the machine, the optimal design alternative is shown in Fig. 5.



Design of the prototype

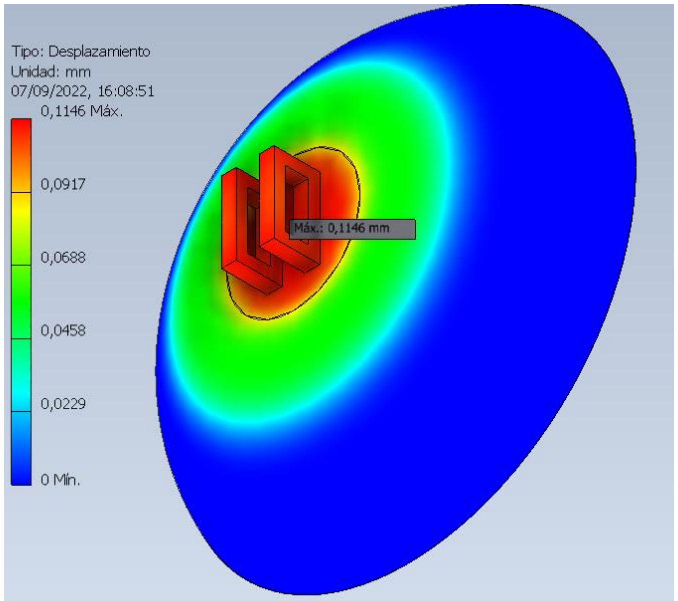
RESULTS

For the results, structure and stress analyses were performed. Fig. 6 shows a range of safety coefficients between 1.71 and 15, which shows that the stainless-steel material withstands the stresses that may be exerted on it during the operation of the machine. The most affected part is the contour of the lid because the forces are more concentrated in that area, therefore a safety factor of 1.7 is needed as shown in Fig. 6.



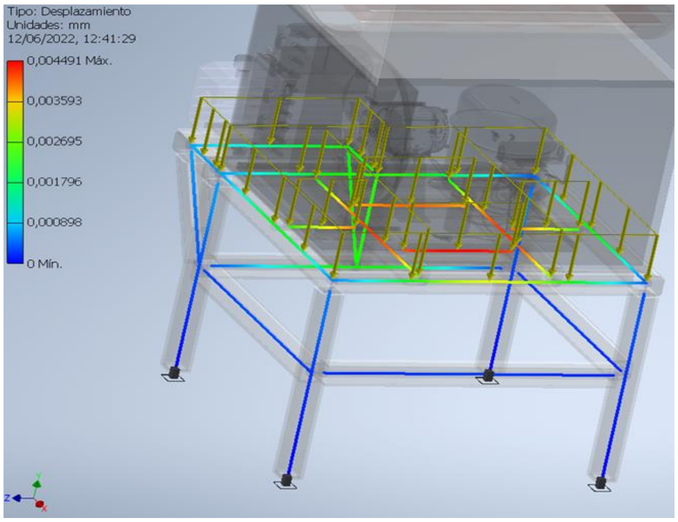
Stress analysis of the freeze-drying machine cover

On the other hand, Fig. 7 shows that the lid of the machine has a maximum displacement of 0.1146 mm in the central part, which shows that the deformation is not a problem to consider, this is because the displacement is too small to impair the operation of the freeze dryer.



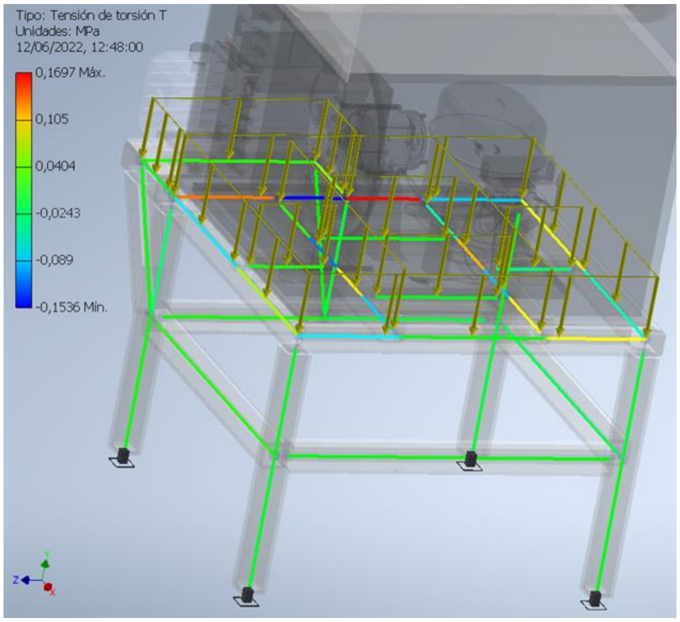
Maximum deformation of the machine cover

Another of the analyses performed is shown in Fig. 8, which shows that the structure supporting the machine has a deformation of 0.004491 mm in the central part, this is because most of the weight is concentrated in the geometric center of the cross-section of the base structure with an area of 460x520 mm2. On the other hand, the deformation obtained in Fig. 8 does not stand for any danger to the stability of the structure. The material used to conduct the tests on the structure is an ISO 657 quadrangular tube with a side of 40 mm and a thickness of 5 mm.



Structural analysis of the freeze dryer

From Fig. 9 it was obtained that the maximum torsional stress is 0.1697 MPa in the red zone of the structure, which stands for the position most affected by the weight of the machine, which is approximately 50 Kg.



Structural analysis of the freeze dryer

Next, a cylindrical shape was obtained for the freeze-drying chamber with the following measurements: 400 mm in diameter and 500 mm in height. The material used for the chamber is stainless steel, which is recommended for food processes [17]. The average production of this machine was 1 kg/batch considering that the average size of the maca was 5 cm in diameter and 6 cm in height.

Conclusions and Discusions

According to Chin Chi Cheng [8], the implementation of an ultrasound device in a freeze-drying process can generate energy savings because the ultrasound can record and analyze the whole progression of the freeze-drying process, in that sense, this project includes ultrasound transducers coupled in the freeze-drying chamber to try to reduce the energy cost of the machine.

According to Nachun Luo [18], to cut freeze-drying times, food should be cut into slices of suitable size and pre-treated with technologies such as ultrasound, which makes the food structure porous for efficient freeze-drying. This project attempts to use ultrasound treatment to reduce the freeze-drying time and energy cost of the machine.

In this work we have proposed a design of a freeze-drying machine with ultrasound pretreatment using VDI 2221 methodology to meet the needs of low production of maca in the high Andean zones of Peru. The proposed design has a height of 600x800x900 mm3, which has a base structure for the machine and for the vacuum pump, which is made of ISO 657 square steel tubes. The freeze dryer has a structure divided mainly into two parts: the freeze-drying chamber and the control system. The freeze-drying chamber is designed in stainless steel and is cylindrical in shape to withstand the different pressures. The chamber has a system of rectangular trays of different sizes with resistance filaments at their bases to aid in the evaporation process.

In the lower part of the freeze-drying chamber is the refrigeration and drying system, which has a refrigeration pump, a condenser, and a piping system. The control system is in the upper part of the machine, it has an HMI for the control of the whole freeze-drying process, it has a PLC that controls the temperature and pressure sensors. On the other hand, the machine has an ultrasound pretreatment to reduce the total freeze-drying time, the control system oversees controlling and monitoring the ultrasound transducers. Finally, this design tries to use all possible systems to save energy and reduce freeze-drying time, among the most important is the use of ultrasound for the pretreatment stage of the maca.

On the other hand, it is concluded that the VDI 2221 methodology used in this research adequately structured the most important functions, processes, and components for this design, but it needs a methodology that complements and systematically reinforces the thermal processes in the different stages of the freeze-drying process. Regarding the structural design of the machine, it is recommended to use square tubes of other dimensions to obtain a safety factor between 1.5 and 2.

For future research, take into consideration a compact piping design for the cooling and drying process. In addition, consider energy optimization in the different freeze-drying processes since these consume a considerable amount of energy. Finally, it is recommended the construction and sampling of freeze-dried maca for the verification of the design proposed by this research.

References

[1] N. Harnkarnsujarit, K. Kawai, M. Watanabe, and T. Suzuki, "Effects of freezing on microstructure and rehydration properties of freeze-dried soybean curd," *J. Food Eng.*, vol. 184, pp. 10–20, 2016.

[2] L. G. Marques, A. M. Silveira, and J. T. Freire, "Freeze-drying characteristics of tropical fruits," *Dry. Technol.*, vol. 24, no. 4, pp. 457–463, 2006.

[3] V. P. Oikonomopoulou, M. K. Krokida, and V. T. Karathanos, "The influence of freeze drying conditions on microstructural changes of food products," *Procedia Food Sci.*, vol. 1, no. Icef 11, pp. 647–654, 2011.

[4] M. Custodio, F. Huaraca-meza, H. De Cruz-solano, R. Peñaloza, and J. C. Alvarado-ibañez, "Scientia Agropecuaria Bacterial composition in maca (Lepidium meyenii Walp) crop soils analyzed by metagenomics : a study in the central Andes of Peru Composición bacteriana en suelos de cultivo de maca (Lepidium meyenii Walp)," vol. 12, no. 2, pp. 177–183, 2021.

[5] G. F. Gonzales, C. Gonzales, and C. Gonzales-Castañeda, "Lepidium meyenii (Maca): A plant from the highlands of Peru - From tradition to science," *Forsch. Komplementarmed.*, vol. 16, no. 6, pp. 373–380, 2009.

[6] T. Sesugh Solomon, D. M. Tiough, and T. U. Nwakonobi, "Design, Construction and Testing Of a Freeze Dryer for Vegetables," *Int. J. Eng. Sci. Invent.*, vol. 8, no. 8, pp. 1–05, 2019.

[7] F. Pei *et al.*, "Comparison of Freeze-Drying and Freeze-Drying Combined with Microwave Vacuum Drying Methods on Drying Kinetics and Rehydration Characteristics of Button Mushroom (Agaricus bisporus) Slices," *Food Bioprocess Technol.*, vol. 7, no. 6, pp. 1629–1639, 2014.

[8] C. C. Cheng, Y. H. Tseng, and S. C. Huang, "An innovative ultrasonic apparatus and technology for diagnosis of freeze-drying process," *Sensors (Switzerland)*, vol. 19, no. 9, 2019.

[9] J. J. Chen *et al.*, "Postharvest Ultrasound-Assisted Freeze-Thaw Pretreatment Improves the Drying Efficiency, Physicochemical

Properties, and Macamide Biosynthesis of Maca (Lepidium meyenii),” *J. Food Sci.*, vol. 83, no. 4, pp. 966–974, 2018.

[10] K. Schössler, H. Jäger, and D. Knorr, “Novel contact ultrasound system for the accelerated freeze-drying of vegetables,” *Innov. Food Sci. Emerg. Technol.*, vol. 16, pp. 113–120, 2012.

[11] A. Ciurzyńska and A. Lenart, “Freeze-drying - application in food processing and biotechnology - a review,” *Polish J. Food Nutr. Sci.*, vol. 61, no. 3, pp. 165–171, 2011.

[12] X. Xu *et al.*, “Ultrasound freeze-thawing style pretreatment to improve the efficiency of the vacuum freeze-drying of okra (Abelmoschus esculentus (L.) Moench) and the quality characteristics of the dried product,” *Ultrason. Sonochem.*, vol. 70, 2021.

[13] A. Reyes, A. Mahn, and P. Huenulaf, “Drying of apple slices in atmospheric and vacuum freeze dryer,” *Dry. Technol.*, vol. 29, no. 9, pp. 1076–1089, 2011.

[14] O. A. Caparino, J. Tang, C. I. Nindo, S. S. Sablani, J. R. Powers, and J. K. Fellman, “Effect of drying methods on the physical properties and microstructures of mango (Philippine ‘Carabao’ var.) powder,” *J. Food Eng.*, vol. 111, no. 1, pp. 135–148, 2012.

[15] J. Jänsch and H. Birkhofer, “The development of the guideline VDI 2221 - The change of direction,” *9th Int. Des. Conf. Des. 2006*, pp. 45–52, 2006.

[16] S. Nidhra, “Black Box and White Box Testing Techniques - A Literature Review,” *Int. J. Embed. Syst. Appl.*, vol. 2, no. 2, pp. 29–50, 2012.

[17] J. McQuilton, “Machinery and methods in freeze-drying,” *Empire’s Patriot. Fund*, vol. 172, pp. 29–39, 2017.

[18] N. Luo and H. Shu, “Analysis of Energy Saving during Food Freeze Drying,” *Procedia Eng.*, vol. 205, pp. 3763–3768, 2017.