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Design of an AS/RS machine for storage and extraction of items in a warehouse using Finite Element Analysis (FEA)

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ABSTRACT

The globalization of markets and high competitiveness impose new challenges every day on companies that develop their activities in the field of logistics, e-commerce, service, and product distribution. The implementation of automated systems becomes relevant when the objective is to increase productivity, efficiency and reduce costs associated with handling, picking and overhead. The AS / RS systems (i.e., Automated Storage and Retrieval System) are automated machines able to move in the 3 coordinate axes (x, y, z), which are responsible for arranging the items in large warehouses generating a decrease in time delivery and storage.

The aim of the article is to show the design of a prototype of an AS / RS (CAD) machine based on Finite Element Analysis (FEA) to verify the behavior before static loads according to Von Misses criteria and to guarantee the appropriate administration, storage, and extraction of each item in the warehouse, respectively. Also, it shows the use of the selection matrix that facilitates the interaction with the articles and executes the primary functions according to customer requirements. The result of this research shows the advantages and disadvantages of the implementation of these systems for companies that manage high volumes of storage, limited physical space and that require an appropriate management of the elements through the help of an easy-to-implement human-machine interface (HMI) that has control over open loop.

Keywords: Automated storage and retrieval system (AS/RS), warehousing, robotic systems, Finite Element Analysis (FEA).

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1. Introduction

The AS / RS systems are automated machines able to move in the 3 coordinate axes (x, y, z), which are responsible for arranging the items in large warehouses generating a decrease in time delivery and storage [1][2]. Commonly, AS/RSs are aisle-captive and can be able to manage horizonal and vertical movements simultaneously, using for example, Chebyshev movement patterns; this being its main characteristic that differentiates it from other vehicles that can be more flexible [3]. Also, these systems are considered good alternatives in logistics area given their precision, accuracy, and speed conditions [4][5][6]. On the other hand, the high cost of the implementation of AS/RS only make sense for high throughput operations [3] and capacity [7]. Simulations based on FLEXSIM Software can be carried out in order to model the entire complete system include on efficient storage location management [8][9] and analyze the dynamic behavior of the system [6][7][10]. Moreover, optimization process is essential to improve the requirements such as rack size, conveyors, storage assignment what are usual of the industrial operations [11].State the objectives of the work and provide an adequate background, relevant literature review but avoiding a detailed literature survey or a summary of the results.

In fact, developments, trends, and challenges should be focused on dynamic optimization using data analytics, recent technologies based on modular system analysis, human-machine interaction, and warehouse sustainability [6].

Clearly, a key task design is to respond to demand efficiently [12], considering the limitations of physical space in a warehouse [1][13]. Then, the physical design is related to system choice and configuration, respectively. Some criteria to make decisions about physical design of the AS/RS can be reported in Figure 1. In addition, control functions can be considered such as: storage assignment, batching, sequencing, and dwell point [1][14].

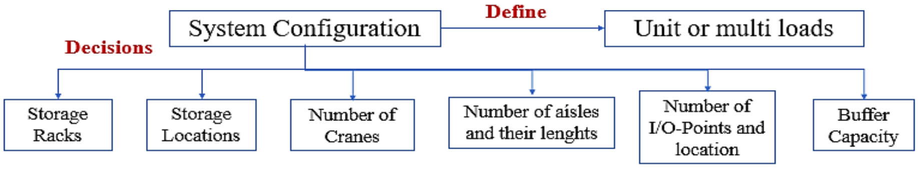

Figure 1. Decisions for AS/RS system configuration

Furthermore, there are several design methodologies for AS/RS systems. A Knowledge-based Engineering (i.e KBE) is a methodology used to size of the AS/RS components taking in to account the input data of users and loads, evaluation of the drivetrain power (i.e., traction and lift drive), dimensioning of beams, sheet metals, shafts among others [2]. As a result, the 2D- drawings, the bill of materials, documentation data for manufacturing.

Another approach to design storage facilities is SIMMAG3D [15] which simulation, visualization and evaluation is strongly related allows mapping of warehouse processes, to select technology, estimate the performance of the system and organize the schedule too.

Currently, Finite Element Analysis (FEA) provides a close prediction of the behavior of a body in real environments, even in the presence of disturbances of field, and forces, among others. Moreover, FEA give an approximate solution of partial differential equations that describe physical problems related to states (e.g., steady, and transient)[16]. Therefore, FEA allows to design the configuration of the AS/RS based on its behavior under static loads, scaling in a reliable way its components guaranteeing a more affordable cost[13]. Besides, to reliably size its components, guaranteeing a more affordable cost, FEA is the most important of the full process because it helps to define if the result of the complete system is optimal and meets the expected conditions or if on the contrary it is necessary to review the system again if the results are not as desired. This approach consists in: pre-processing, solution and post-processing [16]. FEA process is shown in Figure 2.

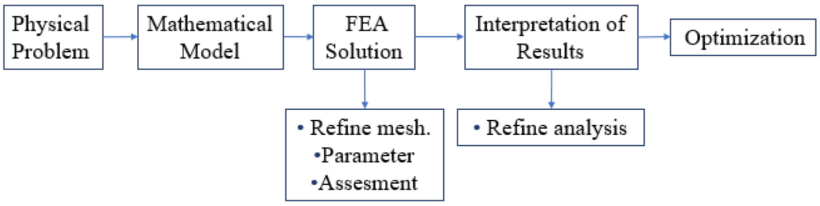

Figure 2. FEA process

Thus, the major advantage of FEA is accuracy level, facilities the critical variables analysis and increase the productivity and computational efficiency [14]. Particularly, in our case study, thanks to CAD such as SolidWorks, which was used to obtain important data in a conventional mechanical design such as deformation, Von Mises stress, among others. Similarly, in this work, FEA is used to check the mechanical resistance[17].Undoubtedly, the requirements for the AS/RS depend on the general environment of the system, especially, production schedule[1][13].

This paper describes the process design of physical/mechanical aspects of AS/RS prototype include requirements, qualities and advantages mainly focused on the automation of industrial warehouse facilities, as well as, to provide a framework and guidelines to manufacture and assembly these machines for many applications or cases.

2. Technical Specifications

2.1 Parameterization and fixed ítems definition

2.1.1 Rack

The rack has wide 0.92m by length 1.5m, the distance from the floor to the first platform is 0.5m with 0.3m of depth, each floor is separated by 0.3m and finally a space designated for the delivery of articles with the capacity to store 18 small boxes and 6 large boxes. The material is steel for its plates or base sheets and iron for the legs of the rack as shown in Figure 3.

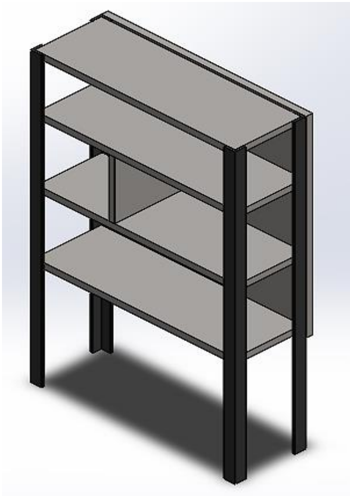

Figure 3. CAD rack view

2.1.2 Size of the articles

The rack includes components of different types with a maximum of 8x5x8cm in such a way that within a floor is have three articles per row and ten articles across the width, considering that the maximum weight of each box is 1 kg.

2.2 Mechanical requirements

Then, based on exhaustive research on different AS/RS machines or related systems such as CNC machines, it was found that not all machines operated with the same mechanisms and in the same way. Therefore, it is necessary to use a selection matrix for comparison and evaluation of all available systems that executes the same work and considerer of the criteria defined by the designer, to stablish the most optimal decision for the specific type of each component.

2.2.1 Load and Unload System

Firstly, it is necessary to define the system that will interact directly with the items in the warehouse, ending with the mechanism which will help generate movement in the 3 coordinate axes. So, for the purpose of the generation of bases with a groove in the lower part, a pallet-type actuator is chosen which is responsible for disposing of each item. Given this is the most common method to facilitate the loading and unloading of the AS / RS machine is proposed to a selection matrix as shows in Table. 1, considering its ease of coupling, low cost and integrity of the box that contains the components.

2.2.2 Final actuator

The final actuator must be able to have a maximum of three (3) items at the same time, therefore, the designed "pallet" will travel a maximum distance of 30cm. This movement will be carried out by a screw-nut system thanks to its great precision when taking the number of boxes that the operator requires to store or extract from the shelf, this means that it will travel distances of 10cm, 20 cm, and 30 cm respectively.

Table 1. Selection matrix for the loading and unloading system

FINAL ACTUATOR / Criteria		Electro-magnetic lock	Vacuum generator	Loading with pallets
Grip strength	3	9	9	9
Ease of coupling	4	3	1	9
Integrity of the box	5	3	3	9
Low cost	3	9	1	9
Final Value		81	49	135

2.2.3 Analysis of the AS/RS components

Once the components have been selected, proceed to verify that the system proposed in Figure. 4 can hold three boxes simultaneously which means one 1kg of weight. The pallets are simulated as a cantilever beam as shown in Figure.5, where “W" is the weight of the pallet and "Wc" the critical load that it must support.

After, shaft deformation analysis was carried out with two different materials (i.e., acrylic vs aluminum) to verify the behavior of each of them when subjected to the critical loads defined. In this case, the selection criteria of these two materials is the easy obtaining of them in the market and their relatively light weight.

To sum up, after performing the analyzes can concluded that the best material for the manufacturing of the pallets is aluminum, since the deformation is minimal, ideal for the system to operate correctly, as can be seen in Figure 6 and Figure 7, In Table 2, a summary of the results obtained is shown.

On the other hand, in the same way, is necessary to assess various materials for the manufacturing of a suitable base that can support the weight of the full system, plus the loads exerted by the items. The simulated weight being equal to 8.76 kgf added with the charges for a total of 12Kgf, at its most critical point (i.e., which is when the system is complete outside). As a result, Figure. 8 shows that the material is fitted with estructural characteristics required since it has a deformation of 1.092e+001 mm which is minimum with the maximum loads.

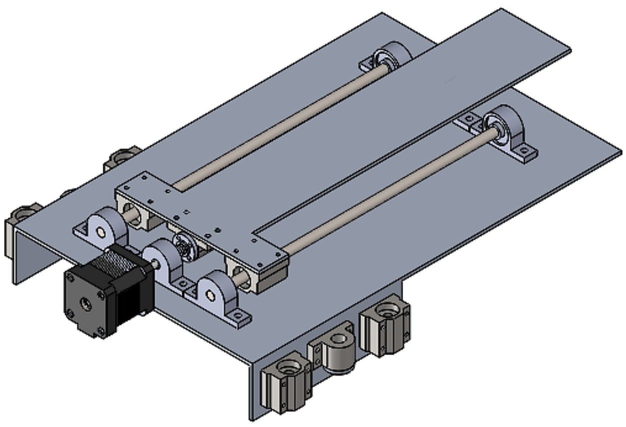

Figure 4. Shafts and support base set assembly view

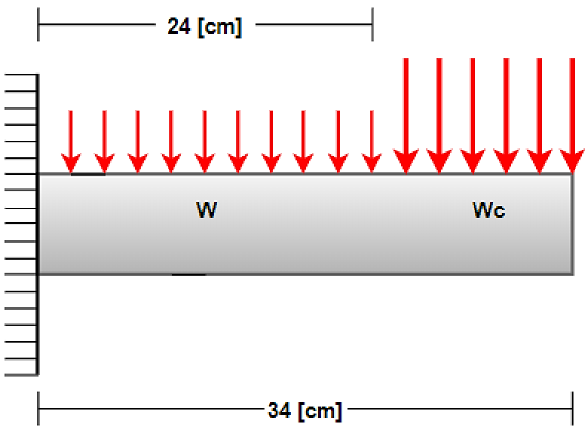

Figure 5. Free-body diagram of the base

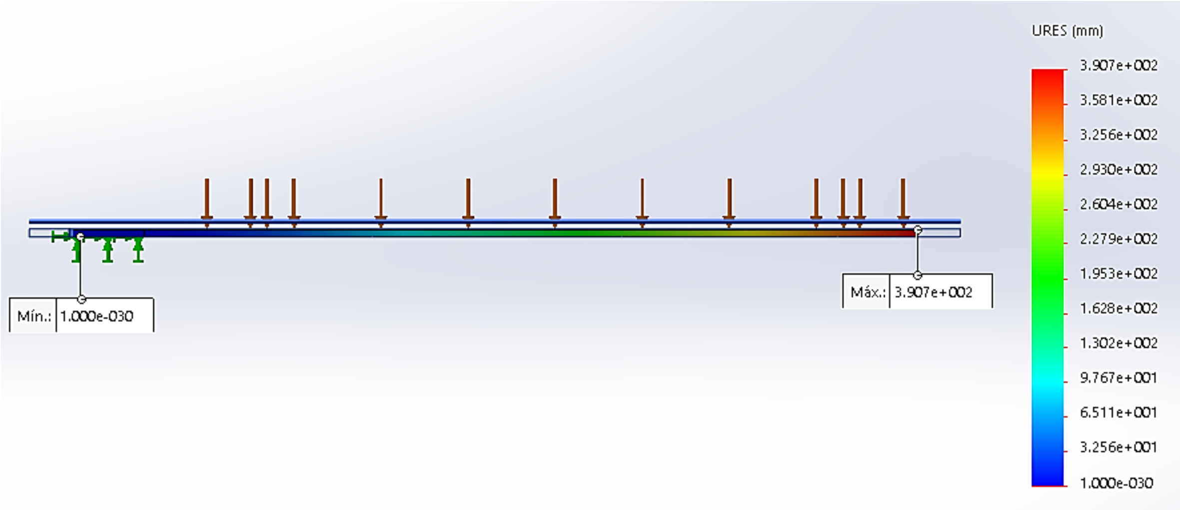

Figure 6. Acrylic deformation analysis

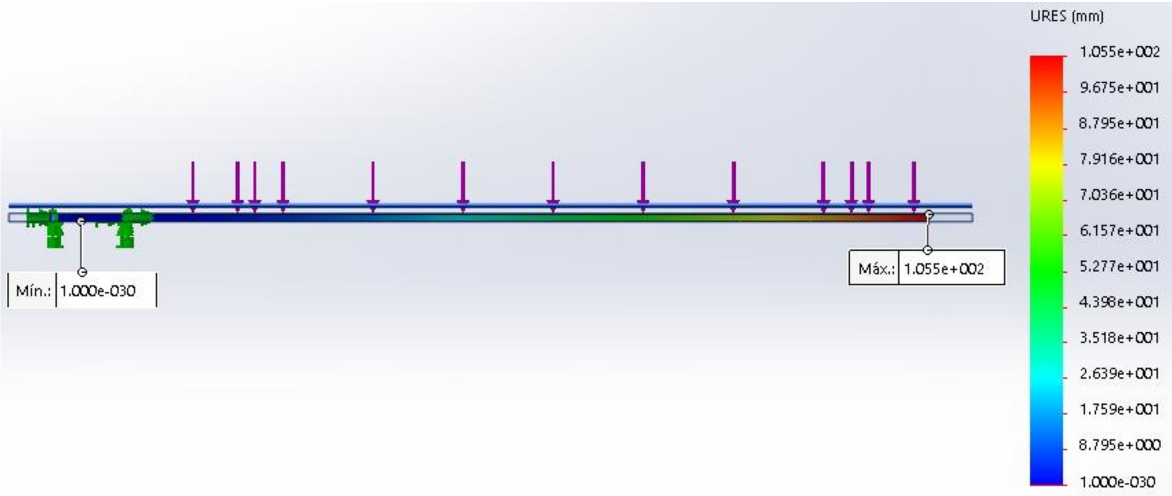

Figure 7 Aluminum deformation analysis

Table 2. Deformation data for the shafts

Material	Deformation [mm]
Acrylic	3.907e+002
Aluminum	1.055e+002

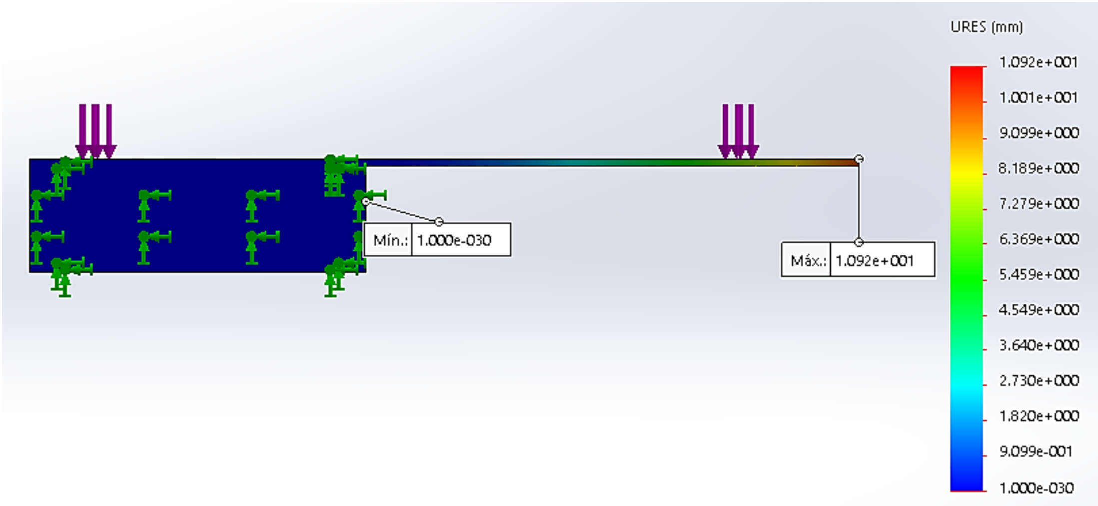

Figure 8. Analysis of support deformation

2.2.4 Drive train system

An AS / RS machine has a cartesian system with two axes that perform independent movements, one vertical and the other horizontal. However, there are different mechanisms that can generate movement to the machine, so, a selection matrix evaluation should be carried out as shown in Table 3.

Table 3. Matrix for drive train system assessment

MECHANISM		Endless screw	Pinion-rack	Belt pulleys
Criteria				
Velocity of displacement	3	3	3	3
Effort Need	2	9	3	3
Availability in the local market	3	9	3	9
Ease of coupling	4	9	3	3
Low cost	4	3	3	9
Final Value		102	48	90

The analysis shows us that the most convenient system for this project is the worm with nut, because its simplified system makes it light and easy to move by any type of motor, added to this in the local market we find spindles of different lengths and diameters, allowing in this way an easy coupling with the basically built system. In the market it will find the reference "trapezoidal threaded rod" with 8 mm diameter with thread.
The total torque required is obtained by adding the continuous torque (Tc) u the acceleration torque (Ta) [18]. A glossary of terms used for this calculation is shown in Table 4.

$$Tc = \frac{p * Fl}{2\pi\eta} \quad (1)$$

$$Ta = \left(J + \frac{m_{carga} * p^2}{\eta * 4\pi^2}\right) * \frac{\pi * n}{30 * t} \quad (2)$$

$$T = 55{,}95 + 5{,}48 = 61{,}44\ [N.mm] = 0.657\ [Kg.Cm]$$

Table 4. Glossary of terms used torque calculation

Data	Symbol
Efficiency	η
Thread pitch	p
Punctual force	Fl
Mass of the System	m
Inertia	J
Time that the movement takes	t

According to the actuators selection is decided to select a stepper motor 5.6 Kg.cm NEMA 17, both for the horizontal and vertical guidance since the torque that needs to exert the system with higher loads needs a motor of the smallest characteristics found in the market, therefore, the vertical axis will have the same NEMA engine. As mentioned above, the actuator that will generate the total movement of the machine on the 3 coordinate axes will be a stepper motor.
One of the most optimal and simplest ways to control a stepper motor is with a DRV8825, following the connection diagram of Figure. 9 for each of the motors which in total are three, one per coordinate axis.

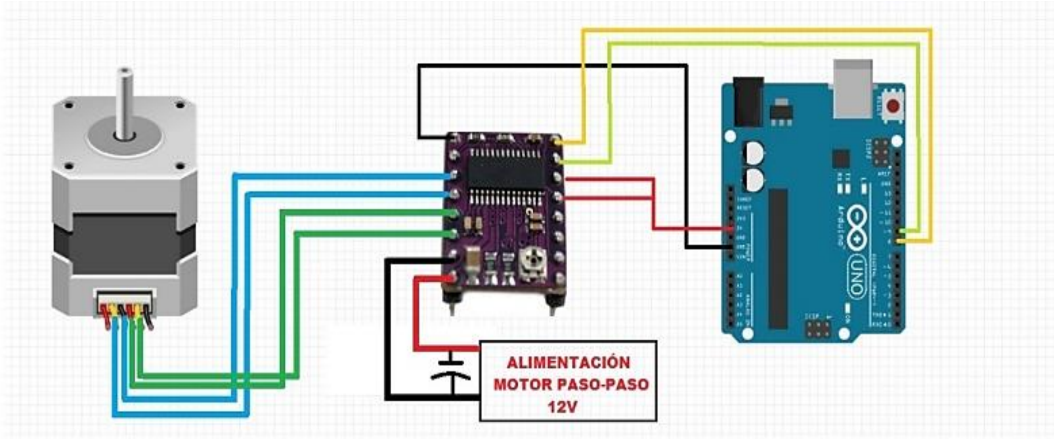

Figure 9. Schematic circuit integrating all systems

Also, it is important to clarify that the system does not have feedback that ensures the correct positioning of the machine, so it was used to select materials with minimal or minimal deformation ensuring good positioning in the coordinate axes and selecting an engine that is capable of move the whole system without landslides or energy losses.

2.2.5 Analysis of the bars on the x-axis

In order to minimize deflections, steel is selected as it is considered an optimal material to manufacture the shafts whose criterion is its modulus of elasticity (i.e., stiffness)[19]. Therefore, this approach was validated thanks to a static simulation (i.e., stress analysis) as illustrated in Figure. 10, based on FEA that with a maximum load of 16N (i.e., force exerted by the complete system), obtaining because of 3.795e-002 mm of deformation at its critical point that is half of the rods so this will be the maximum deformation that the system will have.
The calculation of the forces is necessary to ensure that the axes are not irreversibly deformed, for them we must know the tensile strength of the material or the admissible stress of the material, which for stainless steel AISI 201 has a value of $7.50x10^7 \left[\frac{N}{m^2}\right]$.

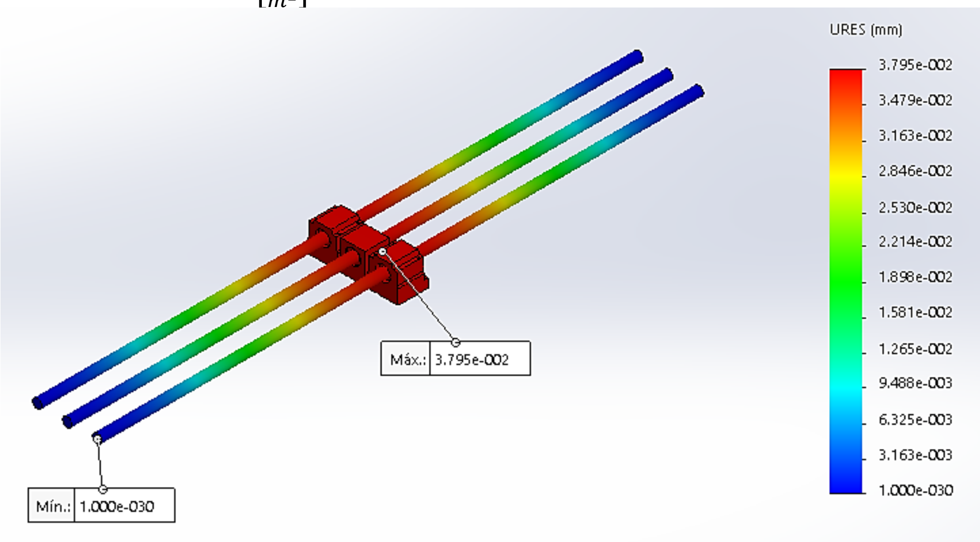

Figure 10. FEA stress analysis

So, to calculate the stress to which the material is subjected, the following equation is available:

$$\sigma = \frac{\frac{M}{I}}{c} \tag{3}$$

where M is the maximum moment in the axis, which is calculated with the help of Software MDSolid, modeling the axes as a beam (see Figure. 11) and applying a vertical load of 0.292044 [N] previously determined due to that is the sum of weights of the whole system, it obtain that the maximum moment is $0.07302\ \left[\frac{N}{m}\right]$ and where I / c is the modulus of resistance of the cross section, which changes according to the cross section of the Figure 10. For our case, due to given is a circular section the equation is given by the following equation:

$$S = \frac{\pi D^3}{32} \tag{4}$$

Replacing these values in the first equation, we obtain the result of the submitted stress:

$$\sigma = 1452683.35\ \left[\frac{N}{m^2}\right]$$

Finally, the stress submitted is much less than the admissible effort, this for our needs means that the diameter of the axes and the material of which they are constituted are adequate for the work carried out by the machine.

2.2.6 Analysis of the bars on the y-axis

Clearly, this study is a crucial task to determine if the bars that remain in motion of the machine buckle or deforms when loading with the components of the warehouse. Then, in a critical position where the buckling is the maximum possible, the extreme edge of the base where the spindle or power screw is fixed. The deformation or buckling of the vertical bars does not exceed $3.055x10^{-7}\ [mm]$. However, in practice the effect of the offset of the diameter of the bearings with respect to the diameter of the smooth rods causes a fall of the system and generates a greater friction in the system, for which the movement will be generated with greater difficulty. Therefore, to mitigate this friction by adding another support to the opposite side to guarantee the horizontality of the system as shown in Figure 12.
Finally, the x-y bars system will generate safety movement for the AS / RS machine as shown in Figure 13. For the anchoring of the whole system, steel plates resistant to the weight of the whole machine were considered together with a rectangular base which ensures that the whole system, despite the vibrations or the inertia of the movement, remains static. A view detailed (i.e., with support base and bearings) is illustrated in Figure 14.

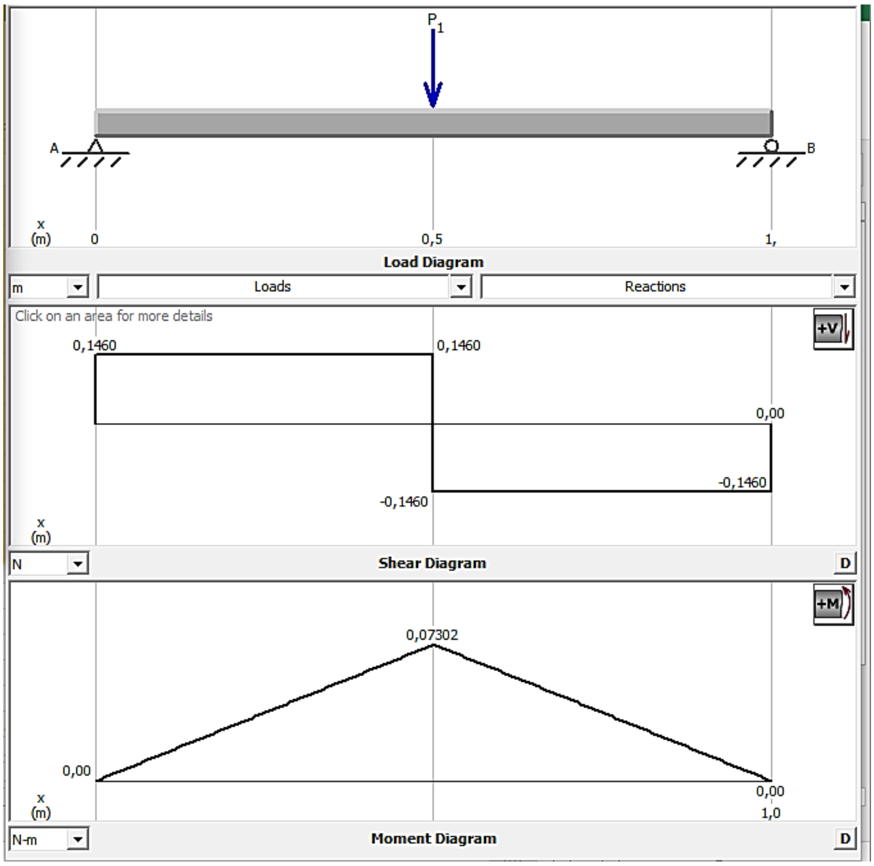

Figure 11. Bending analysis

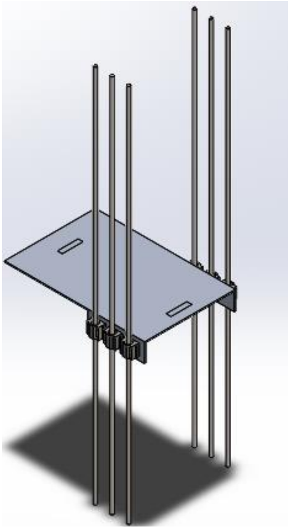

Figure 12. Deformation in vertical axis

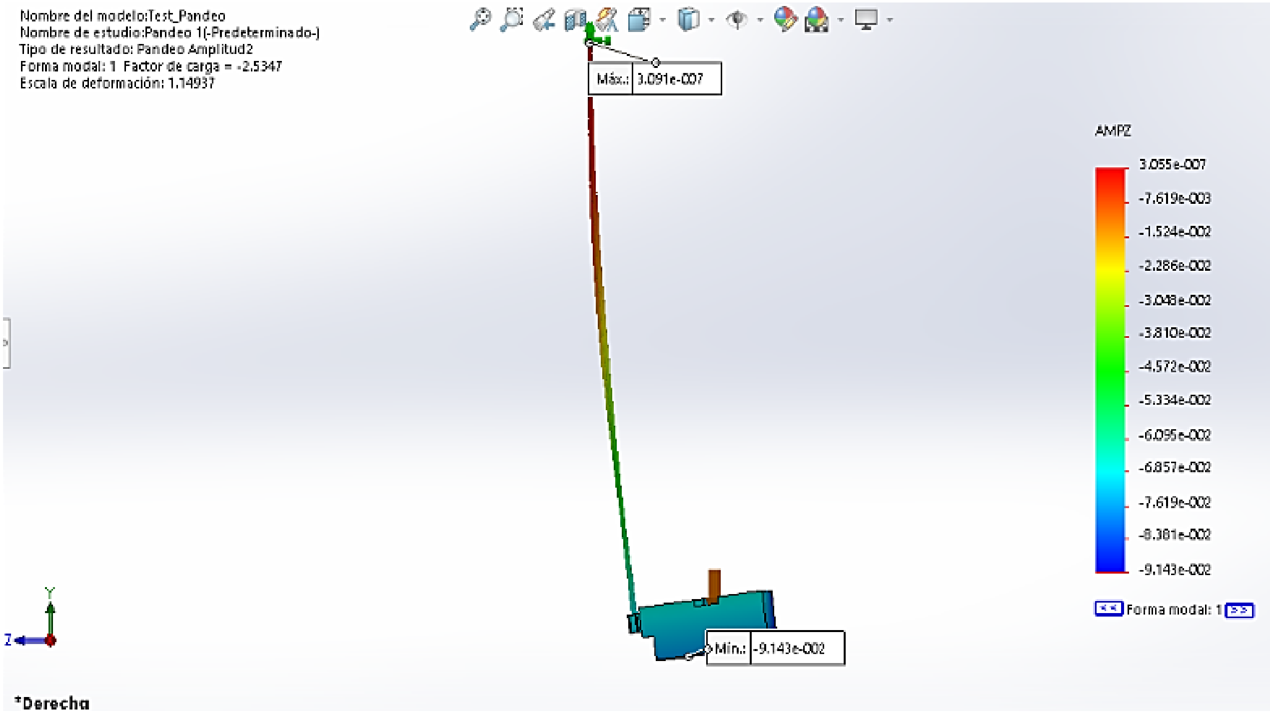

Figure 13. X-Y bar systems view

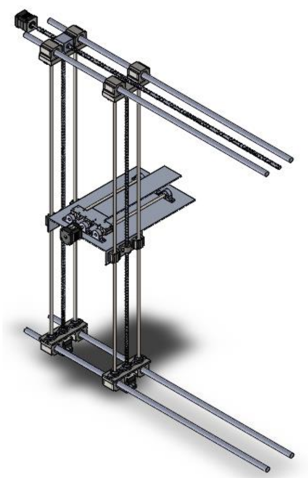

Figure 14. Internal assembly of AS/RS view

2.2.7 HMI Interface

For the user interface, we thought about a software which was able to interact with the database directly, in this case for the database it was decided to use Excel since it allows to store a large amount of both numerical and alphabetical data and the program that is able to interact with it is called Visual Basic for Applications (VBA), in which you can create macros that modify the data that exists in an-Excel sheet. The result can be seen in Figure 15.

An interface where you can add, modify and delete products from the database, see their characteristics such as: reference number, quantity in warehouse, position in warehouse and price. Besides, with a capacity to enter or extract three articles at the same time.

As a result of this work, the final prototype assembly is shown in Figure 16.

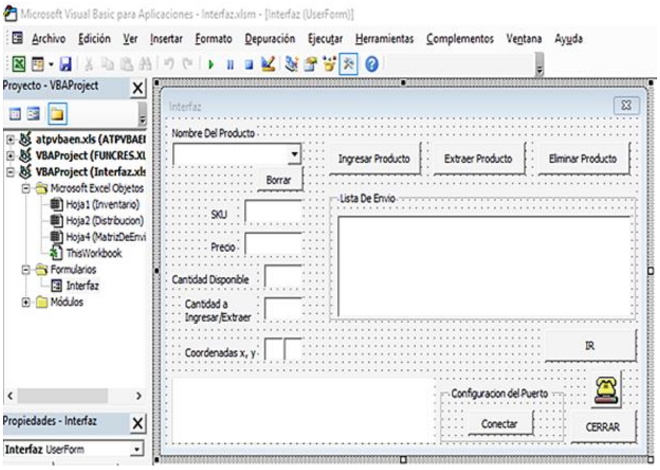

Figure 15. HMI interface

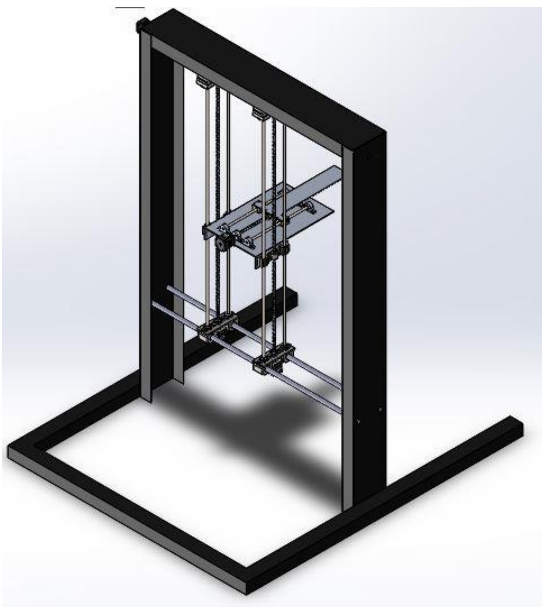

Figure 16. Mechanical design

3. Conclusions

The implementation of this kind of machines in modern industries which include a large number of finished products in their warehouses ready to be dispatched to the client turns out to be a necessity and a great help for the improvement of times and administration of items, which it was able to verify with the start-up of the prototype and the direct relationship with his database and the movement of the machine.

Besides, it is important to select the appropriate method for manufacturing and location of different systems that can execute the same work, establishing advantages and disadvantages according to various important criteria such as space, security and stiffness.
FEA analysis is one of the essential tools to guarantee the correct functioning of the system before building the physical prototype, improving the time and costs for the development of any project.

For future work, is recommended to carry out an close loop control system that guarantees in a more effective way the positioning of the machine at a millimeter scale by implementing sensors that allow achieving this objective.

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Conflict of interest

The authors declare that they have no conflict of interest, and all the authors agree to publish this paper under academic ethics.

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