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Concept and design of a positioning system for sensors in grain storages

MASTER THESIS

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Abstract

Grain storage techniques play an important role in the food supply chain when it comes to food waste. The project *BulkID* is being developed with the aim of controlling cereal spoilage while being stored, and the theoretical work in this thesis is carried out as part of it. This bulk monitoring is achieved with the help of spherical sensors, and the research goal of this study is to establish a reliable and efficient procedure for placing the rounded prototypes among stored grains. In this investigation, the location of the spheres is acutely studied, for the reason that the defined dispersion should fulfil the necessary conditions for an adequate monitoring.

An automatic design of an introduction system is developed, which enables the incorporation of the sensors into the bulk material. The proposed concept is designed considering the necessary requirements and constrains, followed by an evaluation of its hypothetical functioning.

A proper placement of the devices leads to a reliable monitoring of the products, and another aim of this thesis is to provide a suitable disposal of the spheres, after analysing their characteristics. This objective is achieved via computational programs that permit to simulate real situations. Different arranging methods are being compared in order to identify the most suitable dispersion for every case.

Declaration of Authenticity

“I, Iker Totorika, declare on my honour that I completed the Master thesis independently and used only these sources that are listed. All materials used, from published as well as unpublished sources, whether directly quoted or paraphrased, are duly reported. Furthermore, I declare that the Master thesis was not used for any other degree seeking purpose and the submitted work, or any abridgment of it, has not already been published”.

Stuttgart, 21.09.2022

Iker Totorika

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1. Introduction - Motivation

According to the UN, it is expected that the world's population will grow 0.98 percent yearly on average, increasing from 8 billion people in 2022 to 8.5 billion in 2030. The majority of humans get their energy, proteins, and minerals from cereal-based diets and it is necessary to meet the incrementing global demand of grains (Caballero et al., 2003). Millions of tons of food are not consumed by the population yearly due to the fact that it gets wasted in postharvest operations such as simple storing (Kumar & Kalita, 2017). In consequence, the technology focused on bulk storage control is a key aspect to be taken into consideration.

Generally, unfavourable conditions such as high moisture content and temperatures lead to mould expansion and pest infestation, causing cereal spoilage (Kristensen et al., n.d.). Apart from the environmental factors, the type of storage utilized, or the method employed also have a considerable effect on the food losses (Said & Pradhan, 2014). Approximately $1 trillion are lost every year and reducing these losses could easily improve farmers' economy (Gustavsson et al., 2011). If a quick detection is accomplished, tons of cereal grains could be saved. Therefore, the sooner these spoiled zones are detected, the better.

Grain spoilage is often being treated with hazardous chemicals that may be harmful to health. As an example, Phosphine is a common fumigate that in concentrations higher than 0.3 PPM becomes lethal for humans (Coggins & Pricipe, 1998). As an alternative to the application of these substances, new technologies are being developed based on wireless sensor networks. These are able to measure environmental parameters that can be representative for grain spoilage. The purpose of a precise monitoring is to detect spoiled areas of the bulk storage as soon as possible, preventing its rapid expansion.

The work of this master thesis is part of BulkID, a project developed by the Institute of Mechanical Handling and Logistic of the University of Stuttgart. It focuses on bulk storage monitoring for controlling the microbial spoilage, bacteria, mould, and pest infestations such as insects. Inspired by the method applied by intelligent containers used in unit load conveyor technology, the idea is to establish a connection between sensors for transferring information, enabling a wireless data exchange. The concept consists of introducing a bunch of spherical devices inside the bulk material while being able to communicate with each other. These sensors measure relevant parameters for the quality of the grain, and they manage to transmit the information to the outside in order to enable a real time monitoring of the cereal.

This research focuses, among other aspects, on the method of introducing the spheres into the grain. Considering the previously proposed solutions for this question, it is being suggested a theoretical alternative that meets all the hypothetical requirements and constraints for a proper placement of the spheres.

On the other hand, it is also being studied the different ways of distributing the devices inside the bulk. Depending on the characteristics of the bulk storage and the desired level of control over the risks generated by spoilage, different alternatives are being analysed and compared.

2. State of Art

There is a lack of literature related to placement techniques and distribution for sensors that deal with the monitoring of grains. In this section, the current solutions, information about the prototype and the available storing methods are being introduced.

2.1 Current solutions

It is always recommended to examine the stored bulk periodically for possible pest infestations or mould expansion. Historically, this have been achieved by visual and olfactory tests. Over the years, methods like examining grain samples have been carried out to detect early grain spoilage. However, new techniques have been developed against these laborious and slow procedures. Early spoilage detection, and thus, grain loss prevention, require quick and simple solutions (Maier et al., 2017).

There are various indicators of incipient cereal spoilage. Temperature, moisture and CO_2 concentration are the most representative measurable parameters that vary in presence of living organisms. Due to the expansion and breathing of these, the temperature and CO_2 concentration increase in the area, locating the first grains that are being spoiled. By implementing temperature sensors, it is possible to detect representative alterations inside the bulk. Nevertheless, due to the poor thermal diffusivity of the grain, it is not possible to detect temperature changes induced by infestation until the spoilage is a small distance away from the sensors. Therefore, it is logical to add CO_2 concentration sensors, as infestations can be detected farther away from the devices due to the capacity of CO_2 to flow with air currents (White et al., 1982).

An existing method for implementing these devices consists of hanging cables attached to the ceiling of the storage structure and distribute the sensors along these cables. This is a reliable solution for silo-type warehouses (Singh & Fielke, 2017), but it is assumed that it might not be appropriate for other storage methods such as outdoor grain storage or small-scale flat warehouses.

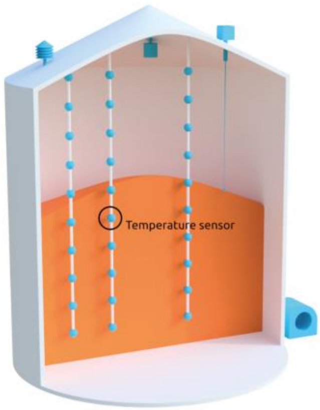

Figure 1 Silo-type storage with hangers [1]

Another actual technique applied in conventional square warehouses relies on grain monitoring probes which perforate the bulk. These probe-type instruments require a certain amount of time to take a measurement and they are settled manually, which may extend the operation time (Armstrong et al., 2017).

The current prototype developed for the project BulkID is built with the aim of meeting the requirements for an adequate monitoring and facing the inconveniences that the methods mentioned above might experience.

2.2 Current prototype

As mentioned, the technique employed consists of introducing a network of spherical sensors that measure environmental parameters representative for grain spoilage. These prototypes are 3D-printed spheres with a diameter of 80mm made of polylactide (PLA). Inside the outer structure, each device contains a temperature sensor and a CO_2 concentration sensor.

For a proper monitoring of the bulk, it is essential for the sensors to fulfil two functions. Firstly, they should operate properly and be able to measure the parameters mentioned with accuracy. And secondly, each sensor should be connected to others in order to enable the wireless information exchange. The sensors can be coupled to one or more devices at a time.

2.3 Storing methods, ZUTHER solution

Bulk materials such as grain require to be stored in order to equilibrate the difference of loading time between the arrival feed and consumption of the grains. As the outlet is much slower than the inlet, the storage of bulk materials is commonly managed by warehouses, piling them with the help of stackers. Their dimension is defined not only by the production capacity but also by feed and a reclaim processes (Droettboom, 2020).

There are two main types of structures used to store granular materials: flat storage buildings or silos. Cylindrical silos are one of the most common storage structures for grains in bulk. Nevertheless, other storage structures, such as flat storage buildings and rectangular temporary piles are also commonly used (Kutz, 2019).

As a reference for the whole development of the work in this thesis, a flat storage system designed by the company ZUTHER is being considered.

ZUTHER GmbH is a company for bulk material handling and provides solutions that adequate to the needs and requirements of the customer. Being infinite the variants of caring and manipulating the grains, it stands out for the design of flat storage systems, using the help of intake pits and loading processes.

Following the main goal of this thesis, in pursuance of considering a real and common solution for the bulk storage of cereals in big scale, a flat storage system from ZUTHER will be used as an existing example and reference. It proposes an automated solution for large storage volumes of grain accumulated in an enclosed space. This type of system provides great versatility compared to other techniques, as it consists of regular structures that can be accessed via large gates that enable the rapid loading and removal of the product (Zuther GmbH, 2022). These structures are normally rectangle-based warehouses covered with a gable roof, which allow to keep a convenient humidity and prevents living organisms from accessing and contaminating the grain (Chakraverty & Majumdar, 2010). In the following figure it is shown an example of a typical flat storage system. This one is located in Verona, North Dakota and has a capacity of 87.000 m^3.

Figure 2 Flat storage system in Verona, North Dakota [2]

Benefits from this solution include the possibility of storing a wide range of agricultural products, in variable size volumes according to the specifications needed and with the previously mentioned large gates for the access of the grain (Bühler Group, 2020). Furthermore, another advantage that it contains is that together with a proper conveying system, the entire volume of the warehouse can be exploited. Instead of storing the product via cone shape methods, this system allows to stack the solids in a more efficient manner, flattening the top of the bulk and providing a flat shape that is in line with the form of the structure. Therefore, the solution that ZUTHER proposes consists of a warehouse with the function of stockpiling the bulk material and a combination of transporting units that will handle the numerous procedures of the grain like loading, transportation, or expulsion.

In situations where the surface´s load-bearing capacity prevents the usage of round silos or where the elevation of the ceiling of the construction is restricted by the maximum permissible height for the surrounding buildings, these flat storage warehouses are a functional substitute for silo systems and a suitable way to store grains. Additionally, according to ZUTHER GmbH, it is also feasible and cost-effective to adapt any existing warehouse into an automated flat storage plant.

The following figure illustrates a complete example of the solution with all the essential components for the proposed technique.

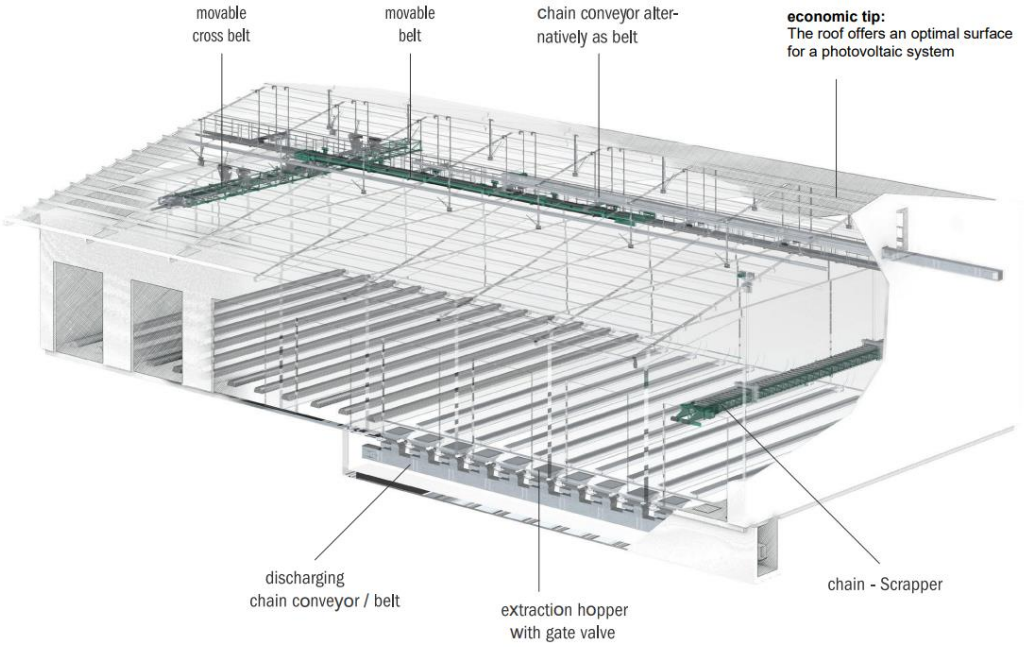

Figure 3 Flat Storage System [3]

The operation procedure of the plant is not very complicated. To understand it, the whole storing system can be divided in 3 parts, where in each of those sections there are some elements that carry out a specific task. These 3 processes are:

- Feeding by a Belt System.
- Conveying, filling and emptying by a Chain-Scrapper.
- Take-Out through Extraction Hopper.

Feeding

This is the entry of the grain into the warehouse, the procedure of filling the inner space of the plant. It is carried out by a set of conveyor belts that possess a high transfer capacity for long distances. A fixed belt, a longitudinal belt that may be moved underneath the fixed one, and a movable transverse belt complete this feeding device, which can be recognized in the *Figure 4*.

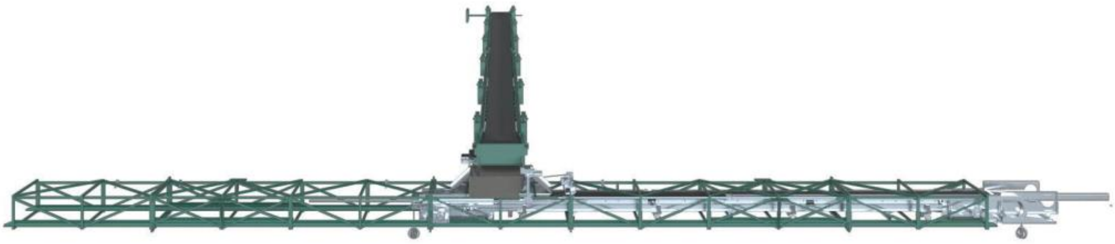

Figure 4 Feeding belts [4]

The bulk material enters through the fixed belt and with the help of the other 2 controllable conveyors, every point of the warehouse could be reached to unload the product. It has the capacity of feeding up to 1000 t/h.

Conveying, filling and emptying

Once the bulk material is loaded, a chain-scrapper manages to fulfil the operation of filling the whole flat storage plant and emptying it with flexibility. The device looks like the one in the *Figure 5*.

Figure 5 Chain-scrapper [5]

The chain-scrapper enables to employ these types of warehouses in a resource-saving and economical way. This is mostly because the scraper conveyor may be modified and adapted at different heights. As it can be seen in the *Figure* 3, it is able to advance along the whole longitudinal direction and push the grains in the transversal orientation once it is in contact with the bulk. This displacement will help firstly to compact the cereals and pack them orderly and secondly, it will be fundamental for the later take-out. Together with a feeding belt system, every point can be reached and occupied thanks to the scrapper. With the right intelligent control technology, the filling and emptying processes can be fully automated.

Take-Out

With the help of grids installed on the edges of the warehouse the grains can be taken out through intake pits. Thanks to the motion of the bulk caused by the chain-scrappers, the product is moved to the corners and due to the gravitational evacuation, the grains enter the grid and are removed using another installed conveyor underneath (see *Figure 6*). Once the grain reaches the evacuation belt it is easily extracted from the warehouse.

Figure 6 Take-Out grids [6]

In conclusion, this automated solution allows to have a high economic efficiency by using both the entire surface area and the entire volume of the warehouse and, therefore, it has been selected this system as an example for an automated storage system.

3. Introduction of the sensors

A stacking method has been established and described in the previous chapter. Now the prior challenge to be fulfilled focuses on the way of integrating the sensors inside the bulk. The manner of approaching this problem will be based on firstly, analysing the characteristics of flat storage system warehouse and the sensors to be placed, and, secondly, gather a list of requirements for a proper placing for a good monitoring. Afterwards, the methodology corresponding to the design of the proposed solution is being described, followed by a theoretical evaluation of the result obtained. All the 3D models developed for the solution and shown in the figures have been drawn with *Autodesk Inventor*.

2.4 Description and characteristics of the problem

It is considered a rectangle plant warehouse with gable roof as the system for storing the bulk material. As mentioned, due to the operation of the conveying belts and chain-scrapper, the grains are evenly stacked among the volume of the warehouse. The *Figure 7* shows the designed reference.

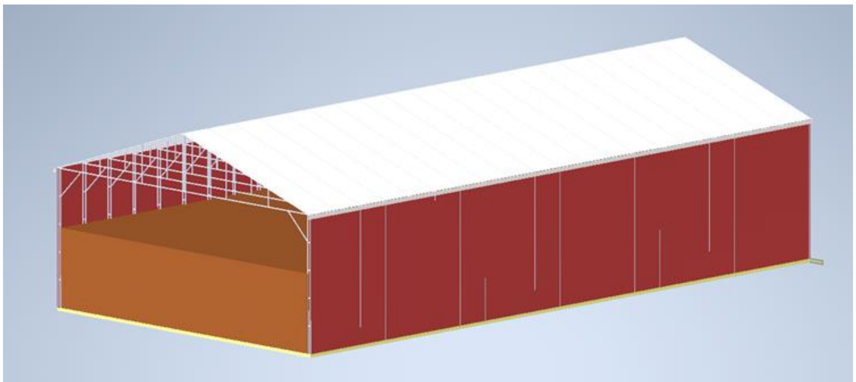

Figure 7 Reference for rectangle plant warehouse

Before proposing a reliable alternative for the procedure of the integration, some assumptions and characteristics are taken into account to simplify and represent the case. These statements and suppositions will help to provide a context for the initial status and will facilitate the later approach to the problem.

- The plant of the warehouse is a rectangle with a longitudinal and transversal dimension. The size of the industrial plant always depends on the volume to be stored. The bigger the quantity of grain, the greater will be the volume needed to cover it. Both longitudinal and transversal dimensions are variables that can be modified to fulfil the required volume. Of course, always maintaining the rectangular form. Later, these two adjustable variables will be helpful to understand the monitoring of the granular material in different cases.

- The stocked grains will be studied as a rectangular parallelepiped. The geometry of the bulk adopts the shape of the warehouse itself. Furthermore, due to the activity of the chain-scrapper, the upper surface can be considered as completely flat. Thus, the whole volume of grain can be calculated with the dimension of the plant and a value for the height.
- The ceiling of the warehouse is high enough and it is prepared to support structures and devices for the conveying of the grain. The feeding, conveying and emptying procedures are carried out by belts that are installed above the product, right under the ceiling. This area is equipped and reinforced to withstand these elements, and if necessary, to support any additional device for storing the sensors.
- The presence of the sensors introduced is negligible inside the grain. The space that the spheres occupy compared to the whole bulks volume is insignificant and will not influence its form at all, maintaining the parallelepiped shape.
- The diameter of the spherical sensors could vary from 70mm to 90mm. As the design of the spheres is still in development, the size of the spherical cover could vary. The designed solution should be able to adapt to the different values of the diameter between the range that was just mentioned. The current standard diameter is of 80mm, therefore, the solution proposed will be developed with that dimension.
- All the sensors are exactly the same. They share the same structure, volume and shape. This spherical shape can be advantageous when designing a solution.
- Each sensor will be considered as a rigid and individual solid. This surface structure is made of 3D-printed PLA for the prototype, therefore, secures the inner elements of the sphere, protecting them when it bears high tensions created by the weight of the bulk material. It is also resistant even in cases of dropping the devices from a considerable height.
- The range of the sensors depends on the type of grain. This means that the capacity of a single sphere to communicate with the others hinges on the media in which they are disposed. To have an idea, it is assumed that the range of a sensor is represented by a hypothetical sphere with a radius of 5m (after some experiments). In pursuance of a good communication, the neighbouring spheres should be placed somewhere in a distance smaller than 5m.

Figure 8 Current prototype of the sensor

2.5 General requirements for the placing of sensors for a good monitoring

- There should not be, in any case, more than 5m between the sensors after the placement (distance constraint for an adequate monitoring ruled by the communication range of the sensors). The closer they are placed, the more robust the solution will be. This would also require a larger number of devices that involves a larger financial effort. It is desirable to establish a number of sensors that is optimal according to some measures like network robustness, financial efforts etc. So, as mentioned, the type of grain will have a significant impact on the number of sensors that will be needed for an adequate measurement and supervision. In consequence, a flexible solution should be proposed, one that could be able to handle different type of cereals and support diverse quantities of measuring instruments.
- Optimal placement of the spheres is required in order to not lose efficiency of the connectivity between them. When introducing the devices into the bulk, there should not be a huge error between the calculated position and the real location where it lands. If considerable errors take place, the gap between the devices would increase and hence risks communication failures. This would lead to a poorer perception of the environment that is obviously not desired. The proposed method must be accurate, being able to drop the spheres with limited displacement errors.
- It is expected to be able to measure the whole volume of the bulk in a regular way. The measurement range of the sensor is considerably small, a few centimetres at best. Every point of the stocked amount should not be further than a certain given distance from the closest sensor. There are some points of the warehouse less accessible than others and hence more difficult to approach. The suggested system must be able to reach all the area of the warehouse, guaranteeing that it is possible to drop a sensor at any place precisely.
- It has been previously specified that the number of spheres needed is variable. This number will vary depending on aspects like the range capacity (directly related to the type of grain), bulk material quantity (how much grain is going to be stored), distribution of the spheres (the way they are disposed on the warehouse) or robustness (what density of sensor/quantity of grain is the desired). Sensor storage capacity must be a fundamental aspect for the approach of this procedure of integration.
- It should be contemplated not only the introduction of sensors but also the extraction of these.
- The selected solution should be as little intrusive as possible. This means that if additional elements or devices are added to the warehouse, these must not be very bulky and cannot have a big effect on the general structure. If possible, have minimal impact on the filling or emptying operations.
- As any other process, a minimum level of effectiveness, rigour and rapid functioning is a strict requisite. Low release times of the spheres would be recommended for an agiler procedure.
- Of course, the solution designed should be economical.

After contemplating all the listed specifications, the goal is to reach the following situation showed in the *Figure 9* and meet all the requirements thoroughly.

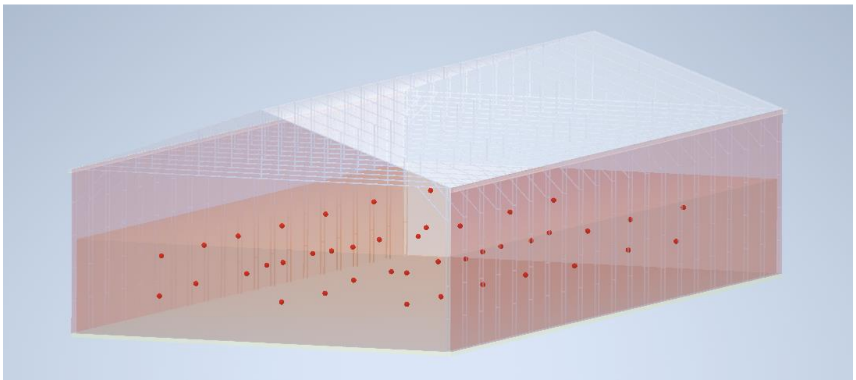

Figure 9 Reference for rectangular plant with sensors

2.6 Alternatives for the introduction method

The sensors are directly introduced in the grain, efficiently distributed. The previous illustration is just a model to picture the desired situation, the number of spheres needed to monitor that volume of bulk material and the proportions have no relevance at all. The challenge now goes in the direction of trying to achieve the conditions of the image. There were two possible alternatives contemplated. The first one would be to proceed with the drop of the spheres while the procedure of filling the warehouse is happening. The other solution would consider the introduction of the sensors once the plant is completely full and insert them in the desired point.

- **Introduction of the sensors while filling the warehouse:** this alternative could be carried out manually as well as automatically, dropping the sensors together with the feeding inlet stream. As the size of the measuring devices is not massive, it would be possible to take advantage of the filling procedure via conveyor belts to create an entrance to the plant. It would be a simple process to accomplish or calculate and would not add a lot of operating time to the whole system. The only inconveniences may appear regarding the accuracy of the position of the sensors, as the grain is still in motion during the feeding process.
- **Introduction of the sensors after filling the warehouse:** once the bulk material is completely static and stocked, the idea is to introduce the sensors with the help of a device that could handle the action of "injecting" them into the grains. The accuracy of this alternative is excellent, but it should also consider the complexity of it and the necessary time that would be needed to fulfil it, which would increase the general operating time of the system.

In the following *Table 1* it is displayed a table representing a comparison of the 2 cases. On the left column the 5 most important aspects to be valued are written and then, to examine which of the solution satisfies it better, it is represented with a tick.

TYPES	Inroduction DURING the filling	Inroduction AFTER the filling
Distribution and placement time	✓	
Accuracy		✓
Solution difficulty	✓	
Cost	✓	
Flexibility	✓	

Table 1 Comparison between introducing method alternatives

It is concluded that an introduction of the spheres during the filling operation looks like the more adequate option, due to appropriateness in most of the aspects being studied. However, there is still a lot to figure out in contemplation of giving a full and reliable development.

As previously mentioned, this insertion can be accomplished manually or via an automatic device that disposes a sensor at a time. In the following lines, both considerations are briefly studied and compared through advantages and disadvantages.

Manual introduction

A worker/operator stays on the fixed belt and drops a sphere from time to time manually.

Advantages	Disadvantages
✓ Cheap. ✓ Simple. ✓ Immediate response from the operator if anything does not go as expected.	x Bad accuracy: the sphere is dropped by an employee. x Not automatic: a human tends to fail more than an automatic mechanism. x Need of a worker.

Table 2 Advantages and disadvantages of the manual introduction

Automatic introduction

As the filling and emptying procedures of a grain storage can be automated with the appropriate intelligent control technology, the introduction of sensors could be also automatized. Taking a flat storage system as a reference and reliable solution, an automatic mechanism could be designed to release a sphere from time to time in a controlled way. The machine could store several sensors and drop them every time it is necessary. It should be easy to control.

Advantages	Disadvantages
✓ Automatic, no need of a worker. ✓ Not very expensive. ✓ More accurate than the manual when placing the sensor.	x More complex compared to the manual option. x Not an immediate response if anything does not go as expected. x Not as cheap as manual introduction.

Table 3 Advantages and disadvantages of the automatic introduction

After contemplating the two options, it looks like the introduction via a machine makes more sense. Therefore, is decided that the automatic form would be more competent and challenging for this master thesis.

Being clear which is the direction that the solution must take, the objective is to give a valid proposal of an automatic sensor dispenser machine. In the following section it is given the details of the design project.

2.7 Methodology corresponding to the proposed design

The flat storage system in a warehouse operates with a completely automated process of filling, stacking, and emptying of the grain. To maintain this form of performing, the insertion of the sensors that are responsible for the monitoring should be carried out without the help of any worker. The design of a mechanism with intelligent control technology will provide a solution proposal able to drop a sphere in the feeding stream every time is required, working exactly like a sensor dispenser machine.

To organize the development of the design, it has been established a number of steps prior to the final product. These steps are summarized in listing the requirements, brainstorming, sketching, drawing and assembling the parts, culminating with the creation of the 2Ds for the manufacturing of the machine.

2.7.1 Objectives to be fulfilled (requirements/constraints)

Apart from the *General requirements for the placing of sensors for a good monitoring*

for the placing of sensors for a good monitoring previously mentioned, there are other specific constraints that the machine should fulfil:

- Automatic. Just like the whole system, no operator is needed.
- Adaptive to different diameters of spheres (70-90mm). The diameter of the spheres may vary with later developments. Thus, the machine should be able to perform with various sizes.
- Release time: 2-3s (until is placed). This value is only an estimation. The operating time of the device should be short, enabling more flexibility for the sphere distribution. The shorter the time between tow dispenses, the closer the sensors will be located.
- Must fit the maximum dimensions of 70cm wide, 70cm deep, 100cm high. These dimensions are also guiding values. As the space in the upper part of the warehouse is limited (next to the fixed inlet conveyor belt), the apparatus cannot be massive. Its weight should be another point to bear in mind.
- Must be able to store up to 150 units. The number of spheres needed for the measurements will depend on the quantity of grain to be stored. As a quick estimation, for a proper monitoring of 1000m^3 of cereal, at least 64 sensors will be needed. This calculation is based on the approximations developed in forthcoming chapters.

- Reliable operation. The sensors should not get stuck in the machine, and they should be released only one at a time.
- Simple mechanism.
- Easy to manufacture.
- Easy to reload. It should be accessible to put the spheres back in the device.
- Easy to control.
- Must be durable.

2.7.2 Brainstorming ideas

The concept of the storage-dispenser machine can be inspired by a typical and quite recognizable example: a gum dispenser machine. This traditional and reliable design basically consists of a manual mechanism that dispenses a spherical gum when the turn handle is rotated. This machine could be divided in 2 main parts: gum bin (for storage) and dispenser mechanism.

Figure 10 Gum dispenser machine [7]

The main ideas obtained from this reference are the following ones:

- ✓ The use of a rotating movement as an actuator for the later release of the sphere.
- ✓ Optimal use of volume for storage and proper design against possible clog or blocking of the spheres.
- ✓ Many different mechanisms can be used as an inspiration for the sensor dispenser.

It is wanted to improve this design and make it more suitable for the displacement of the sensors. Therefore, the idea is to design an automatic machine instead of a completely manual one. To achieve this, a servomotor can be used as an actuator for a mechanism that would be controlled. In conclusion, the machine will be divided in the elements shown in the *Figure 11*:

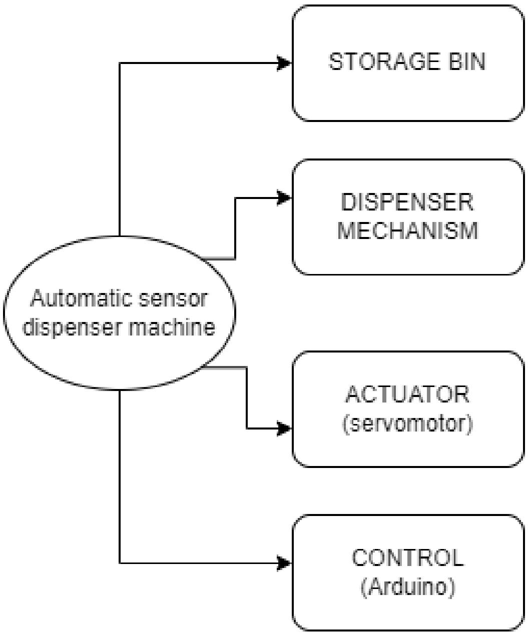

Figure 11 Parts of the sensor dispenser machine

With all the parts being defined, the development of the solution is being described in the following lines. The concept of the elements mentioned in the figure above is defined, together with the drawings and the assembly of the parts.

2.7.3 Storage bin

The simplest and optimal idea that comes to mind is a storage that uses its form to displace the balls. Due to the gravity and the spherical form of the sensors, they roll down and are displaced without any external force. The concept is schematically described in the *Figure 12*.

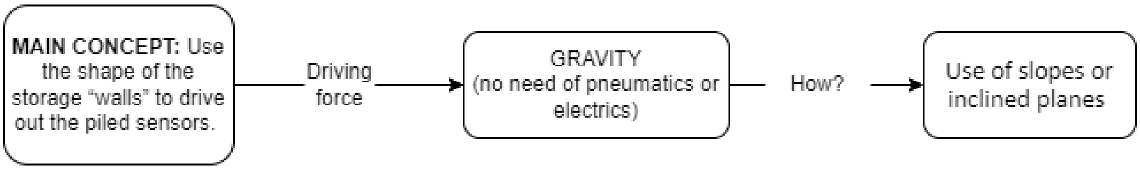

Figure 12 Schematic concept of the storage bin

These is the theoretical list of requirements and functions assumed that should be fulfilled by the storage bin:

- Dimension constrains depending on the position of the machine (approximately 70cm x 70cm x 100cm).
- Proper shape for smooth movement of the sensors avoiding their blocking.
- Capable of storing up to 150 sensors.
- Relatively light.
- Compact.
- Easy to refill.

As a result of analysing the mentioned list of constraints, basic examples and first sketches are developed for the bins. The following options are basic draws developed as representative models for different alternatives that fulfil the same function.

Prism with inclined planes

This is a simple proposition that is based on a storage box with straight and inclined surfaces. It could be designed with one or more outlets so it can drop more than one sensor at a time. There is also the possibility of a thinner body that would minimize the sphere blocking. Three different alternatives are shown in the *Figure 13*.

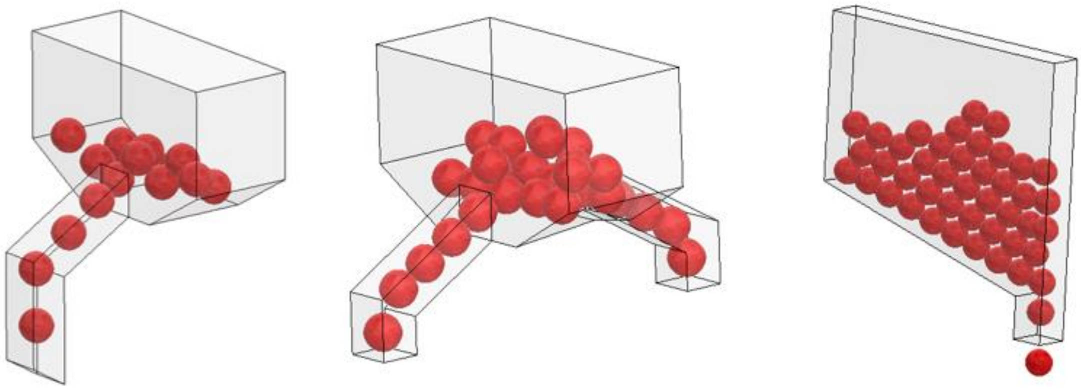

Figure 13 Alternatives for prism with inclined planes

Standard round shape

This is the typical form of the gum dispenser machine. The sphere is cut in half in order to facilitate the reload of the bin.

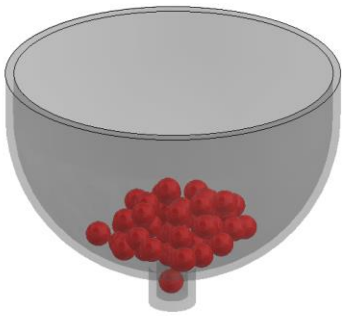

Figure 14 Standard round shaped bin

Inverted pyramid shape

Quite similar to the previous one, but with straight surfaces. Might be easier to manufacture.

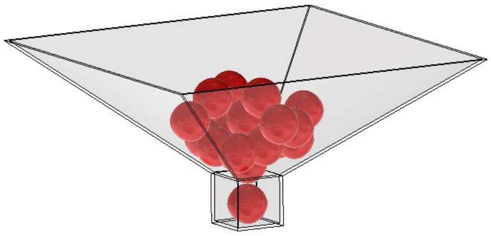

Figure 15 Inverted pyramid shaped bin

All the presented alternatives share a potential issue: the spheres might get stuck at the exit parts of the bins and might not get out one at a time. Different shapes for storing the sensors can also be considered to avoid this problem, based on tubular storage.

Straight tube/pipe

This is a simple pipe that can have a cylindrical or square crossed section.

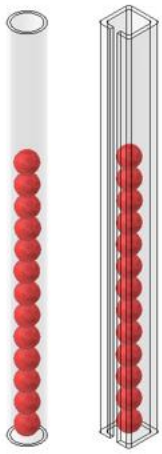

Figure 16 Tubular bins

Spiral tube

The previous tubular storage bins may have problems with the dimension constraints, as they are quite large in a specific direction. Therefore, an alternative with the same principles can be designed, avoiding the mentioned problems.

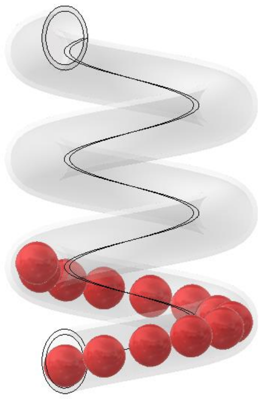

Figure 17 Spiral shaped bin

Channel with slopes

The last option consists of a mix between the previous two. It is composed of extruded channels that guide the spheres through slopes and curves.

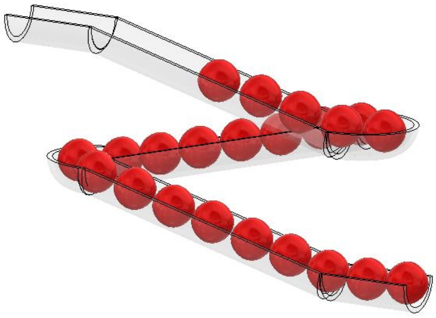

Figure 18 Channel with slopes

To decide what type of storage bin is being designed a decision matrix is made to choose the shape that would provide the best efficiency, capacity and functionality, while costing the least. In a scale from 1 to 10 it has been rated the following aspects:

- Functionality: for the proper operation of the machine the spheres should not get stuck and should move smoothly due to the shape of the storage bin.
- Capacity: the number of sensors that it can store.
- Compactness: what is the volume of the bin in relation to its dimensions.
- Ease of reload: rates the difficulty when reloading the bin when all the sensors are dispensed.
- Ease of manufacturing: difficulty for the manufacturing of the storage bin.
- Cost: how much money will it cost to manufacture it.

The resulting matrix is shown in the *Table 4.*

TYPES	Functionality	Capacity	Compactness	Ease of reload	Ease of manufacturing	Cost (low)	TOTAL
Prism with inclinated planes (box)	4	8	7	7	6	6	38
Standard round shape (classic gum dispenser)	6	10	8	9	4	5	42
Inverted piramid shape	3	8	6	9	7	8	41
Spiral tube	10	6	4	5	8	8	41
Straight tube/pipe (cilindrical or square)	10	4	6	5	10	9	44
Extruded channel with slopes	7	7	8	6	5	3	36

Table 4 Decision Matrix

According to the early decision matrix the most appropriate solution would be a straight tube or a pipe shaped storage. Although this design is quite convenient when it comes to functionality, there are some other aims or aspects such as capacity and compactness that are not that thoroughly accomplished. Considering the magnitude of the warehouse and the positions of the conveyor belts, there are some dimension constraints that cannot be ignored. As the structure of the flat storage system is quite high and relatively close to the ceiling of the warehouse, the volume of the storage designed cannot be bulky, especially on the vertical direction. Therefore, a straight vertical pipe would not be the most favourable option, since there would not be enough space in the warehouse if a relatively high number of sensors is required. In the direction of solving this problem, the first solution that comes to mind would be placing the pipe horizontally and tilt it slightly so that the spheres could roll down. Some vertical tubes could also be added to increase the capacity of the design and ease the reload of the sensors. The proposed solution would look like the one in the *Figure 19.*

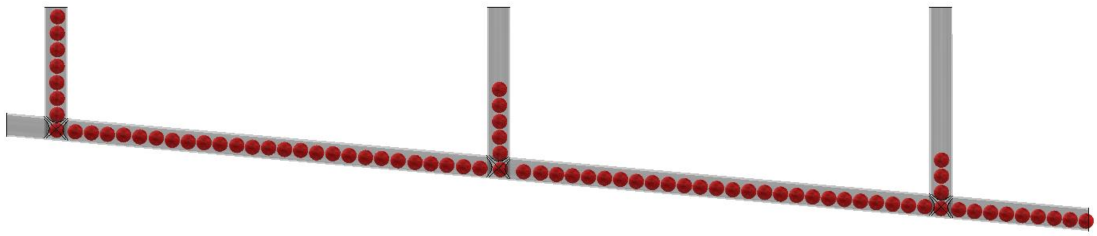

Figure 19 Tilted tubular solution

However, there are some inconveniences that this design does not overcome:

- It would be uncomfortable to load the sensors into the pipe**.** The idea of the implementation of vertical pipes is developed to shorten the tilted pipe longitudinally so it does not have to store all the sensors. As there is a height constraint due to the warehouse ceiling, more than one vertical pipe would be added instead of a single long one. These vertical tubes would be the way in of the sensors into the storage; therefore, if there would be more than one loading point it would be slightly uncomfortable and involve a large manual effort.
- There would be more than one element to be controlled. There should be an opening and closing mechanism at the end of the tilted pipe and exists the possibility of needing more mechanisms at the intersections between the vertical pipes and the tilted one with the aim of preventing sphere blockings. Consequently, there would be different parts to be controlled and that could lead to more difficulties.
- The probability of blocking increases**.** Due to the intersection of the pipes, the possibility of the sensors getting stuck and not coming out the vertical tubes increases considerably. This is also something that should be taken into account when designing the hypothetical opening and closing mechanisms.
- Great longitudinal dimension**.** The length of the storage could be too large and difficult to place and handle. Making a rough calculation, if it is wanted to store

50 spheres of 80mm of diameter a pipe of at least 4m should be placed. This dimension can be quite critical depending on the size of the warehouse.

In the pursuance of dealing with these significant obstacles, it is a good idea to reconsider the previous storage designs, developing a new decision matrix with weight factors. Thanks to this, some aspects will be more significant compared to others. For the weight factor distribution, the following priorities have been taken into consideration, shown in the *Table 5*.

FUNCTIONALITY	2
CAPACITY	1.5
COMPACTNESS	2.5
EASE OF REALOAD	1.5
EASE OF MANUFACTURING	1
COST	1

Table 5 Weight factors of the aspects being analysed

After the modifications, the results obtained are shown in the improved decision matrix in the *Table 6*:

TYPES	Functionality (x2)	Capacity (x1.5)	Compactness (x2.5)	Ease of reload (x1.5)	Ease of manufacturing (x1)	Cost (low) (x1)	TOTAL
Prism with inclinated planes (box)	4	8	7	7	6	6	60
Standard round shape (classic gum dispenser)	6	10	8	9	4	5	69,5
Inverted piramid shape	3	8	6	9	7	8	61,5
Spiral tube	10	6	4	5	8	8	62,5
Straight tube/pipe (cilindrical or square)	10	4	6	5	10	9	67,5
Extruded channel with slopes	7	7	8	6	5	3	61,5

Table 6 Improved Decision Matrix

The new results obtained claim that the most appropriate solution that overcomes the mentioned inconveniences is the standard round shape.

Contrary to the bubble gum dispenser storage bin, this design proposal would not be shaped as a whole sphere. In order to ease the load of sensors into the bin, only half of the sphere is considered, as seen in the *Figure 20*.

Figure 20 Standard round shape concept

It is concluded that this type of design is the most convenient for the task of storing the sensors. However, it is not perfect, and therefore it is improvable. The weaknesses of the proposal should be studied and corrected to increase the reliability of the design. To achieve this, the decision matrix is again analysed. The 3 weak aspects where this idea fails to success would be its functionality, ease of manufacturing and cost.

On the one hand, the design should be modified and defined to upgrade its efficiency related to cost and ease of manufacture. These two aspects could be enhanced by applying some variations exposed in the following proposed solution. Instead of a continuous round surface that holds all the spheres due to the extension of the material of the bin, thinner wires can be used to achieve the aim of lightening the object. Something like a wire basket made with openwork patterns of metal (steel for example) that has the function of a container.

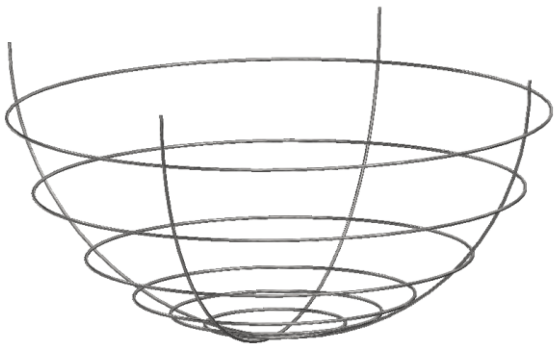

Figure 21 Improved round shape

Thanks to this concept, these aspects are upgraded:

- ✓ Less material used and therefore cheaper.
- ✓ Made with thin metal wires and therefore easier to manufacture.
- ✓ Lighter and therefore easier to handle.

On the other hand, when it comes to functionality, the only facet that may be worrying is the previously mentioned risk of blocking of the spheres. To overcome this potential problem, the shape of the bin should be adjusted. Furthermore, the implementation of a mechanism that would stir up the sensors so it impedes the blockage may be necessary.

This is a typical problem that takes place in many different applications nowadays such as pill dispensers or golf and tennis balls dispensers. There are several ways of smoothening the exit flux of a spherical product that can be studied. In this case, it has been concluded that the issue can be compared to the one present on industrial orange juicers. The diameter of a standard orange is quite like the diameter of the sensors, thus, the mechanism that takes care of generating a continuous flux of the fruit can be taken as a reference or inspiration. As an example, the automatic industrial machine *Zummo Z40 Nature* is shown in the *Figure 22*:

Figure 22 Zummo Z40 Nature [8]

The only part of interest of this machine would be the upper one, that is in charge of storing the oranges and taking them out regularly. In the following lines it is explained how the juicer overcomes the problem of orange blocking and which elements are used. The sensor dispenser machine is clearly inspired in the technique used in the example and might contain coinciding features.

The system of the juicer is based on a rotational actuator that excites the static product inside the basket and provoke its movement for a controlled evacuation. Its configuration consists of 3 main elements: a separator, an inner basket, and an external basket. It should be mentioned that there are some other essential parts that are indispensable for the proper functioning of the machine that are not shown in the *Figure 23*.

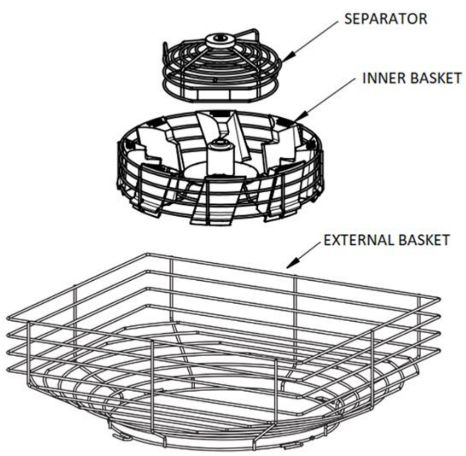

Figure 23 Scheme of Z40 [9]

The externals basket is intended to create an enclosure for the spherical products and keep them together stored. This static element defines the dimension of the storage bin, as it manages to enclose all the other elements inside of it. On the bottom of the basket there is a hole that has the task of evacuating the products that are agitated by the spinning basket. This inner basket is the only mobile component that deals with the necessary motion for the blocking prevention. Thanks to the rotational movement, the rounded shaped product (oranges or sensors) will fall into the gaps and in consequence they will be unitarily separated. These individual gaps are directly connected to the exit opening in the external basket, constituting in such a way the scape path of the spheres.

The separator is another fixed element that due to its shape facilitates the introduction of the units into the gaps in the inner basket. Depending on the size of the separator, the gap will have a bigger or smaller volume, which will lead to the possibility of processing different size of sensors. If the separator has a bigger diameter, the space left for the spheres is more limited. On the other hand, for smaller separators the gap is more spacious and larger sensors could be handled. This property guarantees the possibility of using spheres with the diameter between 70 and 90mm.

Applying this functioning principle to the case of the spheres, the mentioned 3 elements have been drawn in detail.

Firstly, as it can be observed in the *Figure 24*, there is the illustration of the external basket. Following the aspects and conclusions obtained from the *Improved Decision Matrix*, a circular shape formed with steel wires is designed. This element consists of a base plate attached to vertical wires joined with rings that keep the spheres stored. There are two holes on the base plate. The big one will be the outlet of the spheres, which will lead them to another part of the dispenser machine. The small one, right in the middle, is the gap needed for the shaft that will transfer the rotation to the inner basket. As previously commented, the external basket is completely static, it has no rotation.

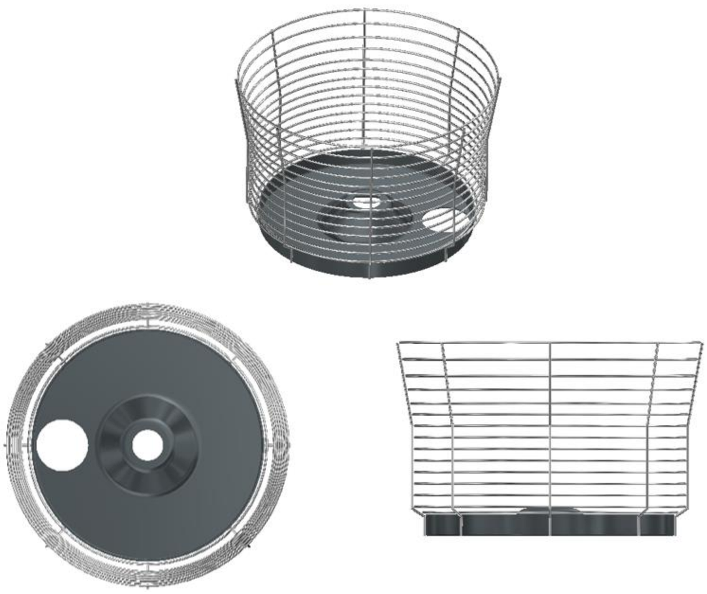

Figure 24 Design of external basket

Secondly, there is the inner basket represented on the *Figure 25*. It is constituted by a bunch of bent steel wires joint with rings and attached to a circular base that will be fixed to the rotating shaft. Inside the basket, there are pushers implemented with the shape of the sensors. The shape of these pushers will allow the motion of the spheres, and, as a result of the rotation, they will escape through the hole of the external basket.

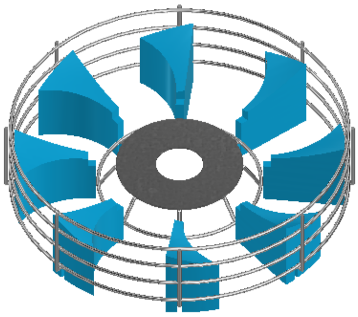

Figure 25 Design of inner basket

Finally, it comes the separator. This element is located on top of the inner basket and is formed by circular wires attached to a base.

Figure 26 Design of separator

The assembly of the three elements together is shown in the *Figure 27*:

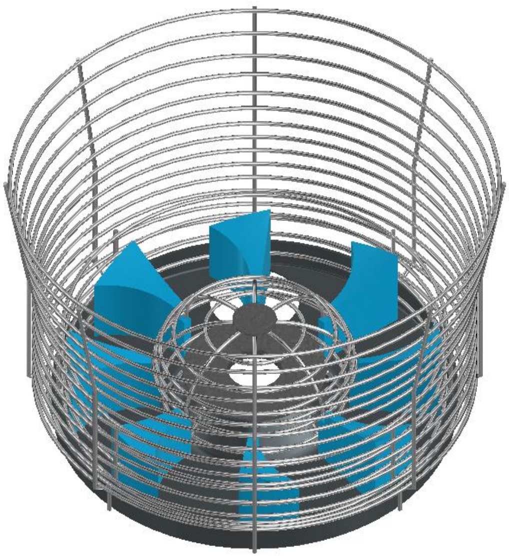

Figure 27 Design of the assembly of the storage bin

With this design, the issue with functionality is completely solved, as the solution works in real situations (the oranges do not get blocked and get out one at a time). Therefore, it can be concluded that this concept is quite adequate for the storage bin. The next issue to be faced corresponds to the dispenser mechanism design.

2.7.4 Dispenser mechanism

As a result of the previous method for handling the sensors, it is possible to discharge one device at a time, releasing it through the hole on the base of the storage bin. However, it is fundamental to be able to control in detail the emission rate of the spheres, and, unfortunately, the suggested model does not provide that condition. The constant rotation of the inner basket induced by the shaft implies that the sensors will be taken out regularly at a constant rate. It is assumed that for low revolutions of the shaft the discharge rate will decrease; for higher revolutions, by contrast, the exit rate will increase. Although in these terms it can be said that the evacuation is partially controlled, it cannot be considered as reliable for the following reason: it is unclear that when a high discharge rate is needed the spheres will be constantly dropped without any interruption or miss. If the shaft is rotating at high velocities, the impact between the sensors and the pushers will be more aggressive due to the increase of linear momentum. This will lead to stronger movements of the devices, even causing little bounces. In consequence, it may be the case where a sphere misses the exit hole and cause a discontinuity of the discharge rate.

To avoid the previous complication, it has been determined that a dispenser mechanism must be studied so that it is possible to achieve the desired regulation of discharge. This mechanism would fulfil the same function as the turn handle in the gum machine: drop a sphere every time a signal is received. In the case of the gum dispenser, this signal is as simple as turning the handle manually. On the other hand, in the case of the sensor dispenser, it would be an electronic signal. The question to be managed now focuses on how it can be done to adapt the exit of the storage bin to the dispenser mechanism.

The next component to be drawn should be the linker between the two elements that were just mentioned. A round channel that would guide the sensors would be the simplest solution. It must fulfil the following requirements:

- Connect the exit of the storage bin with the entrance of the dispenser mechanism.
- Be able to store up to 10 sensors (estimated value). This would be the little depository that feeds the dispenser mechanism. As the sensors would be all in line and well organized, there would not be a problem with blockings.
- Should have the capacity of dealing with sensors with different diameters (70-90mm).

After considering the defined demands and maintaining the style of the storage bin, the designed linker looks like the one on *Figure 28*:

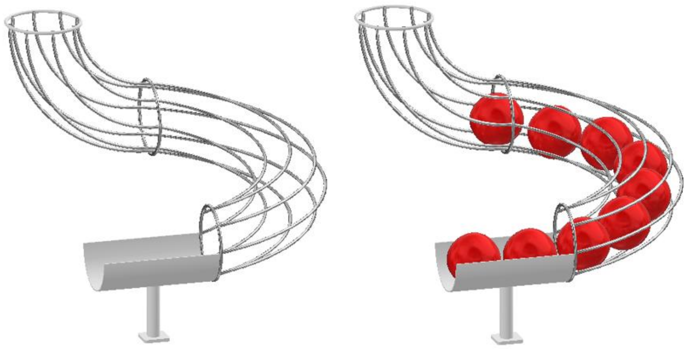

Figure 28 Designed linker

It is formed by steel wires which create a tubular channel that guides the sensors creating a spiral form. This spiral form will provide compactness to the design, giving sufficient space for the temporary storage of the spheres. The curled shape structure is supported by circular rings, and it is attached to a semi cylinder at the end. This final part has the purpose of containing the devices to be dropped, meaning that it is a little container that will be directly in contact with the dispenser tool.

Attaching this element to the storage bin will create a system capable of establishing a connection between two depositories. Basically, the bin is a big bucket that holds the majority of spheres, and it feeds the linker thanks to the stirring created by the revolutions of the inner basket. The linker carries a reduced number of devices that will be later evacuated by a completely controlled mechanism. For a proper functioning, the linker must be always filled, so it can release one unit every time it is necessary. To accomplish this, it would be a good idea to implement a sensor that could detect whether a minimum number of devices (for example, 10) remain inside the linker. If it is detected that the linker is full, a signal would be sent to the storage bin and the feeding would immediately pause by stopping the rotational movement of the shaft. On the contrary, when the 10th sphere is not detected the feeding must be resumed.

These two parts combined are shown in the figure. Some structural elements have been added in order to give support and stability. These parts are composed primarily of square profiles, tubes and welded steel plates.

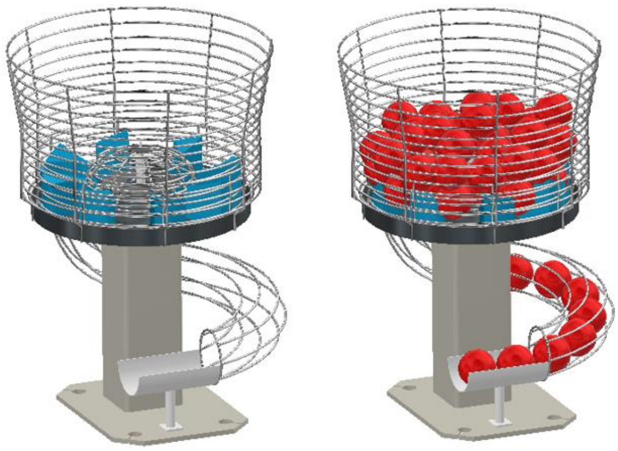

Figure 29 Designed storage bin and linker

The only missing part now is the dispenser. As mentioned before, if the gum dispenser is taken as reference, a mechanism based on rotational actuator could be designed. However, there are other types that could be also considered, for example, mechanisms based on linear actuators. There are abounding of logical alternatives that can be studied, but the aim is to choose and design the most appropriate that fulfils the following functions and requirements.

- Main function: catch a single sphere direct from the connecting channel every time the actuator makes a specific movement and separate the sensor from the others so it can be released later.
- Make it as simple as possible with a low number of elements to limit the probability of failure.
- It should prevent the blocking of the spheres.
- Must be able to operate with spheres of different diameters.

After analysing various examples, very simplified extraction methods (rotational and linear) have been drawn with the aim of comparing them visually. Real cases such as pill dispensers have been considered as inspiration. The following sketches have been created with Rhinoceros 3D.

Three examples of linear actuators:

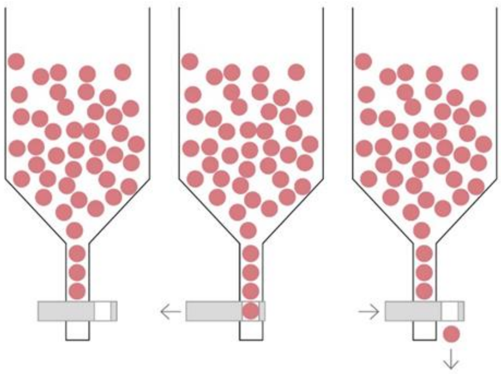

Figure 30 Linear actuator 1

The operating system of the alternative in the *Figure 30* is simple. The extraction is being accomplished due to the horizontal oscillating movement of the grey element.

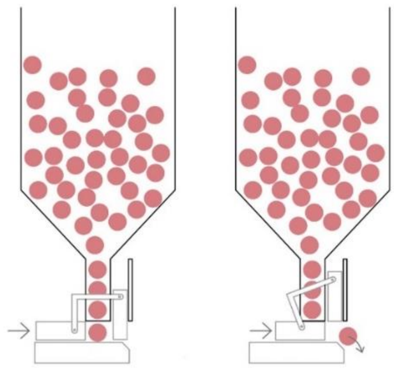

Figure 31 Linear actuator 2

The one shown in the *Figure 31* is also actuated by a horizontal movement. However, this mechanism relies on a swivel that enables the expulsion of the spheres.

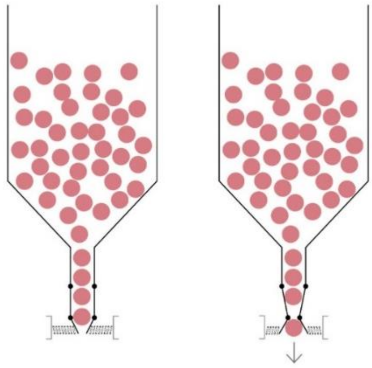

Figure 32 Linear actuator 3

The mechanism in the *Figure 32* is formed by two springs and ball joints. By pushing in the correct spots, it is possible to extract one sensor at a time.

Two examples of rotational actuators:

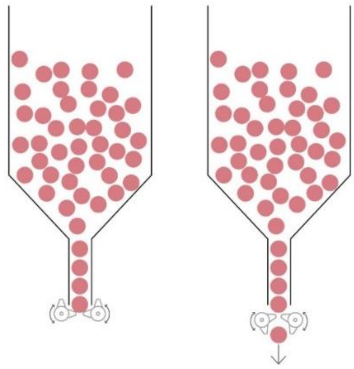

Figure 33 Rotational actuator 1

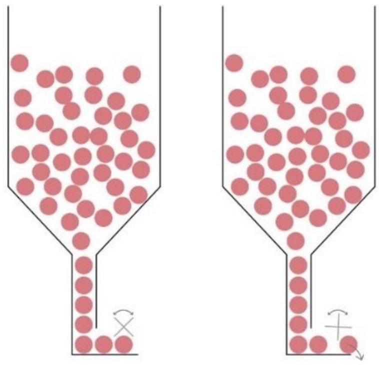

Figure 34 Rotational actuator 2

The alternatives shown in the *Figure 33* and *Figure 34* share the same operating system. The extraction is achieved with the help of rotational pushers. The main difference between the two options is the number of pushers and the way of distributing them.

There are many possible options that adequate to the current solution and lots of them are equally capable. In this case, the decision of choosing an inspiration for the drawing is based on the simplicity of the alternative. It is also checked which one fits best the existing assembly. In consequence, it is determined that a rotational actuator can be in charge of transferring the movement to some blades that will push one sensor and take it out of the assembly, something similar to what can be seen in the *Figure 34*. The mechanism consists of 4 pushers that adequate to the shape of the spheres attached to a cylindrical shaft that will be directly connected to a rotational servomotor. Every time that the system needs to release a sensor, a signal will arrive to the motor, and it will rotate 90 degrees, moving also the pushers. Once the closest sphere to the mechanism is pushed out, it will leave the machine and will be dropped directly inside the inlet grain feed.

The final drawn concept can be seen in the following *Figure 35*.

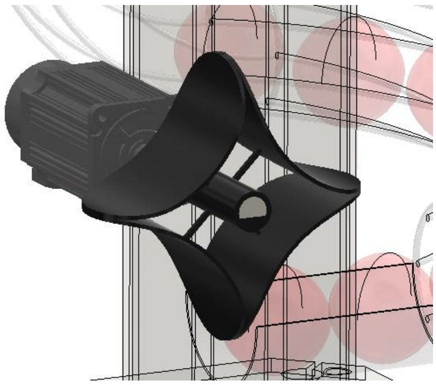

Figure 35 Designed dispenser mechanism

Having explained the development of the actuator mechanism, it is concluded the design of all the elements of the machine.

2.7.5 Actuators and control

It has been mentioned during the whole design process of the assembly that there are two different motions to be aware of. The first one is the rotational movement that will cause the stir of the sensors in the storage bin to prevent the blocking. This operation can be driven by a servomotor connected to the shaft that is attached to inner basket. The motor can be placed inside the square pillar that holds the external basket. Naturally, this rotation must be controlled and should not be operating the whole time, that is why it was mentioned that the system should be able to detect a minimum number of spheres inside the linker storage.

On the other hand, it is the rotational movement of the dispenser mechanism. Its motor can be added to one side of the central pillar with the help of a plate with screws. To determine the frequency in which the shaft must rotate, a calculation of how many sensors and how are they distributed must be carried out. Nevertheless, it is assumed that the velocities that these motors can reach are high enough to assure fast release times. All these rotational operations should not be difficult to control via Arduino.

2.7.6 Final product and evaluation of the results

The final solution proposal looks like the one in the *Figure 36*. A more detailed view with the different elements and parts being displayed on 2D are attached at the *Appendix*

of the thesis.

Figure 36 Assembly of the solution

Theoretically the proposed concept meets the general requirements established for the initial problem. It would enable to place sensors relatively close to each other and it is assumed that it would place them with accuracy. The designed bin permits the sensor storage and due to the movable feeding belts of the flat storage system it is possible to reach every point of the warehouse.

It is essential to a evaluate the solution by checking if it fulfils the requirements stated at the beginning of this chapter.

- ✓ Automation. It has been proven that this machine can work independently without the need of an operator, therefore, it can be argued that it is completely automatic.
- ✓ Flexible with to different size of spheres. Thanks to the dimensions defined for the elements that will hold the measuring devices (for example guiding channels or gaps), it is possible to operate with sensors with an estimated diameter between 60 and 95mm.
- ✓ Short release time. It is possible to achieve a high discharge frequency caused by the rapid rotation of the servomotors. It should not be very difficult to achieve the aim of 2-3s of release time.
- ✓ The values of the dimensions in the 3 main directions are 770mm in height, 550mm wide and 550mm deep. These values more than meet the requirements established for the maximum volume of the machine. There would not be any problem to place it somewhere in the upper part of the warehouse, alongside the

fixed conveyor belt. The apparatus has also been planned to be light, without many solid pieces of steel.

- ✓ The storage has an estimated capacity of 170 units. After a brief calculation, it has been determined that between the storage bin and the linker it has a potential of holding more than the minimum value of 150 units.
- ✓ It is reliable in terms of functionality. The sensors would not get stuck and would be dropped fluently.
- ✓ The whole mechanism is quite simple and has not big issues when it comes to manufacturing.
- ✓ It would be easy to refill the system. Once the displacement of the sensors is fulfilled and the storage bin is empty, thanks to the substantial gap on the top of the external basket it would be easy to recharge the machine with a new bunch of spheres.

As an overview, it is assured that the solution proposed is adequate, as it meets all of the requirements mentioned.

To conclude, it is interesting to consider the hypothetical extraction of the sensors from the bulk. After the take-out of the grains, thanks to the of grids installed on the edges of the flat storage warehouse, the sensors would not pass through the intake pits because of their size. They would be separated from the cereals, just like a filtration. It is expected that this is a simple procedure would not affect the actual take-out of the grains and that the sensors could be reused later for additional monitoring purposes.

4. Number of sensors and distribution

Through the previous sections of the thesis a technical implementation of introducing the sensors into a volume of grain has been studied, designed, and proposed. The aim of the current chapter is to calculate and specify the number of spheres needed to fulfil the necessary conditions for an adequate monitoring. In pursuance of this objective, the proper location of the spheres must be also studied since the dispersion should be suitable to achieve the convenient conditions for decent measurements. The distribution of the devices will depend on the robustness of the solution desired: if a very accurate monitoring is necessary, the sensors should be concentrated among the grain one closely next to each other, and, contrarily, for a more general overview, there can be larger distances between them. To determine an ideal location, it is fundamental to define some conditions which are related to the measuring characteristics and capacities of the spheres. Different ways of distributing the sensors are also analysed, studied, and compared with the objective of determining the most suitable dispersion.

Real cases in which this kind of monitoring is needed may differ remarkably from one another depending on parameters like, for example, the dimensions of the warehouse. These parameters are also being examined and analysed, evaluating their impact on the general distribution for a satisfactory performance.

To obtain interpretable results, general examples with several variables are being simulated with MATLAB. The aim is to determine both the quantity and exact distribution of the spheres, considering changeful situations that may influence the general conditions. In the following lines, after the terms for a proper monitoring being clarified, the recently mentioned variables are described, together with the distribution possibilities that are taken into account to develop the simulation programs. Afterwards, the methodology of the programs is being explained followed by comments about the results obtained.

4.1 Conditions for an adequate monitoring

For a proper inspection of the grains, it is key to place the spheres in locations where they can cover as much grain as possible. It is fundamental to understand how it can be achieved and what requirements should be fulfilled corresponding to the measuring characteristics of the devices.

According to their characteristics, their functioning is fulfilled with two different ranges: the measuring range and the communication range. The first one can be defined as the maximum distance that the sensors' spoiling detection ability can reach. When at any point of the grain volume spoiling occurs, it is desired for the devices to detect it as soon as possible. If this specific location is not inside the measuring range of any of the spheres, it will grow and expand until one of the ranges is reached. Thus, a larger measuring range means a faster detection of infected areas. It can be assumed that the current prototypes can detect spoiled grains that are 5 cm away from the sensor in any direction, making the detection almost impossible if the spoiled area is not basically in touch with the device.

On the other hand, the communication range defines itself as the maximum distance that a sphere is able to reach in order to communicate with other sensors. Pairing with devices to a network is the central concept of the entire system, absolutely necessary for its functioning. This means that a single sphere should be connected to a certain number of neighbours all the time, resulting in a placement constraint. If one of the sensors detects that the grain is spoiling around its location, it will send a signal to the closest devices, to those which are inside the communication range. In the case of the prototypes, the value of this range is 5 m, meaning that a sensor can communicate with any other that is inside the space delimited by a hypothetical concentric sphere with a 5m diameter. It is known that for a reliable operation, each sensor must be paired with a logical number of neighbours, not only to a single partner. This avoids the possibility of connectivity isolation of a sensor. For example, if a single-paired sensor detects spoiled grain and it occurs that the sphere to which it is connected happens to be damaged or inoperative, the detection signal would not be received, and thus, the system would not perform correctly. Therefore, a robust connectivity overlap ruled by the quantity and distribution of the sensors must be considered for a successful performance.

4.2 Variables

Before developing a software that can simulate real cases, it is important to define the basic variables that will help to adapt to different situations. Once these flexible parameters are determined, the software should be able to calculate the distribution and number of the spheres. Some of the variables are directly related to the characteristics of the case to be studied, and, on the other hand, there is another one that depends on the grade of robustness needed for the desired monitoring.

The parameters that are related to the specific case are the following ones:

- Quantity of the grain: this is the volume of cereal to be stored. The size of the bulk has proportional influence on the number of spheres that should be used. As in the previous chapter, the shape of the stocked grains is going to be considered as a rectangular parallelepiped.
- Warehouse dimensions: the warehouse has a plant size that is defined by a longitudinal value and transversal value. The dimension of this rectangle has an obvious effect on the shape of the bulk. If the longitudinal value is remarkably bigger than the transversal, the shape of the grain volume will be narrower compared to the case of a warehouse with similar longitudinal and transversal values.
- Type of grain: this has a minor effect on the ranges of the sensors. Depending on the cereal to be stored, it has been tested that the measuring and communication ranges of the sensors vary. For example, in wheat, the sensors

have a communication range of roughly 5 m. This is, at first, the value that is considered for the simulations.

The final parameter that completes the variable influences robustness of the monitoring:

- Distance to the closest sensor: this is the separation between one sphere and the ones that surround it. To achieve a balanced and organized distribution, it is logical to disperse the sensors following regular pattern with a constant gap between them. If the distance between the sensors is short, the high concentration of them enables a more detailed and accurate monitoring, also increasing the connectivity overlap. Assuming that the connectivity range is 5 m, it is obvious that the distance between the sensors cannot be higher than that value.

All those parameters above mentioned are the input variables in the programs used to resemble the simulation to real situations. However, there are also some considerations that play an important part in the pursuance of this resemblance. Firstly, it is probable that due to the introduction method, the real location of the sphere may not coincide with the desired theoretical one. This positioning accuracy is affected by movements of the grain around the sensors. In consequence, a positioning error is being considered for the later results analysis. Another point to bear in mind is the error of the range of the spheres. Although during the development of the program this value is handled as constant, the actual value may vary slightly from one sensor to another.

4.3 Distribution types

There are many forms of organizing the sensors in the bulk. A good way of understanding the distinct options is by visualizing the crystal structure arranged by atoms in a crystalline structure. Following the same idea, the distribution of the sensors can be based on a repeated pattern maintaining them connected with as many partners as possible. A proper distribution enables the measuring ranges to embrace a large volume, while keeping the quantity of sensors low. There should also exist a considerable connectivity overlap to assure the permanent correct operation of the devices.

A comparison between different options of organization is carried out to determine which is the most efficient disposal. The objective consists of choosing the most appropriate distribution for specific cases, optimizing the number of sensors needed for the monitorization of a certain amount of bulk material. To accomplish that, the dispersion types must be examined in the space.

For the development of a distribution in 3D, a distribution pattern is considered among one plane at first, allocating the sensors with coordinates in two directions (x and y). Afterwards, the distribution composed in the plane is being repeatedly projected in the third dimension (z), following the same previous pattern or a defining different one. In this way, it is possible to arrange different distributions in the space by combining distinct types of dispersions.

In the case of this thesis, there are 2 possible patterns that are analysed and contrasted: square and diamond distribution.

- Square distribution

It consists of placing the spheres at the same distance among the 2 main directions of the plane (x and y) forming a regular pattern. As it is shown in the next figure, this uniform dispersion forms regular squares with the spheres as vertices.

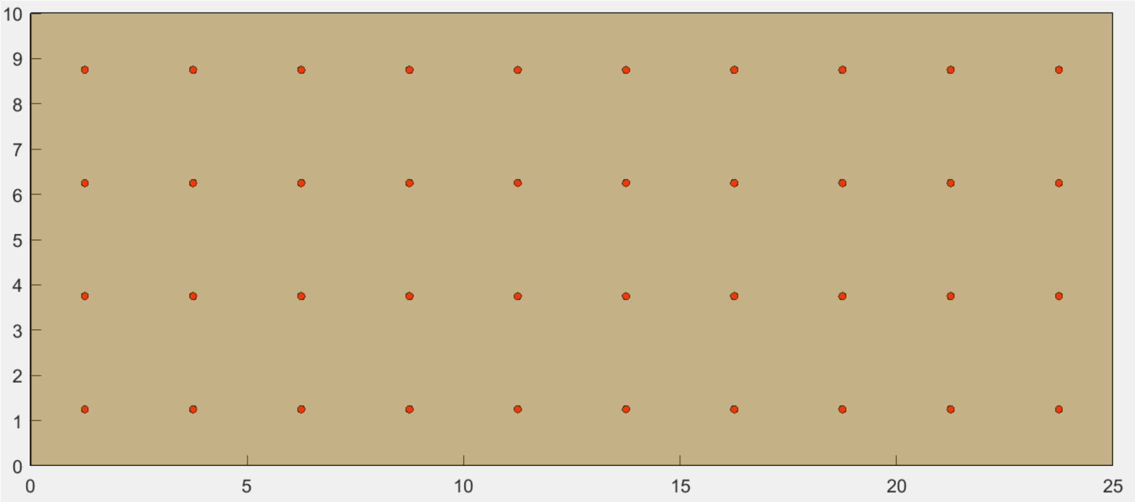

Figure 37 Square distribution in 2D

- Diamond distribution

Compared to the previous one, this distribution is formed like if the square pattern would be rotated 45°. This time the spheres delimitate a diamond shape with the sides being the actual distance between the sensors.

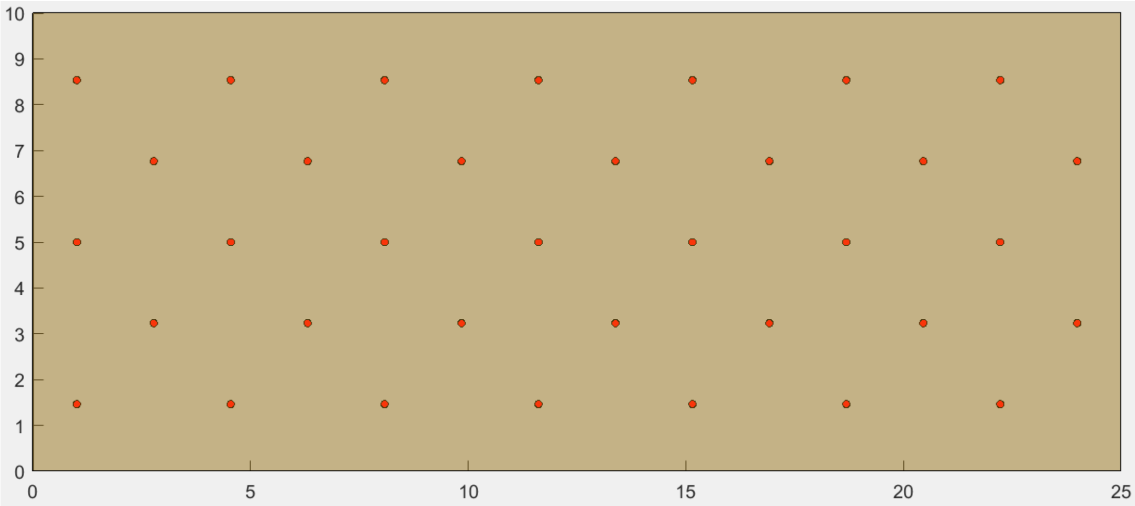

Figure 38 Diamond distribution in 2D

The presented distribution types have been represented in a plane, not in the three-dimensional space. As mentioned, to achieve the dispersion in 3D, the planes must be expanded along the third direction. This expansion can also be carried out following different patterns, and being only two that are studied in this case, it results in 4 possible combinations:

- Square distribution in plane and square distribution along the third direction.

- Square distribution in plane and diamond distribution along the third direction.
- Diamond distribution in plane and square distribution along the third direction.
- Diamond distribution in plane and diamond distribution along the third direction.

These 3D distributions alternatives are the ones being analysed later in the thesis. However, before approaching the problem along the three dimensions, the comparison is carried out in 2D.

4.4 Distribution programs

To decide what would be the most proper and optimal 2D distribution of the spheres inside the warehouse, some codes in MATLAB have been developed. The aim of the programs is to compare the two options of distribution evaluating the results obtained. Depending on the variable parameters before mentioned and the type of dispersion chosen, the number of spheres used for the monitoring and some of their operating characteristics may vary.

In the next paragraphs some of these programs are described. Firstly, the basic code is explained, being the reference for the following simulation programs.

4.4.1 Basic programs

There are two different codes that have been written with the aim of obtaining results that will help to evaluate the adequacy and robustness of the two distributions to be compared. One of the programs is applied to review the square distribution in 2D while the other refers to the diamond distribution in 2D. The codes are displayed in the *Appendix*

.

Both codes are quite similar when it comes to content and development path. The main disparity between them is that they are inspired by the two different patterns to distribute the sensors. After entering some parameters that help to adapt the situation to a real case, the programs give back some results that are later interpreted. The input variables are the ones commented in the Variables section:

- Dimension of the warehouse.
  - Longitudinal dimension.
  - Transversal dimension.
- Range of the sensors.
- Distance between the sensors.

The inputs are a total of 4 parameters, that are enough for the programs to give back the following outputs:

- Visual display of the rectangular layout of the warehouse together with their respective values in meters represented on the axes x and y.
- Visual distribution of the sensors and the diameter of their communication range. The exact position of every sensor is displayed along the layout of the

warehouse. The values of the coordinates in the plane can also be read in the graph.

- Number of sensors needed to monitor the whole area of the warehouse layout.
- Histogram representing the number of overlaps between the communication range of a sphere and the neighbour sensors. This histogram displays the quantity of connection pairs that a sphere has. It is reminded that for two sensors to be communicated it is mandatory that one is inside the communication range of the other.

For a better understanding, 2 examples are displayed below, one for each type of distribution.

Firstly, for both cases the input values are the same:

```
distlong =20;
disttrans = 8;
distcent = 3;
range = 5;
```

Figure 39 Input values for the basic program example

The dimensions of the hypothetical warehouse's layout are 20 meters in the longitudinal direction and 8 meters in the transversal direction. In this case, it has been decided that the distance between adjacent sensors is going to be 3 m. This value allows that, the communication range being 5m, there is a certain overlap of the communication ranges.

<u>Square distribution</u>

The visual results and the histogram of the square distribution program can be observed in the following Figure 40 and *Figure 41:*

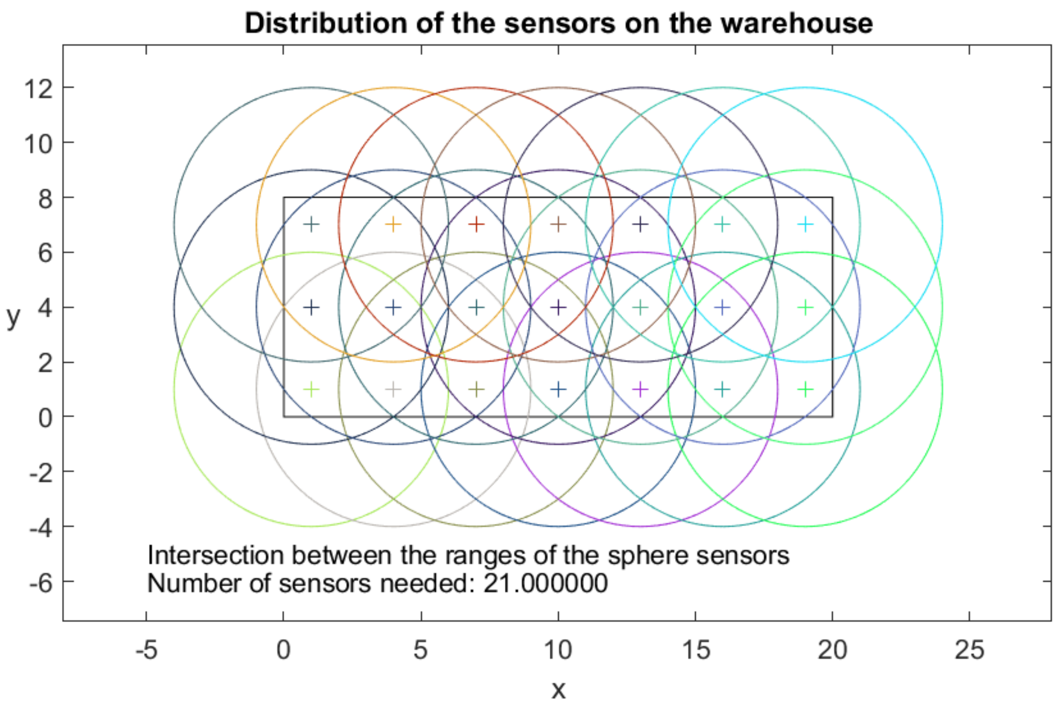

Figure 40 Square distribution, visual result

The black rectangle represents the layout of the warehouse in 2D, while the coloured crosses display the location of each sensor. If the accuracy of the visual representation is not enough to identify the location of a sphere, it is possible to get the exact coordinates by clicking on the desired cross. For example, the coordinates of the green sensor on the bottom left are (1,1).

The total number of sensors needed to cover the whole area is also displaced right over the x axis. In the case of the square distribution, 21 spheres would be enough.

Around every cross, there is a circumference of the same colour representing communication range. This range is useful for understanding the histogram.

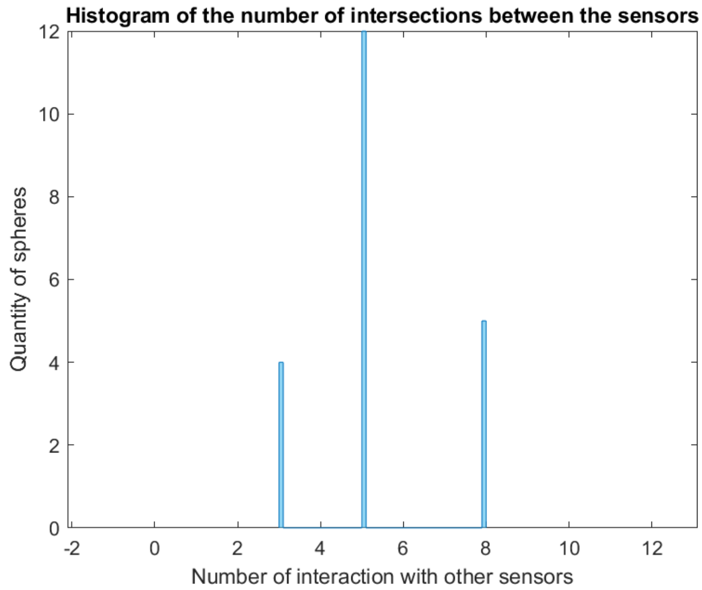

Figure 41 Square distribution, histogram

The x axis of the histogram shows the number of connected neighbours that a single sphere has. In other words, it represents the quantity of devices that are placed inside the communication range of a specific sensor. On the y axis, on the other hand, it is represented how many spheres have the corresponding number of neighbours. This means that if the first column on the left is examined, it can be determined that there are 4 sensors in the plane that are in constant communication with other three. For example, that would be the case of the bottom left green sensor, as three other crosses are placed inside the green range circumference.

More than half of the sensors, 12 to be precise, are able to communicate with other 5, and it is also remarkable that the maximum number of partners that can be achieved is 8, this being achieved by 5 different sensors. Adding up all these values of the vertical axis, the total amount of sensors is obtained:

$$4 + 12 + 5 = 21 \text{ spheres}$$

Diamond distribution:

The visual representation in this case looks like the one in the Figure 42, followed by the histogram in the *Figure 43*.

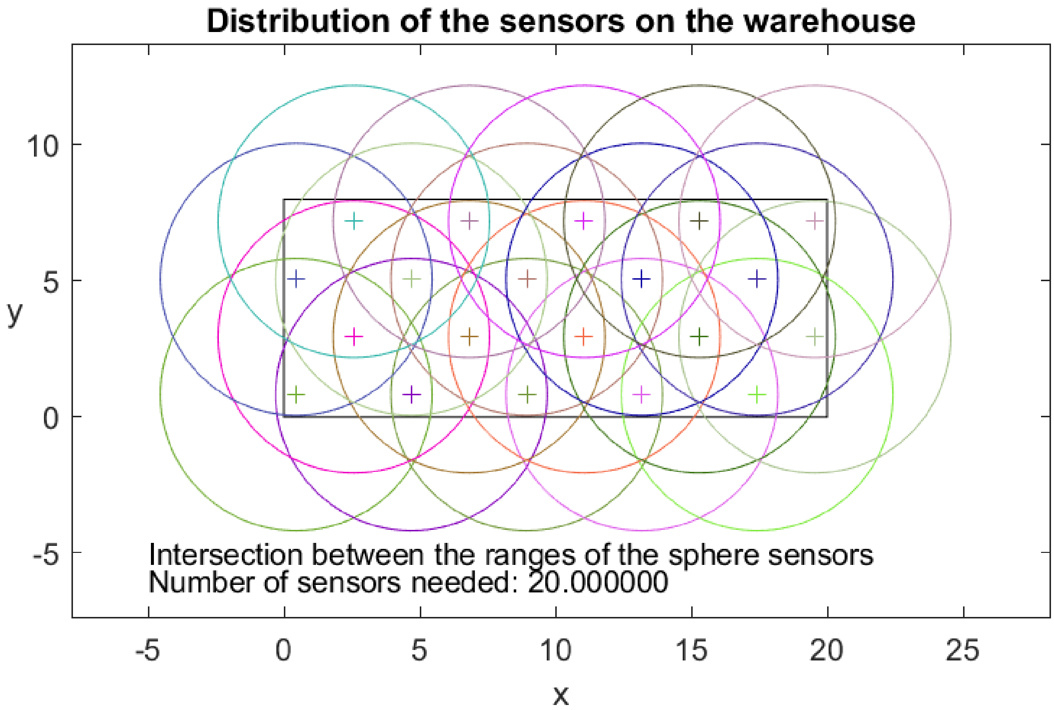

Figure 42 Diamond distribution, visual result

The rectangle and the crosses give the same information as the ones in the square example. In this case, it seems that the distribution is not as organized or symmetric as the previous one, as it looks like there are areas such as the top corners that may not be fully covered by the sensors. However, the number of sensors needed to monitor the plane is 20, less units than with the square pattern.

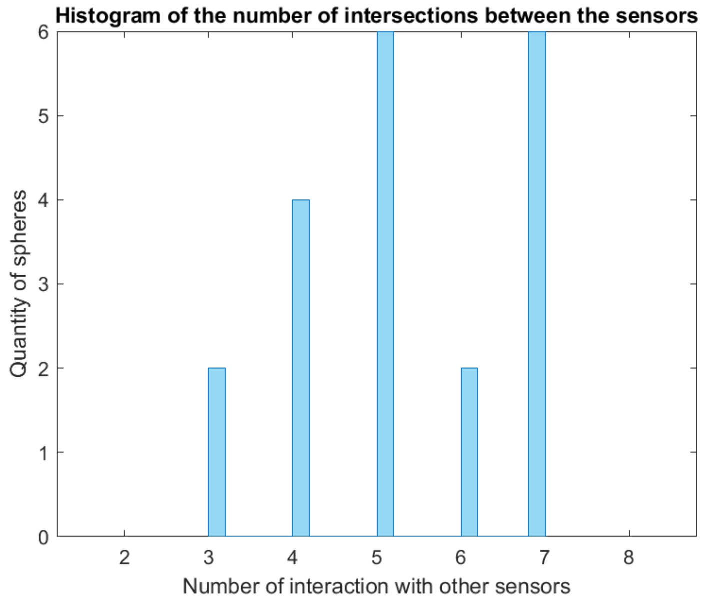

Figure 43 Diamond distribution, histogram

When it comes to the histogram, the values are more dispersed in contrast to the other alternative. The minimum number of partners coincides with the previous one, 3. However, the sensors with the highest connection rate have less connected couples, being 7 instead of 8. This condition undermines slightly the robustness of the diamond distribution because a higher number of connections per sphere enables a more reliable performance of the system.

Just like in the case of the square pattern, the quantity of the sensors is obtained by adding up all the values on the y axis:

$$2 + 4 + 6 + 2 + 6 = 20 \text{ spheres}$$

The two examples that have been just explained allow to compare two distributions in a very specific case. Under these circumstances defined by the input parameters, it has been concluded that the diamond distribution needs less sensors than the square distribution to handle the warehouse layout. Nevertheless, it may have some connectivity disadvantages compared to the first alternative, which can be appreciated by plotting the cumulative values of the 2 histograms.

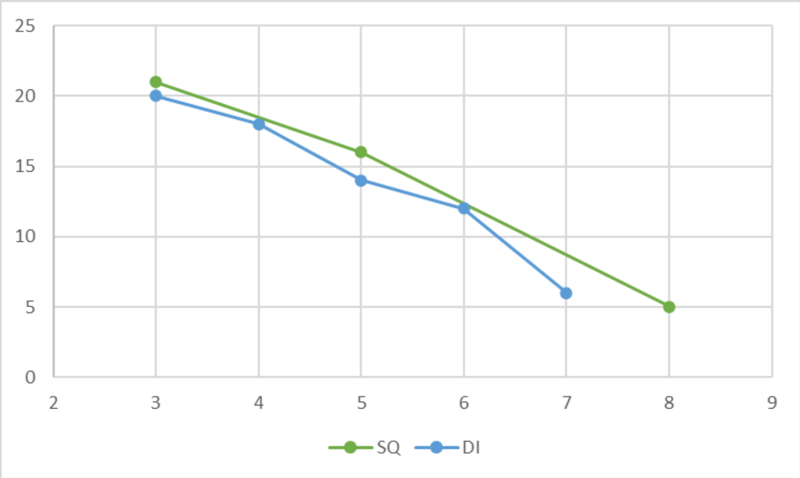

Figure 44 Cumulative histogram

In the *Figure 44* a comparison between the histograms obtained for the square pattern (in green) and the diamond pattern (in blue) is displayed. This graph shows the number of sensors on the vertical axis that have the number of connection couples displayed on the horizontal axis or more. This means that, for example, interpreting the first green point on the left, there are 21 sensors that have at least 3 neighbours. The two curves have a similar negative slope, which means that they both may have a similar average connectivity per sensor. However, the green curve always stays above the blue one and its last value goes a little further. This means that there are sensors in the square distribution that have a bigger number of couples than any of the sensors in the diamond pattern.

To understand the value of this brief analysis, it is essential to understand the methodology that has been carried out to develop the code. The subsequent paragraphs contain a concise explanation of the procedure followed to obtain the two programs.

4.4.2 Methodology for the basic programs

Both programs share the same structure, and the codes can be divided in 2 sections. The first one has the purpose of placing the sensors and giving every device a set of coordinates in the plane. Logically, each of the programs will have a particular way of arranging the sensors' location, this being the main dissimilarity between them. The second part, on the other hand, is the one responsible for calculating the results once the coordinates are calculated. In this second segment both codes are identically written.

Placement of the sensors with a square distribution – Calculating the coordinates

After the input variables are collected, two vectors are created corresponding to the two dimensions of the plane. The vector X gathers the coordinates in the longitudinal direction while the vector Y does the same in the transversal direction. Both are simultaneously and simply calculated. The first sensor is placed half the distance between the spheres (input parameter) away from the wall in both directions, giving like this the first values to the vectors X and Y. The criteria of giving these first coordinates to one sphere are discussed later. Taking this point as reference, more spheres are added in both directions distanced by the settled input parameter while filling the coordinate vectors. The addition of the sensors stops when the longitudinal dimension and transversal dimension input parameters are reached, in other words, when they meet the walls at the end of the warehouse.

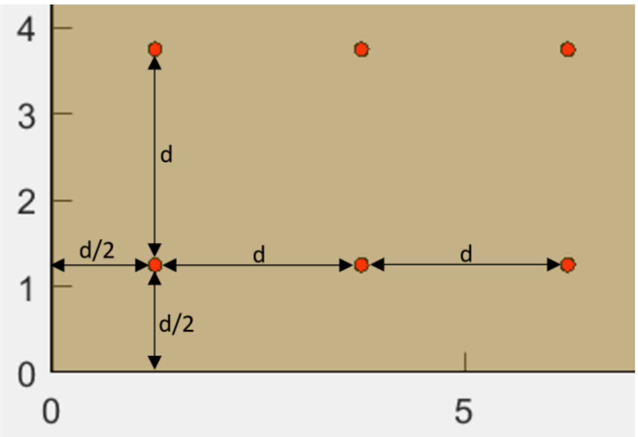

Figure 45 Sensor reference for square distribution

Once the complete allocation is fulfilled, the sensors are centred in both directions of the plane rearranging their coordinates. This is fulfilled with the aim of adjusting their position to an optimal and more symmetrical dispersion. The effect of this adjustment is shown in the *Figure 46*, as the distribution on the right is slightly lower than the one on the left.

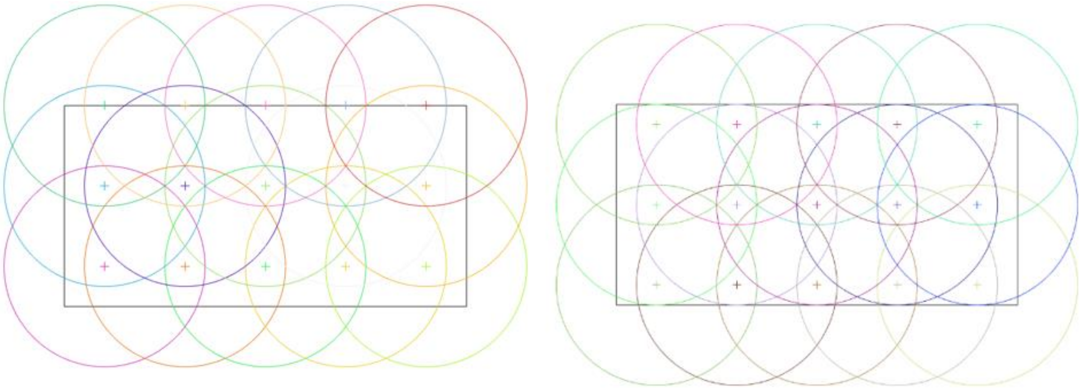

Figure 46 Not centred vs centred distribution

After defining the coordinates of the vectors X and Y, the first part of the code is finished.

Coming back to the criteria used to place the first reference sensor, it is going to be argued which is the value decided to use as initial separation to the wall. In principle, the main reason for taking half the sphere distance as initial separation from the wall is to give all points in the warehouse an equal distance to the closest sensor. Considering the worst case possible, it may happen that the spoiling starts right in the middle of a square delimited by 4 sensors. The spoiling would develop and augment until one of the sensors is reached, having the maximum time to expand freely. This would be the case where the most quantity of grain is spoiled without the sensors noticing, and it happens because this point is the one with the largest distance to the next sensor. It is decided that an adequate position for the first sensor is half the separation between the spheres away from the wall of the warehouse. By doing so, it is accomplished that the furthest points from the sensors located on the edges (walls) will be at a similar distance as the points in the centre of the warehouse.

Half the distance between the sensors is the distance of the reference sensor from the wall, in principle. It should not be forgotten that the coordinates are being rearranged right after in order to centre the whole distribution. Due to this rearrangement, the distance to the wall between the sensors on the edges may increase or decrease slightly. After some mathematical calculations based on examples, it is concluded that the value of the real distance between the reference sensors and the walls will always be inside the following range:

$$d_w \in \left[\frac{d}{4}, \frac{3d}{4}\right]$$

Being d_w the distance to the wall and d the fixed distance between the sensors. Interpreting the range, the value of d_w will always be $d/4$ larger or $d/4$ shorter than half the distance between the sensors, the value that was established in the beginning. The factors that will determine what is the real value of d_w inside the range are the dimensions chosen for the warehouse.

The veracity of this mathematical range is being supported by another code named *first_distance_to_wall*. The input parameters are the same ones that have been used for the previous codes. The difference is that in this occasion, the longitudinal dimension is entered as a changing variable, meaning that this program can calculate the coordinates after the rearrangement of the first sphere for all the values entered as a vector for the longitudinal dimension. This way, it considers multiple cases with different sizes of warehouses and afterwards determines which are the cases where the maximum and minimum distance to the wall occurs, giving the value of these separations. The following example will be used for a better understanding.

Considered these values as input parameters in the *Figure 47*:

```
distlong = 10:0.01:100;
disttrans = 10;
distcent = 2.5;
range = 5;
```

Figure 47 Input parameters for the wall distance example

The variable *distlong* is a successive vector that goes from 10 m to 100 m increasing 0.1 m at a time. This means that the longitudinal dimension of the warehouse has 9001 different values and therefore, 9001 cases to be studied. The parameters *disttrans*, *distcent*, and range represent the fixed values of the transversal dimension, distance between the sensors and communication range respectively. Following the mathematical range, it is calculated that the theoretical values for the maximum and minimum separation from the wall are:

$$d_{w,min} = \frac{d}{4} = \frac{2.5}{4} = 0.625m \qquad d_{w,max} = \frac{3d}{4} = \frac{7.5}{4} = 1.875m$$

Running the program, the results obtained are shown in the *Figure 48*:

```
MinumumSQ =

    0.6250


MaximumSQ =

    1.8700
```

Figure 48 Results obtained for d_w with the program for square distribution

As expected, it can be said the values coincide. In the case of the *MaximumSQ*, the value obtained for the program is 0.005 lower than the theoretical value. This occurs because every time that the case maximum separation is going to happen, the program adds another sphere in that direction and decreases the distance to the wall.

Summarizing, although firstly it is thought to place the reference sphere *d/2* meters away from the walls, most of the times this distance changes because of the rearranging. There are some cases in which the gap increases, creating a negative consequence for the spoiling detection. A good way of correcting this issue would be to placing the reference sphere a little bit closer to the edge from the beginning. Therefore, from now on, the reference sphere is being located *d/4* from the walls. This will minimize the space between the sensors on the edges and the walls, which is a positive aspect when it comes to spoiling detection quickness.

Placement of the sensors with a diamond distribution – Calculating the coordinates

The calculation of the coordinates in this case is not as simple as the previous one. It begins with the same reference, placing the first sphere separated from the edges at half the distance between the sensors, which is shown in the *Figure 49*.

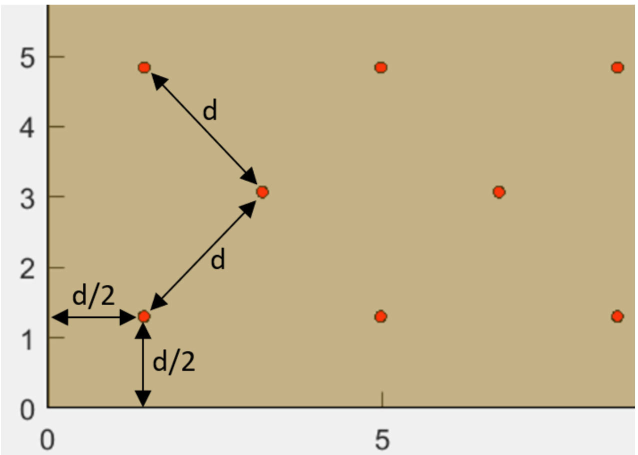

Figure 49 Sensor reference for diamond distribution

Once the reference is placed, the vectors that carry the coordinates are filled. This time, there are 4 vectors instead of 2. Although the sensor pattern is formed by placing one after the other in a diagonal direction separated by the distance *d*, the coordinate vectors have been formed following horizontal and vertical directions. Therefore, firstly the vectors *X1* and *Y1* are formed separating the spheres d_{sph} away from each other, and secondly the vectors *X2* and *Y2* are created the same way but considering the displacement that can be observed in the *Figure 50*. After calculating the couples of coordinate vectors, both are united and reordered in a single pair, just like in the square version.

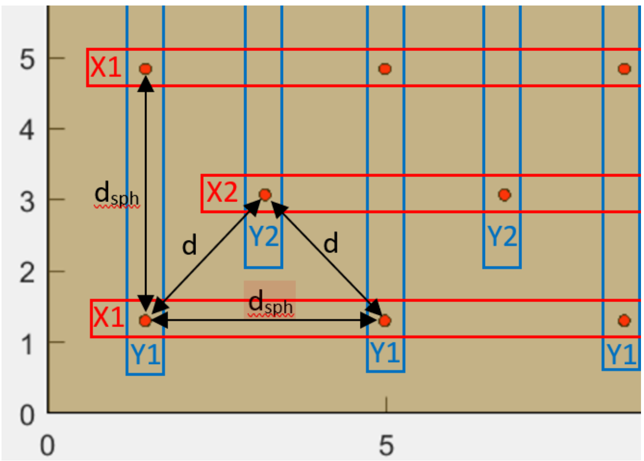

Figure 50 Coordinates vectors for diamond distribution

The value of d_{sph} can be easily calculated by trigonometry knowing the value of *d*. As the distance d_{sph} is quite large, it may happen that, for example, at the end of the *X1* vector a considerable gap is left in the warehouse without a sensor. To avoid that, the program adds a new sphere at the end of the axis when it is required. For a more detailed explanation of how these vectors are created, the detailed comments about the program can be read in the *Appendix*

.

The value applied to place the first reference sensor is also a concern for this case. It has not been possible to develop a mathematical range for this distribution due to the greater complexity compared to the square one. Nevertheless, it is viable to take advantage of the *first_distance_to_wall* program. Adjusting the code will add the chance to calculate the range of the gap between the first sphere and the wall for diamond distribution, which would help to understand if the criterion used is valid or not.

Considering the same input parameters used in the *Figure 47*, the results obtained are the following ones.

```
MinumumDI =

    0.6250


MaximumDI =

    1.5086
```

Figure 51 Results obtained for d_w with the program for square distribution

Comparing them with the ones obtained for the square distribution, it is clear that the minimum value of d_w coincide, and the maximum value, the one that matters, is slightly smaller.

After checking the code with different input values, it has been concluded that the minimum distance always matches the value of the square. The maximum distance, which is more critical, is always a smaller than the one obtained in the other distribution. Therefore, if this criterion has been accepted for the previous distribution, it is also accepted for this one: the reference sensor is being placed *d/4* from the edges.

<u>Calculating the results</u>

The coordinates in 2D of the sensors in both distributions are completely defined. It is possible then to follow to the second part of the codes. As mentioned, this segment is repeated for the two options.

After calculating the vectors X and Y and knowing the communication range, it is relatively simple to plot the distribution among the rectangular layout of the warehouse. It is also straightforward to obtain the number of sensors used to cover the whole area, as it matches the length of the placement vectors. The only result that needs to be developed is the information displayed on the histogram.

It has been established earlier that for two sensors to be connected, one must be placed inside the communication range of the other, and vice versa. To calculate the number of spheres which a single sensor interferes with, a circumference has been added (that will not be shown in the visual results) to every sensor, with a size of half the diameter of the range. The idea is to see if two devices are close enough for these imaginary circumferences to overlap. In the case of an overlap of the new circumferences, the sensors are in communication. On the other hand, if there is no overlap, the spheres are too far to communicate. In the *Figure 52* and *Figure 53,* the two options are shown.

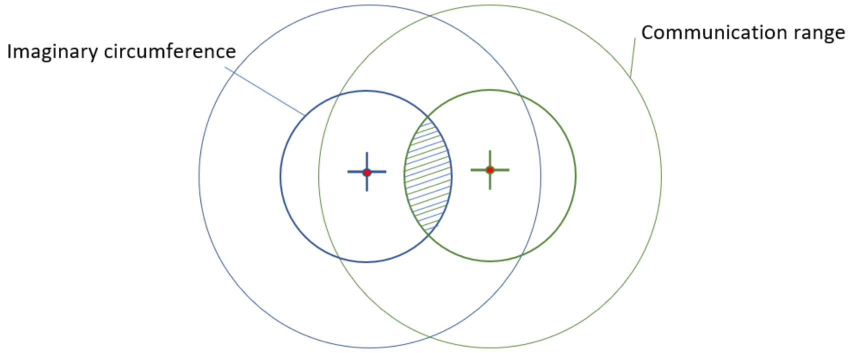

Figure 52 Overlap between two connected sensors

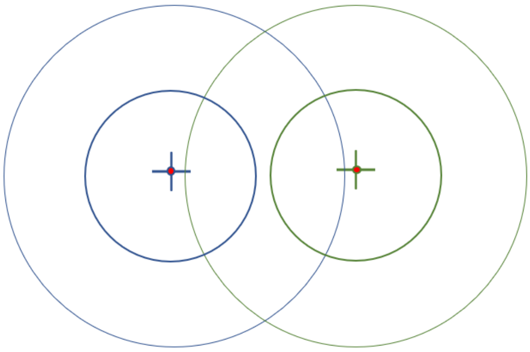

Figure 53 No overlap between not connected sensors

To determine the number of overlaps that each sensor experiences, a matrix has been created to represent the interaction between all the devices. The dimension of this square and symmetric matrix coincides with the total number of sensors. Each row (and column) of the matrix is related to a particular sphere. For example, all the values that appear in the first row share information about the sensor number 1. In the same way, all the data held in the first column also belongs to the first sensor. The elements of the matrix represent the area that is overlapped between the imaginary circumferences of two devices. For instance, the value that appears in the element $\alpha 23$, gives the superposition area between the second and third sensor. If the element is null, it means that there is no overlap and thus, the spheres that are studied are not communicating. Here is an example of a system with 6 sensors.

	1	2	3	4	5	6
1	19.6350	5.5912	0	5.5912	1.3575	0
2	5.5912	19.6350	5.5912	1.3575	5.5912	1.3575
3	0	5.5912	19.6350	0	1.3575	5.5912
4	5.5912	1.3575	0	19.6350	5.5912	0
5	1.3575	5.5912	1.3575	5.5912	19.6350	5.5912
6	0	1.3575	5.5912	0	5.5912	19.6350

Figure 54 Example of overlap matrix

With this data being calculated it is simple to plot a histogram representing the overall communication of the distribution.

4.5 Comparison between square and diamond distribution

In the explanation of these two ways of organizing the spheres in a plane, it has been analysed a specific case with particular characteristics. Obviously, a deep comparison between the methods cannot be based on an individual example, hence it would be appropriate to contemplate abundant situations to obtain an overall analysis. Together with the help of additional codes, a comparison between square and diamond distributions is explained in the following section.

This report focuses on three main aspects that are representative for evaluating if a monitoring is optimal or not:

- Number of spheres required to monitor the whole area.
- Distance between an arbitrary point and the closest sensor.
- Number of communication partners per sensor.

4.5.1 Number of spheres required to monitor the whole area

Depending on the nature of the bulk material that is controlled for grain degradation, the necessary number of devices vary extensively. This quantity has a direct impact on the spending budget of the solution. If the amount required is large, the economical effort to carry out the procedure is higher than the one expected for a small quantity. This specification is of great significance, as it is directly related to the financial plan of the project.

There are many parameters that refer to the bulk characteristics which have a huge influence on the aspect to be studied. It would be impractical to try to analyse how the variables affect the number of sensors all together. Therefore, it is tried to synthesize all these elements into the most representative variables and observe how this influences the number of sensors via programs that simulate real cases approximately.

Firstly, the bulk volume dependency is studied. If the number of stored grains increases, the sensors needed to control them will also increase. To compare the behaviour of both distributions, the program *longitudinal_variable* is developed.

Depending on the amount of bulk material, the dimensions of the warehouses need to be adjusted. This program shares similarities with *first_distance_to_wall* and it poses different situations by varying the dimensions of the warehouse. All the other changeable parameters are maintained fixed while the input longitudinal size is entered as a vector with multiple values. By doing this, it is studied how the number of spheres increases while increasing the length of the layout and it is checked how this increment grows in both distributions. The output of the program is a graph that indicates the length of the longitudinal dimension on the horizontal axis and displays the number of sensors with red points for the square distribution and blue points for diamond distribution. The values of these points can be read on the vertical axis.

For these input variables, the outcome obtained is later commented.

```
distlong = 10:0.5:100;
disttrans = 10;
distcent = 4;
range = 5;
```

Figure 55 Input variables for longitudinal_variable

There are 181 different cases examined, all of them with different longitudinal dimensions. The first warehouse starts with a length of 10 m, incrementing by 0.5 m until the last case of 100 m is reached. The transversal length is maintained constant together with the distance of 4 m between the sensors and the communication range of 5 m. The achieved results are shown in the *Figure 56:*

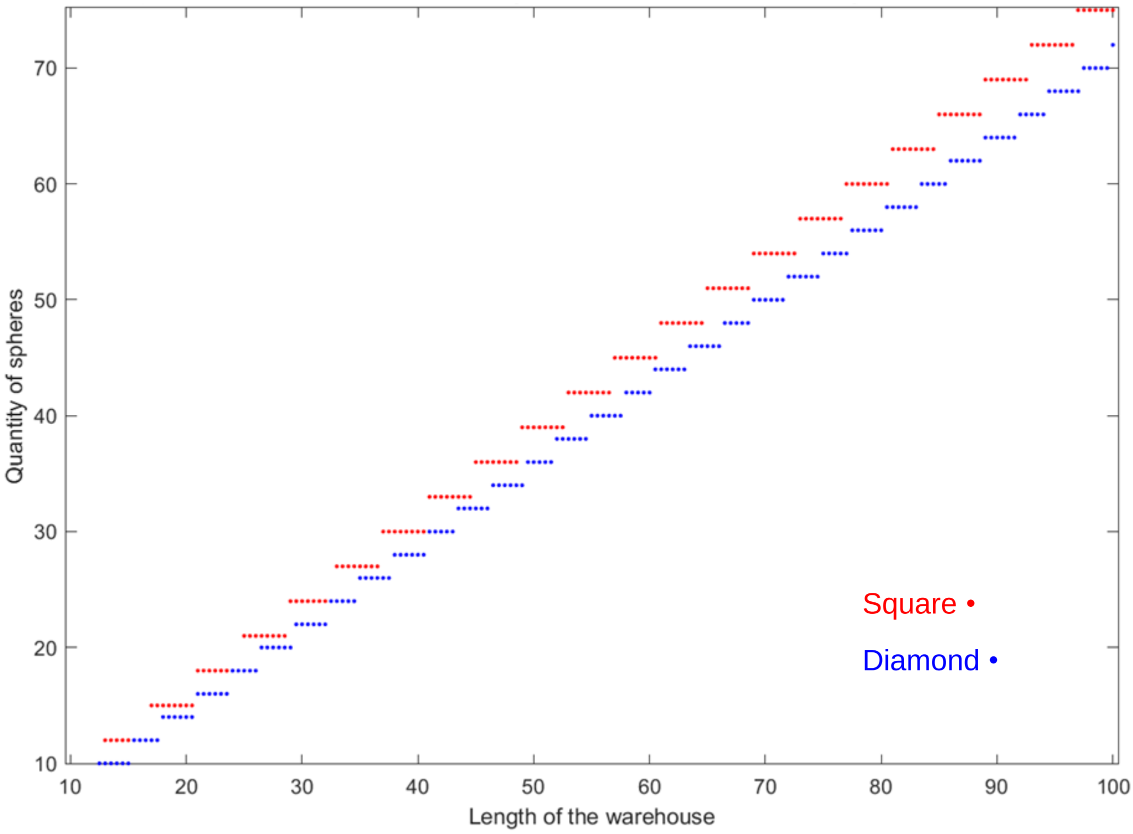

Figure 56 Number of spheres with the variation of the length of the warehouse

As expected, the number of sensors increases when the size of the warehouse enlarges. However, the growth achieved with the square distribution is more prominent than with the diamond distribution. In every case the diamond pattern uses less devices compared to the other one, as the blue dots are always underneath the red ones. This means that the diamond distribution can be considered as a more economical solution due to the smaller requirement of investments in resources.

In the early stages of the graph, in other words, for shorter warehouses, the results are quite similar in both distributions. Despite that, as the length of the layout grows, there is a more pronounced difference between the values of the two alternatives. To understand this gap enlargement there are two cases presented in the following figures, representing a relatively standard warehouse on one side, and a longer example on the other.

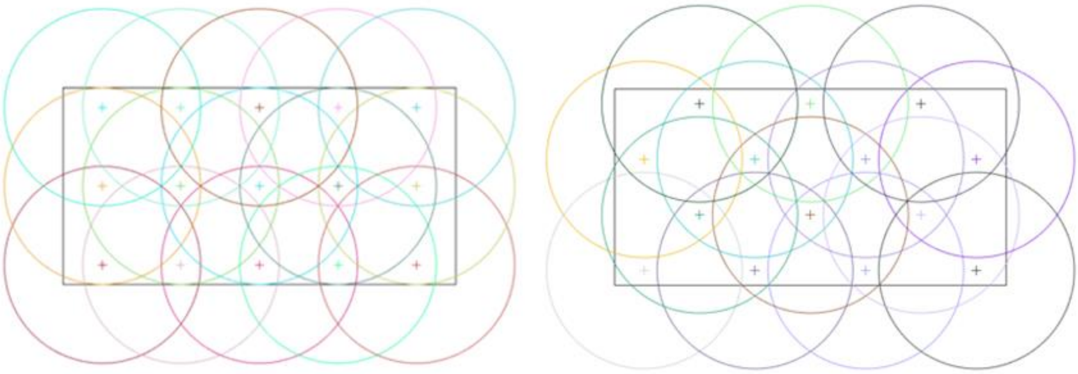

Figure 57 Example of a short warehouse

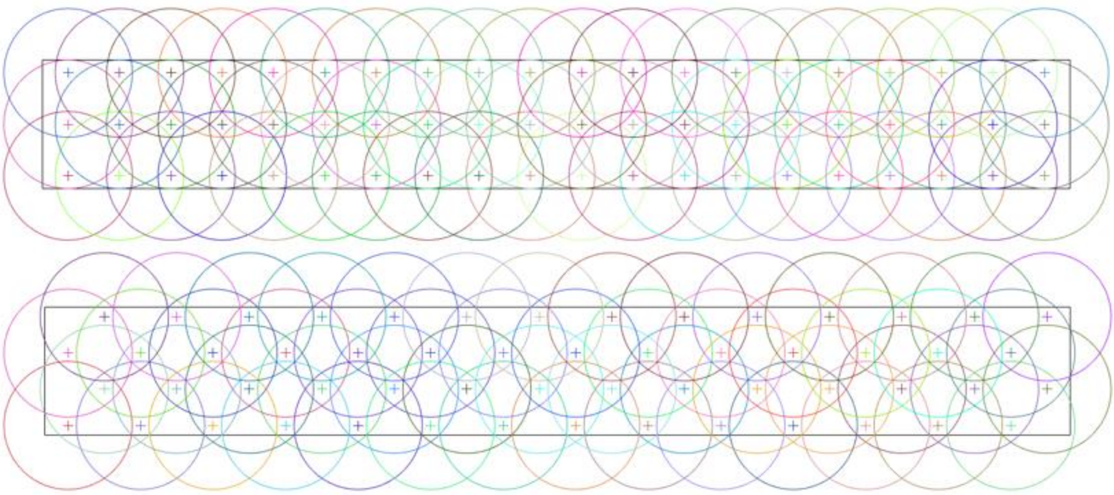

Figure 58 Example of a large warehouse

The case shown in the *Figure 57* belongs to a longitudinal value of 20 m. On the left, 15 sensors are distributed following the square pattern, while on the right the diamond distribution is built with 14. If the dispersion is examined, it seems that the sensors on the left are more densely packed than the ones on the right, particularly near the longitudinal limits of the warehouse. The same happens when the length of the layout increases until 80 m, the case in the Figure 58. 60 devices are displayed for the square distribution while only 56 are needed for the diamond. The gap between these two values has increased compared to the previous example and it is due to the mentioned concentration of sensors along the edges; if the length of the walls increases, the sensors around it will do the same.

Before drawing any conclusion, several simulations are being carried out with distinct fixed inputs like, for example, the transversal dimension or the distance between the sensors. The results obtained can be found in the *Appendix*

. All the cases studied share similar characteristics to the example examined, except for a couple of exceptions that will be later commented.

Besides the bulk quantity to be stored, the effect of a changing distance between sensors is also analysed. A program named *diset_sensor_variable* is developed to observe how the number of devices changes in both distributions when the distance between the sensors is increased or decreased for a fixed layout size. The fundaments of this program are almost identical to the previous one. Maintaining the dimensions of the warehouse, the influence of a variable sensor gap is examined. The output graph of the program is nearly equal to the one obtained for the variable length; the only difference is that the horizontal axis represents the changing separation.

A result report can be contemplated at the *Appendix*

. All the graphs displayed belong to different sizes of the warehouse, all of them represented above the figures. It is observed that in every case that the gap between the sensor increases, the number of sensors to be placed decreases. However, there is not a clear interpretable pattern to compare the two distributions. The values obtained for the two alternatives are very similar and the regressions that the points follow overlay depending on the gap. This effect can be observed in the following example, which is representative for all the result obtained:

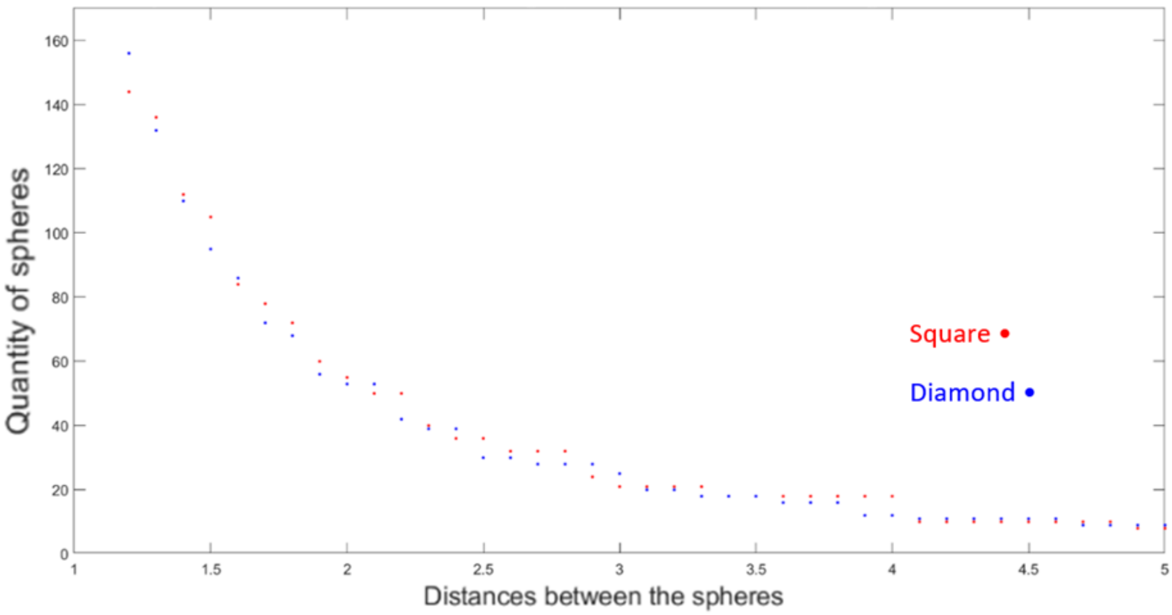

Figure 59 Example of number of spheres with variable separation between them

All the cases studied look similar to the example above, with no exception. Therefore, it is concluded that the varied variable makes no significant difference between the two alternatives.

With all the collected data from *first_distance_to_wall* it can be assured that in the great majority of the possible real situations, the diamond distribution needs less sensors than the square to control the same amount of grain. There are a couple of exceptions that can be found in the results report. These irregularities are caused because of the method used to compute the coordinates, but this only occurs with very specific input variables. Still, the diamond pattern has an advantage over the square when it comes to budget.

On the other hand, using less sensors can also lead to communication deficiency and risk the robust operation. It has been contemplated that in some diamond examples the distribution shows lack of a balanced organization indicated by large gaps without a sensor nearby. This issue, together with communication capacity, is going to be approached later.

4.5.2 Distance between an arbitrary point and the closest sensor

One of the fundaments for a proper monitoring is a symmetric distribution. This means that every point of the warehouse should be at the same conditions as the others. Of course, in the ideal case sensors would be able reach every point at the same time and read the measuring parameters constantly. Logically this is not achievable with the spherical prototypes since it is not possible to maintain every grain in contact with the sensor. Therefore, there will always be some areas in the bulk volume that are closer to the spheres than others. It is essential that there are no significant gaps far away from the measuring point. Isolated areas like these could cause unfavourable consequences. In the case of developing rot in this precise spot, the time expired between the start of the spoiling and the detection by the sensors would be relatively high, delaying the time to take action. This delay will lead to larger amount of grain loss, increasing the economic losses for the farmers. That is why it is appropriated to maintain the whole distribution symmetrical and well-balanced, to ensure that statistically there will not be any isolated point that can cause serious grain damages.

The criteria of placing the reference sensors *d/4* away from the walls is reassured by the statements above. It would not be beneficial to maintain a larger separation near the walls because it would lead to the appearance of critical areas around them. For that reason, it is favourable to maintain the isolated spots placed between the area limited only by sensors, and not in the edges near the walls.

The programs *mesh_square* and *mesh_diamond* have been developed to compute the distance between every point in a plane and the closest sensor to it. This helps to detect these critical spots and give a general overview of the dispersion balance. Both patterns (square and diamond) are being analysed if the isolated grain areas are symmetric or if there are locations that may be in danger. A good way of comparing them would be to check which is the maximum distance between an arbitrary point and the closest sensor, locating the areas where the grains are the farthest from the devices. It would be also convenient to observe if the distribution is balanced.

Both codes operate in exactly the same manner, one for the square distribution and the other for the diamond. When the input variables are introduced, it computes the coordinate vectors just like all the previous programs developed before. After the sensor's location is calculated, the whole layout of the warehouse is divided into finite small parts. A grid is created with a gap of 10cm between the points in representation of every spot of the warehouse. This value could be minimized to achieve a more exact examination of the problem, but 10 cm is enough to obtain a general overview. Knowing the exact coordinates of every point of the grid, it is identified which is the closest sensor in every case and the distance to it is computed. As a result, it is accomplished to approximate a continuous area to a finite system easier to handle.

With the data of the distances being stored, it is displayed which is the maximum value, together with a visual description of the state of the layout. The data is represented in a map in which every point of the grid is presented with a colour, just like a heatmap. Depending on the colour conceded, it can be deduced how far the location is from the closest sphere. The caption of the heatmap helps to identify if the point studied has a good location or not.

Figure 60 Caption of the heatmap

In the *Appendix*

attached, the results obtained for different situations can be observed. The following example is a representative case with the most common aspects that have been repeating among all the results collected.

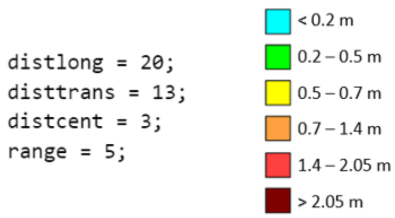

Figure 61 Input parameters and caption for the example

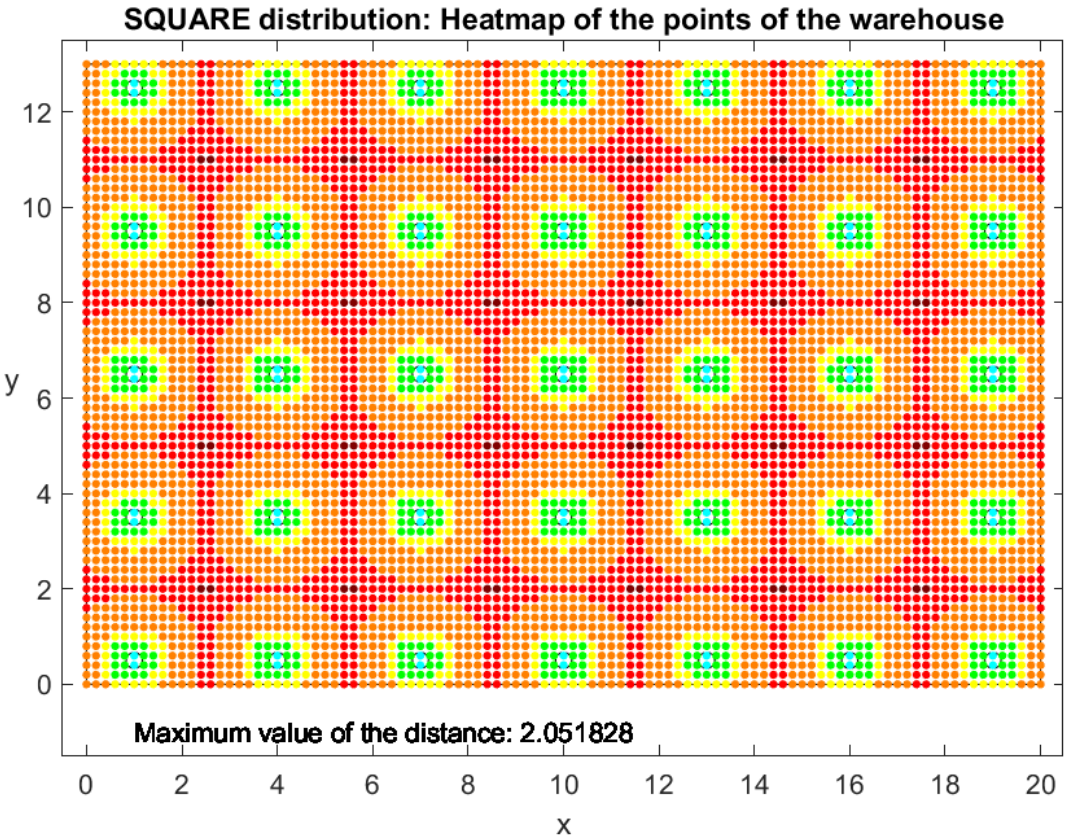

Figure 62 Example of heatmap for square distribution

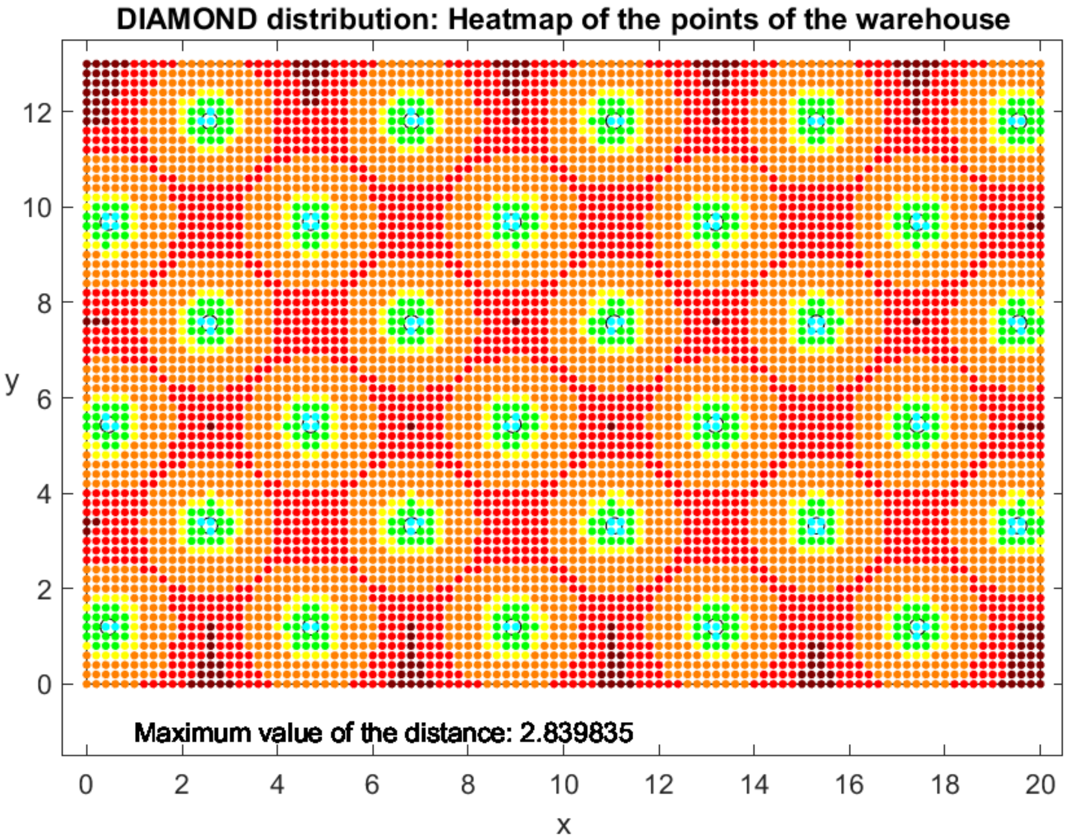

Figure 63 Example of heatmap for diamond distribution

The dimensions of the warehouse are 20x13m and the sensors are distributed 3m away from each other. As usual, the square distribution uses more sensors compared to the diamond, with a difference of 5 devices. When it comes to the maximum distance between an arbitrary point and the closest sensor, the diamond pattern has a clear disadvantage. Its value is 2,84 m, while the one obtained for the square distribution is 2,05 m. Although it seems that this variance may be insignificant, it can cause negative consequences related to the amount of grain lost due to spoiling. Apart from that, it is also remarkable that the number of dark areas in the diamond case are significantly larger than in the other case, meaning that there are much more critically located grains.

In terms of symmetry of the isolated spots, it can be argued that the square pattern achieves a more balanced distribution. Placing all the sensors close to the walls enables that the most critical points appear right in the middle of the pattern. In the case of the diamond, apart from the critical points inside the pattern area, there are abundant spots located far from the closest sphere. These areas tend to appear near the edges and along the walls of the warehouse. This happens because the way that the distribution is programmed, it will not place a sensor that would break the symmetry of the pattern.

In conclusion, it is true that a system based on the diamond distribution has economic advantages, but it must be considered if it is worth it to potentially risk a larger amount of grain by leaving more critical areas with isolated grains. This could be a matter of what is the monitored grain is used for; for example, the wheat applied for sowing is more expensive and requires a more careful monitoring, justifying the use of more sensors. While the one used to feed animals may require less control, and thus, less sensors.

4.5.3 Number of communication partners per sensor

It has already been explained that the sensors must be able to interact between each other in order to manifest a spoiling detection. This interaction is ruled by the communication range and the distance between the devices. More than one contact per sensor is needed, forcing a distance limit of the sensors. The farther the devices are, the worse will be the global communication. For an optimal functioning of the system, a minimum number of connections per sensor should be established, one value that would assure that there will not be any operation errors. Again, this cannot be a fixed value, as the robustness of the solution will always depend on the objectives and characteristics of the case.

The robustness of a solution is defined by the average number of connected couples an arbitrary sphere has. This value is directly dependent on the number of sensors used and the total communicative associations that are being established. As expected, not every sensor shares the same number of couples and depending on the distribution used, the dispersion of this numbers may increase. The most critical values, thus, the sensors with less neighbours, belong to the ones located at the edges of the warehouse. As it has been observed during the different examples, the devices near the walls do not have neighbours in all the directions due to the limits of the warehouse; therefore, hypothetically they have a higher risk of becoming isolated. This isolation must be always avoided, as it causes not only uselessness of the sensors but also economic losses due to a delayed spoiling detection. The communication isolation can be caused by location errors created at the placement, sensor failures or problems with the communication range.

It is now being studied how the distributions deal with the number of communication partners per sensor. With two different programs, various cases are being analysed while an input variable is being altered. This variable is the sensor separation, since it is directly related to the aspect that is going to be examined.

The first code *contacts_variable_dist* gives a set of histograms with information about the distribution of the neighbours' quantity, that is to say, how many spheres have a specific number of connections. The dimension of the warehouse together with the communication range is fixed, while each histogram displayed belongs to a specific sensor separation. This distance goes from 2.3 m to 3.7 m, increasing 0.2 m for every case. This means that every time the program is simulated 16 different histograms will appear, referring to 8 different situations per distribution type. For a general overview, the results obtained can be visually compared. For a more precise examination it is possible to read the values directly on the graphs and contrast the possible solutions.

The second program *cumulative_histogram* gives the same information than the previous one, but the results are displayed in a different way. This time both distributions are being compared in the same graph, giving a more visual interpretability to the histograms previously calculated. For the same 8 cases, it displays the number of sensors that have at least the connection couples displayed on the horizontal axis. This means that the first point from the left in the graph coincides with the total amount of spheres and the minimum quantity of coupling possible for an arbitrary sensor, because all the devices have at least the minimum connection value. The square distribution is being displayed in red while the blue data is for the diamond pattern.

Right next to the graphs, the average number of connected couples per sensor is shown for both patterns. This result is also essential to evaluate the capacities of the alternatives. In situations where the average is higher, the communication is more robust.

For a general representation of the cases studied, the example with the following inputs is being examined.

```
distlong = 20;
disttrans = 10;
distcent = 2.5:0.2:3.9;
range = 5;
```

Figure 64 Inputs for communication example

As mentioned, the values of the connection numbers can be read directly on the histograms and compare every case individually. However, resulting histograms of the example are not being displayed because examining specific comparisons is not the main goal. For an overall review it is easier to observe the cumulative histograms in the *Figure 65*.

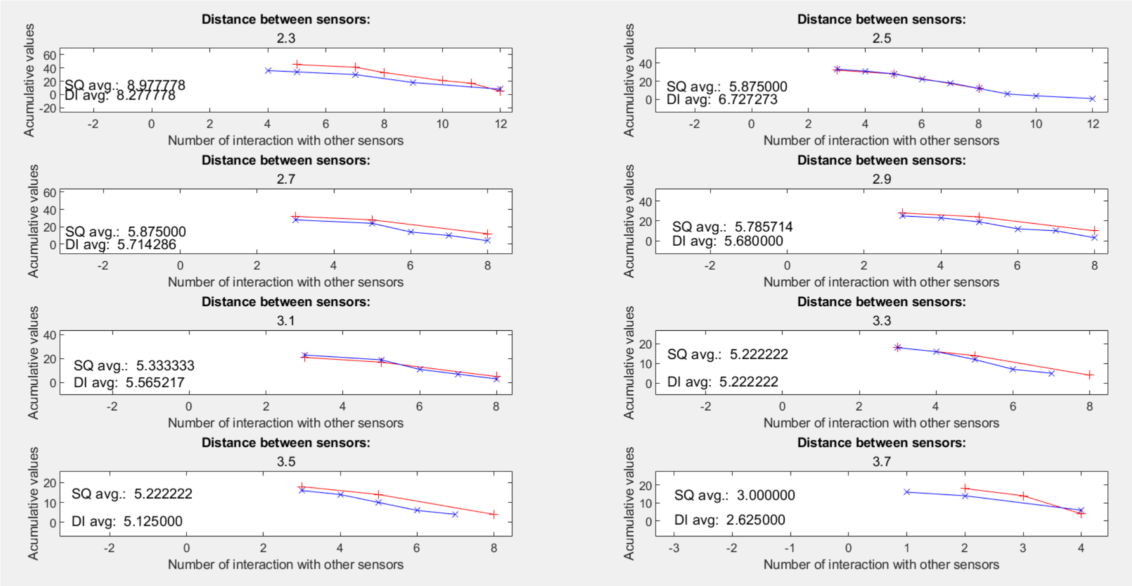

Figure 65 Cumulative histogram examples

It is observed that the red points are most of the times above the blue ones. It is clear the square distribution uses a larger number of sensors for the monitoring; however, this does not mean that its connectivity is better. Noticing the average values, it is concluded that there is not a clear succeeder. It is true that in various occasions the average obtained for the square pattern is slightly higher than the average for the diamond distribution, but the difference is far from decisive. The same happens in the cases where the diamond overtakes its alternative, the gap is insignificant. Therefore, it cannot be said that in general one distribution has a better average connectivity compared to the other.

Besides that, it is noticeable that there are more points displayed in blue than in red in every case. This means that there is a higher variation in the number of couples that a sensor can acquire if it is distributed with a diamond pattern. For example, checking the graph corresponding to a separation of 2.9m, there are 3 points in red against 6 points in blue. When it comes to the square distribution, an average sensor will only have 3 possible options: being connected with 3, with 5 or with 8 other spheres. For the diamond distribution, a random device would be coupled with 3, 4, 5, 6, 7 or 8, 6 possible options. What it can be concluded from this phenomenon is that the balance of the square distribution leads to symmetry and equality of conditions for all the sensors, while the diamond patterns permits a wider range of conditions.

It is also remarkable that in some cases, the minimum value of neighbour number is lower for the diamond distribution. This is clearly a disadvantage for this alternative, as it risks the communication of some of the devices.

Finally, yet importantly, the diagrams displayed help to define some parameters for recommendable operation conditions. It has been argued that it is not desirable to set a distribution with sensors being coupled with only one communication pair. As an assumption, an adequate minimum value would be 3 couples, as it would significantly minimize the isolation probability. For ensuring this, the sensors cannot be placed at a distance far from each other. Examining the graphs, it is shown that in the case of the 3.7m separation, the minimum values of couplings for square and diamond are 2 and 1 respectively. These numbers are below the recommendation, therefore, the distance between the sensors should never be 3.7 m or more. On the other hand, for a suggested minimum separation the case of 2.3m can be noticed. The spheres located on the edges, thus, the ones with the worst communication conditions, have at least 4 paired neighbours. This situation can be considered as excessive, and it may suppose unnecessary expenses on overcrowding of sensors. Therefore, 2.3m is a recommendable limit value for the separation gap when it comes to communication. However, it cannot be forgotten that there are cases in which a more robust solution is required, and a high number of sensors is needed for a better control and more exact measurements. In these cases, there would not be any lower limit for the sensor gap.

In conclusion, the value of the distance between the sensors will always be fixed depending on the robustness desired for the solution. A recommendable approximate range for appropriate communication conditions would be between 2.3 and 3.7m, for both distributions.

4.6 3D analysis

The previous analysis fulfilled for the 2D distribution of the spheres is valid for a 3D study. The results obtained when it comes to operating conditions are also applicable to the space dispersion. In the following chapter a collection of programs is presented, that will give a visual representation of a grain storage warehouse with the measuring devices being placed. The aim is to obtain a general idea for a real situation and examine the sensor location depending on the dispersion used. In this way the exact theoretical coordinates in space of the spheres can be determined and the different possible combinations of patterns compared. The effect that an external perturbation such as dropping error may have is also considered.

As mentioned at the *Distribution types* chapter, there are 4 possible combinations of patterns to fill the space occupied by the bulk:

- Square in plane and square in vertical direction.
- Square in plane and diamond in vertical direction.
- Diamond in plane and square in vertical direction.
- Diamond in plane and diamond in vertical direction.

4 different programs have been developed, one per combination. Their names are *SQ_SQ, SQ_DI, DI_DI* and *DI_DI*. All of them share the same structure and input parameters, as well as the way of showing results. These programs are similar to the ones developed for the computation of coordinates in 2D, starting from the premise that it is necessary to begin from a plane in order to assign the location in the space. The first thing that the programs do is compute the coordinates in two dimensions depending on the distribution selected. It is done by following the criteria from previous codes for square or diamond. Once determined, the third direction is developed, also being able

to choose between the two alternatives. In the *Figure 66* and *Figure 67* it is shown how a square pattern in 2D can be developed in two different ways along the vertical direction.

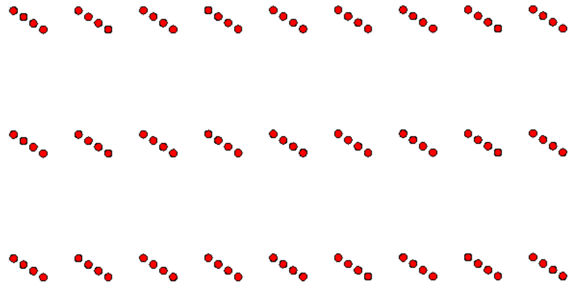

Figure 66 Square development among vertical axis

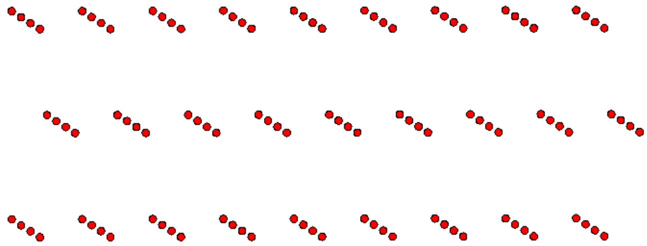

Figure 67 Diamond development among vertical axis

The square development repeats the plane pattern one on top of each other with no alteration. In the case of diamond development there is a small deviation of the plane in the middle, as it can be seen that is moved slightly to the right. Both vertical growth types can be used for a diamond plane pattern.

In respect of the input variables of the code, these are needed parameters for the computation:

- Longitudinal dimension of the warehouse.
- Transversal dimension of the warehouse.
- Vertical dimension of the bulk.
- Distance between the sensors.
- Communication range.

For a real case of grain monitoring, it is quite simple to calculate the vertical dimension of the bulk, as long as the volume of the grain to be stored and the size of the warehouse are provided. Once the input parameters are introduced, the program presents a visual simulation of the warehouse, with all the sensors introduced into the grain. The exact theoretical coordinates of each device can be read in the results given. Apart from that, a histogram is provided, that shows the number of neighbours per sensor, which can be analysed for a communication evaluation.

Now a real case situation is considered as an example to explain the code. Assuming that 1200 m^3 of grain are stored and monitored in a flat storage system warehouse with the dimensions of 20 x 10 m. A proper communication between the sensors is wanted, therefore a separation of 2.5 m is considered. Consequently, the inputs that should be entered are:

```
distlong =20;
disttrans = 10;
distcent = 2.5;
distgra = 6;
range = 5;
```

Figure 68 Inputs for real case situation

The results obtained for the square in plane and square in vertical direction distribution are shown as an example.

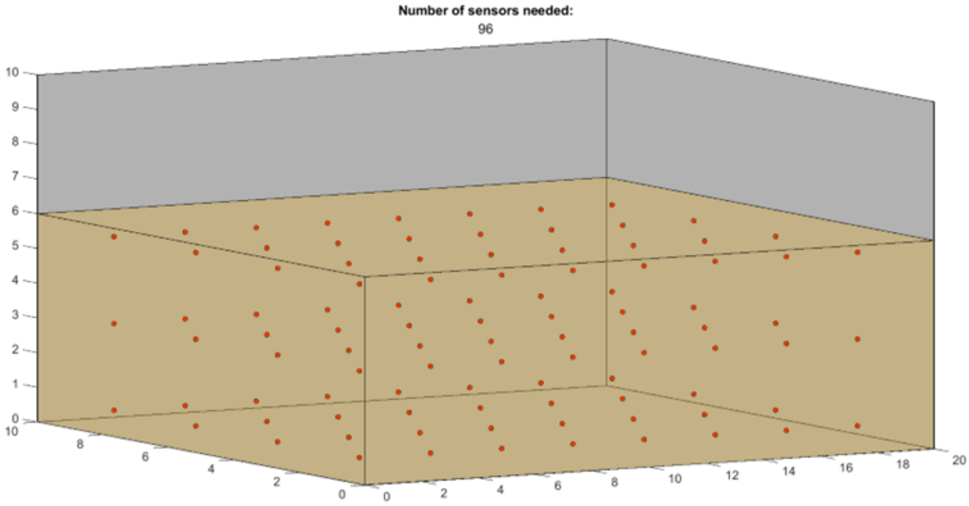

Figure 69 Real case example simulation

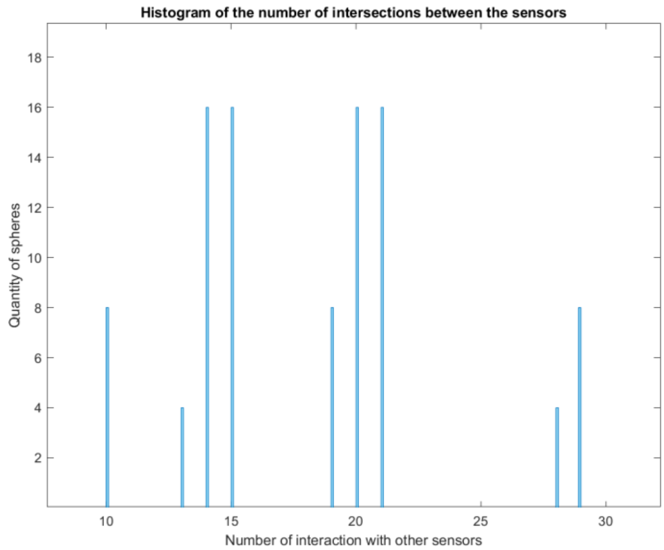

Figure 70 Histogram of a real case situation

The *Figure 69* shows the distribution of the sensors inside the grain, together with the number of devices used (in this case 96). The *Figure 70* displays the histogram representing the communication capacity. It must be mentioned that the minimum number of neighbours that an arbitrary sensor has is 10, meaning that the solution proposed is quite robust. This value cannot be compared with the results obtained in the previous chapter because it is logical that a distribution studied in the space will always have higher average neighbours per sphere. Therefore, it cannot be assumed that the previously proposed recommendable range will be valid.

In order to suggest a new range, the same procedure as in *cumulative_histogram* has been followed, this time for 3D distributions. 8 cases have been studied in which sensor separation varies from 2.9 to 3.6m. These are the results obtained for all the combinations considered:

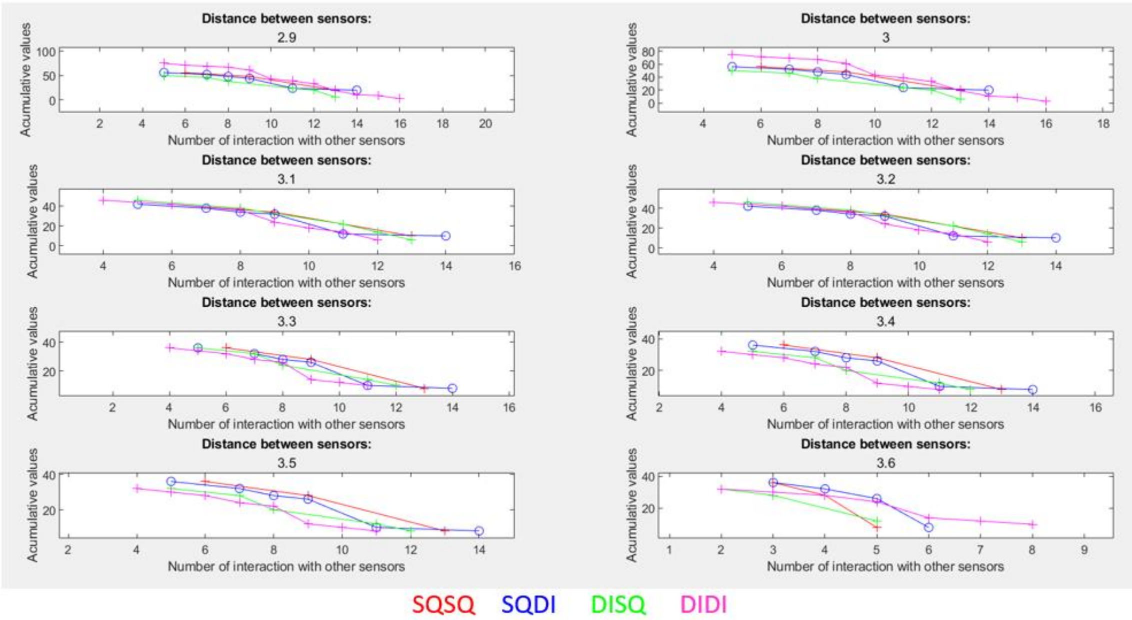

Figure 71 Cumulative histograms for space distributions

In the case of the separation being 3.6m, it is checked that the minimum value of communication couples is 2 for the cases of diamond in plane and square in vertical direction and diamond in plane and diamond in vertical direction. This number may increment the isolation risk of some spheres; therefore, it is not recommended to place the sensors with a gap larger than 3.5m. There will not be a limit set for a minimum separation this time, as it will always depend on the robustness desired for the solution.

Apart from this study, the effect of a probable phenomenon is also examined: the placement error of the sensors. Until now, the theoretical value of the coordinates was calculated, but there will be some cases in which they may differ from the real ones. If the proposed solution for the introduction of the spheres is considered, it is probable that the devices will bear some deviations when dropping them from the feeding belt due to the motion of the grain. This deviation may generate some communication issues, as the separation between some sensors may increase. This would be a potential complication for the spheres placed on the edges, as they are the ones with the minimum number of neighbours. To analyse this phenomenon in the four possibilities, 4 programs have been developed. These programs compare the total number of communication couplings in two different cases. The first one considers that the dropping error is zero, thus, the ideal case in which the real location of the spheres coincides with the theoretical computed values. The second considers a placement error, placing all the sensors of the edges

0.55 m away from the other spheres. By doing this, the separation between the devices on the edge and the closer sensors increases by the established difference. This is an assumed value for the error taking into account the height of the feeding belts.

The two opposed cases are compared in the histogram displayed by the programs, in which the reduction of communication couples is displayed, that a system undergoes when the error is considered. The percentage of connections lost is also determined, which will help to compare the 4 alternatives.

Some of the histogram results for different situations can be checked at the *Appendix*

at the end of the document. A representative example is shown in the *Figure 72*, a *SQ-SQ* distribution.

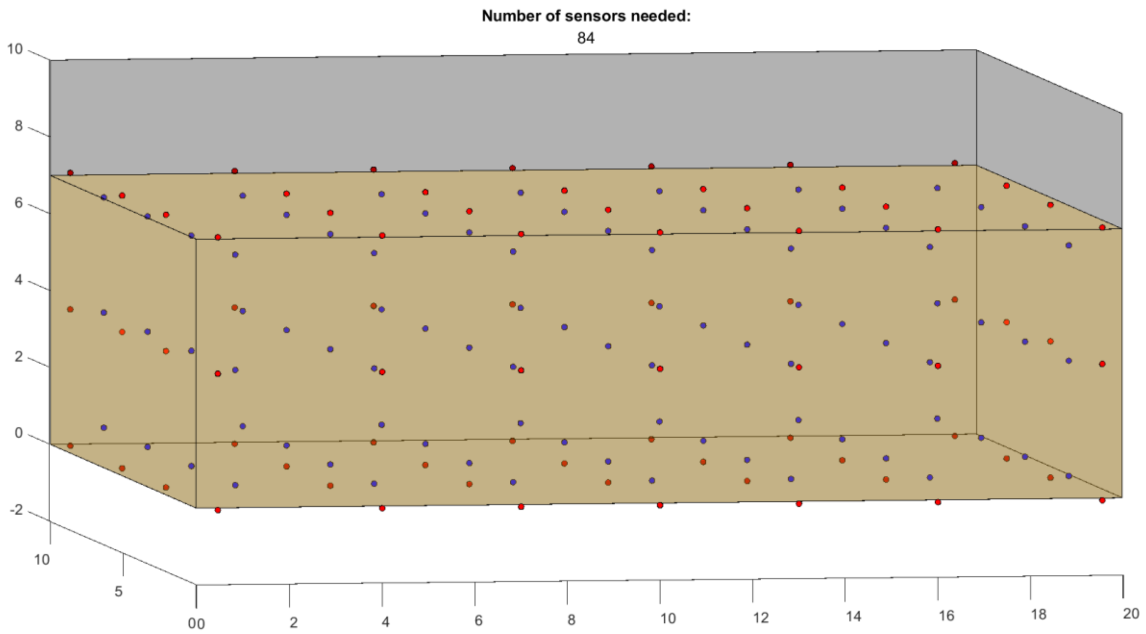

Figure 72 Drop error effect in SQ-SQ distribution

The spheres shown in blue belong to the ideal case, when the dropping error is not considered. The ones shown in red allude to the worst-case scenario, when the edge sensors are separated from the others. The histogram displayed is the following one.

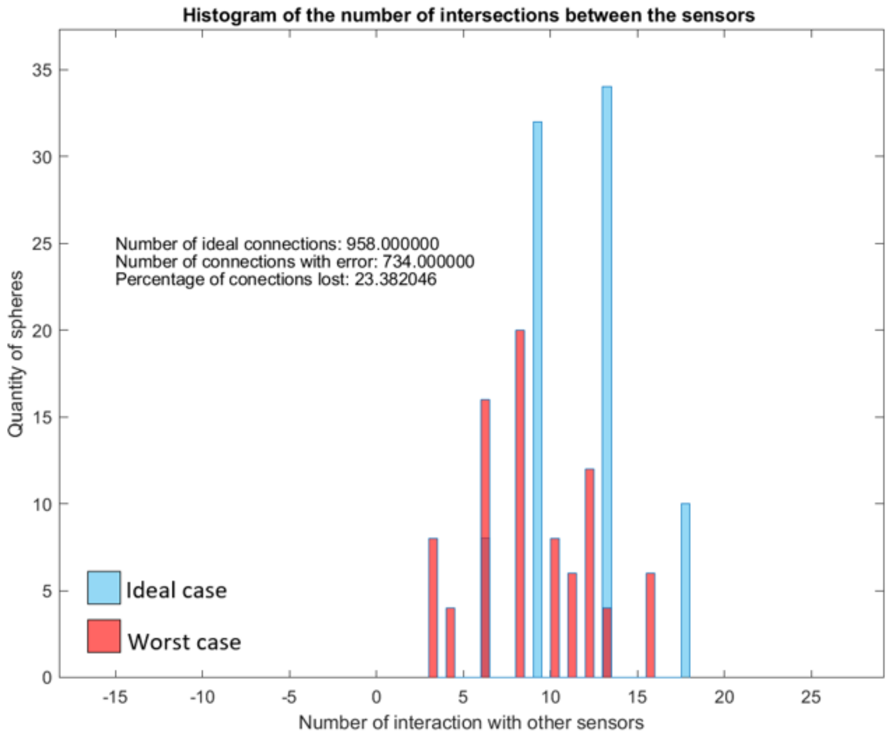

Figure 73 Histogram comparing the ideal case with the worst case

As expected, the general number of connections has decreased significantly, moving the histogram to the left and reducing its size. This can also be reassured by checking the values on the left side of the histogram. The total number of couples has decreased by a 23.38%, which can be assumed as a serious proportion. It is also remarkable that the minimum neighbours per sensor have decreased from 6 to 3, implying the mentioned risks. In general, although these results show a substantial difference between the options, it must be reminded that these are two limit cases.

Examining the general results, it cannot be said that there is a combination that stays ahead of the others when it comes to the percentage of communication loss. There are plenty of variables that have an effect on the distributions in the space, and every possible situation implies specific values for those variables. Therefore, it will always depend on the characteristics of the problem when a combination is selected.

In general, for choosing a proper distribution in the space, it is recommended to simulate all the programs related to this chapter and make a specific analysis for the case. It is suggested to apply a separation between the sensors depending on the robustness desired and budget for the system, being 3.5m at most for an adequate communication.

5. Conclusions and future work

This research had the objectives of finding an adequate way of integrating the sensors and studying the necessary conditions for the proper monitoring of grains. The evaluation of different alternatives has been carried out together with the comparison between different methods. The results of the analyses obtained lead to theoretical solution proposals described through this written dissertation.

The proposed introduction method based on a dispenser machine has been designed by virtue of investigating similar mechanisms applied in diverse sectors. The concept is developed bearing in mind the ability for facing issues related to functioning, anticipating to hypothetical problems such as sphere blockage. It is not possible to assess its real efficiency and reliability as it has not been carried out a practical approach by manufacturing it. However, the level of detail deployed in the development of the solution enable to predict overall capacities like the theoretical number of devices that it can store (170 units). The size of the drawn model also fits the compactness constrains considered for a flat storage system warehouse, and its form enables a comfortable reload operation.

It is true that some aspects that have been assumed cannot be tested until an actual prototype is manufactured. Substantial characteristics like the cost of the machine or the fabrication difficulty could have been also hypothetically approximated, but it was decided that it was simply not worth it to invest time to study those thoroughly. Nevertheless, more effort has been put on achieving the simplicity of mechanisms and elements, which will for sure facilitate the later production.

Further ways of expanding this work could focus on a more detailed model of the dispenser, refining the structural parts and defining a suitable control method. After achieving this, it would be possible to fabricate a prototype and review its effectiveness and automation. Only then it is feasible to perform a global and reliable evaluation, by carrying out actual experiments and measurements that determine the utility of the proposed solution.

Summarizing, it can be assured that the proposed alternative meets all the requirements established and can be taken as a reference for future projects.

In terms of the placement and quantity of spheres needed for the monitoring, the results obtained in 2D show that the diamond pattern uses less devices than the square to measure the same area of the warehouse. In principle, this can be considered as an economic advantage, but there are other aspects to be considered for choosing one or another. It has been proved that the square distribution achieves a more balanced situation, controlling all the critical spots confined between the spheres. Implementing fewer sensors also lead to communication deficiency in the case of the diamond distribution, which could carry the risk of losing higher amounts of grain due to the sensor isolation. Therefore, it recommended to perform cost-risk analysis and determine if it is worth to invest in more sensors in order to avoid more product loss.

If a type of distribution had to be chosen in a general sense, I am under the impression that the square distribution fits better the type of warehouses examined, due to the fact that in respect of equilibrium of the isolated areas it achieves a more organized situation. It makes sense that for a rectangular shaped layout, the pattern followed by the displaced sensors coincides in form. That would not be the case for the diamond distribution, which would be more appropriate for a rhombus shaped warehouse.

The programs developed for this thesis clearly help to determine a distribution in the space. Knowing the characteristics of any situation it is possible to simulate the different alternatives and compare them until the proper one is chosen. The fixed distance between the sensors will always be decided depending on the robustness desired for the case and it has been proven that a recommendable upper limit for adequate operating conditions would be 3.5 m.

Further research can be done to improve the reliability of the simulations or to increase the field in which these programs can be used. As a suggestion, developing another code that could compute the maximum volume lost because due to rotting before it is detected by the closest sensor would be beneficial for a space distribution election. This would also be helpful for determining the potential grain loss and determining if it is worth it to spend more budget on placing more sensors in the critical areas.

Apart from this improvement, it would be favourable to be able to adapt the introduction system together with the codes for sensor distribution to different storage methods. It quite common nowadays to collect the grains in cylindrical silos, being the monitoring in this case a possible future work to be done.

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[5] Figure 5

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Appendix

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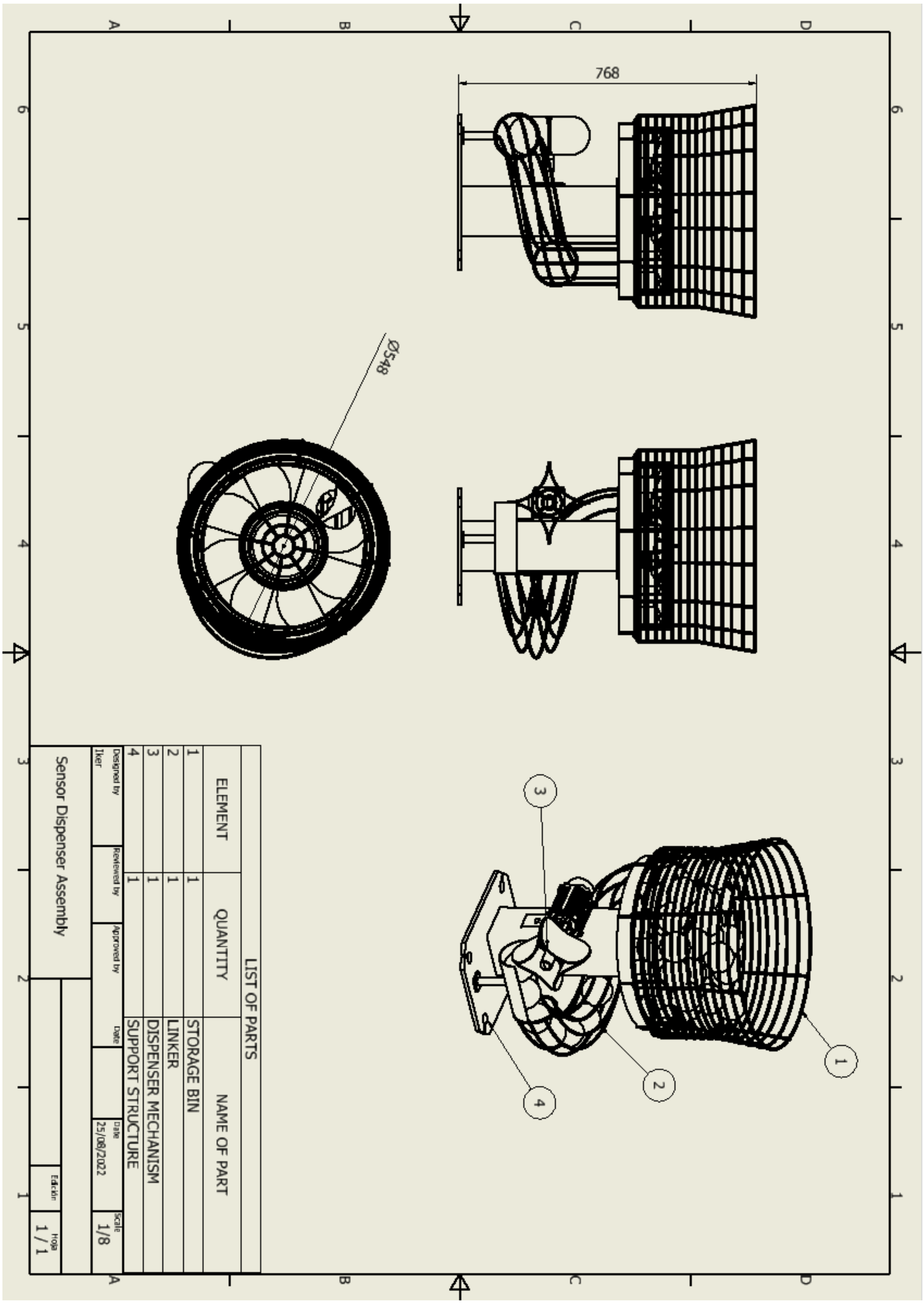
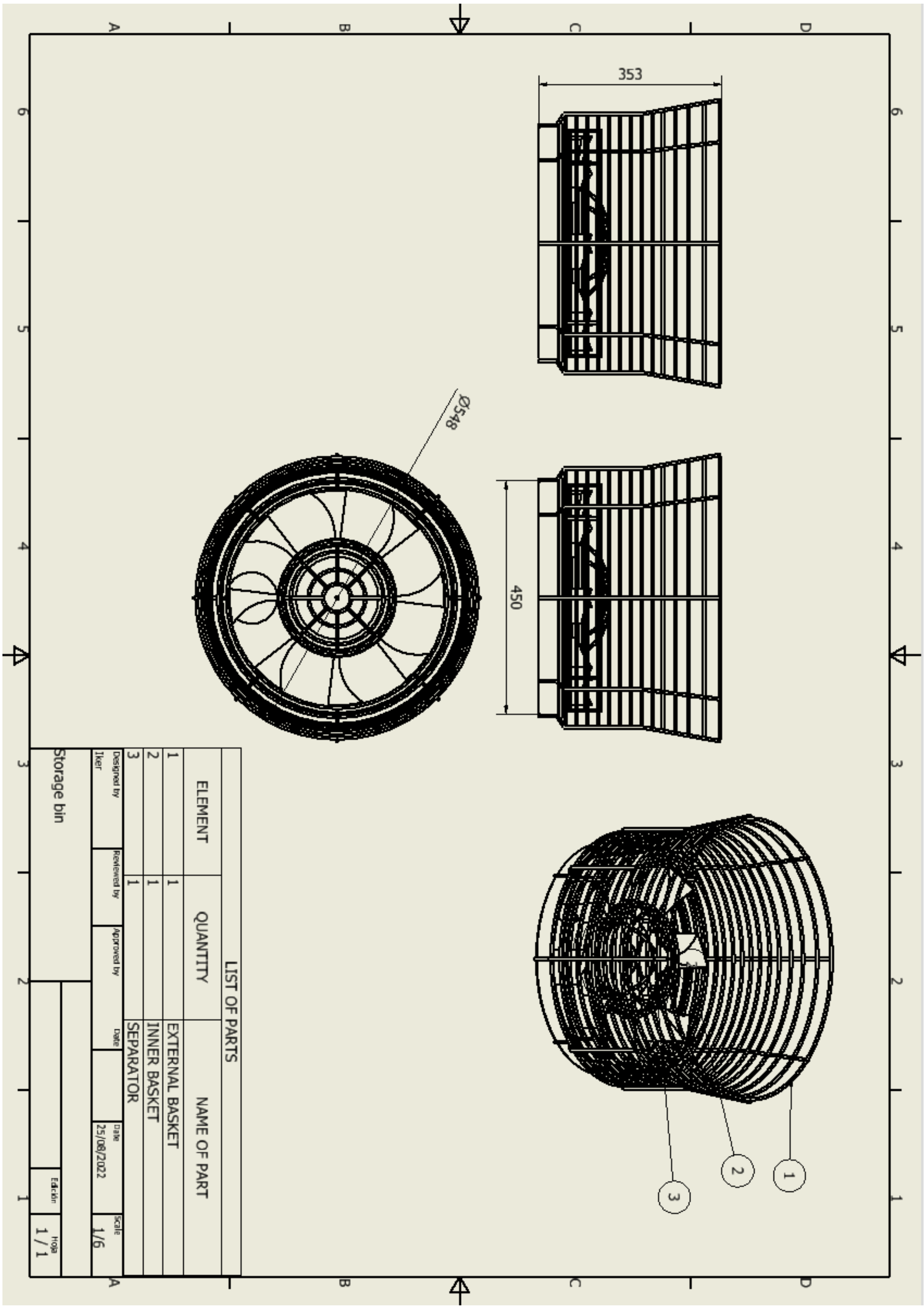
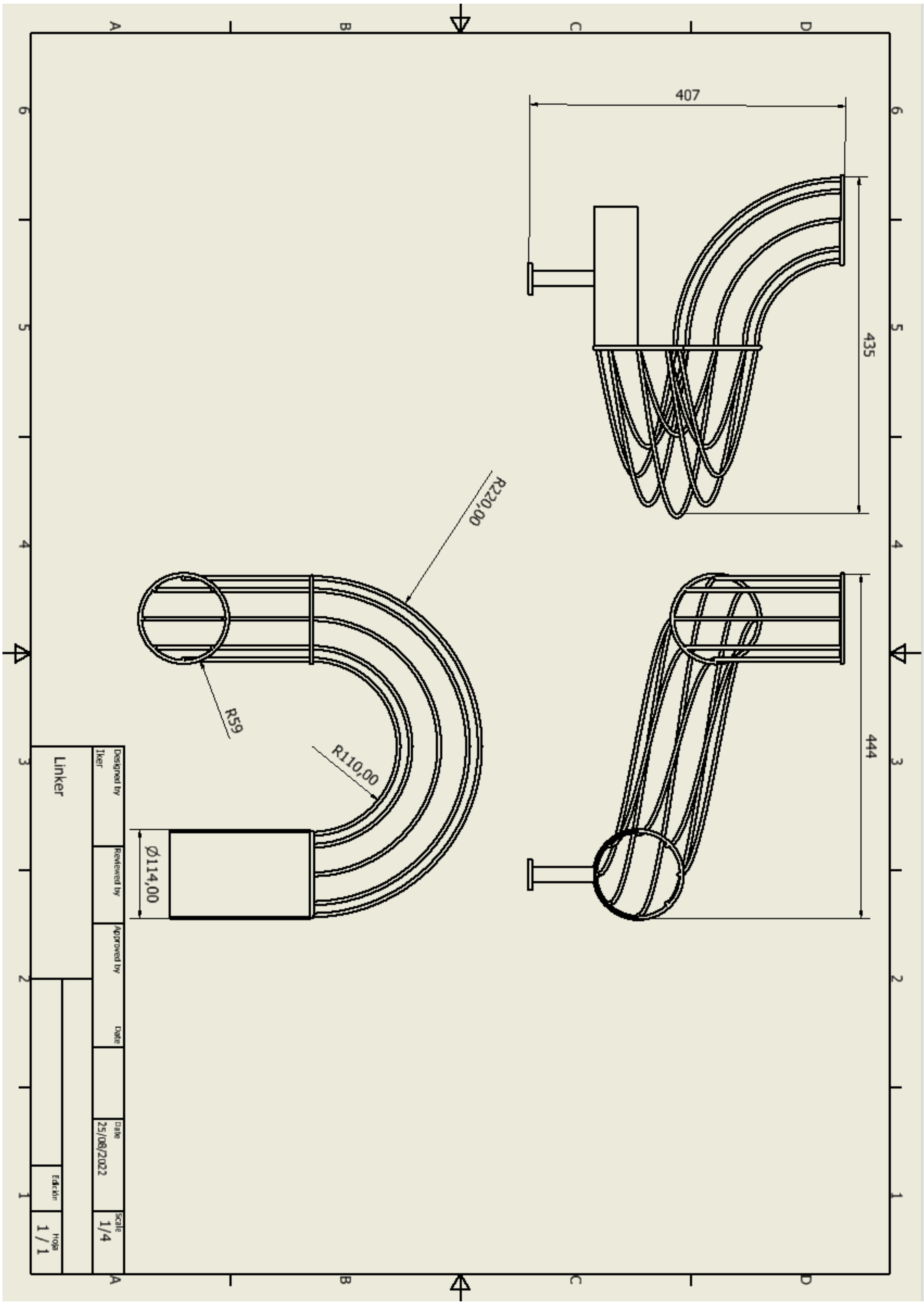
Sensor Dispenser Assembly 2D



Storage Bin 2D



Linker 2D


407
435
444
R220,00
R59
R110,00
Ø114,00
Linker
Designed by
Iker
Reviewed by
Approved by
Date
Date
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Hoja
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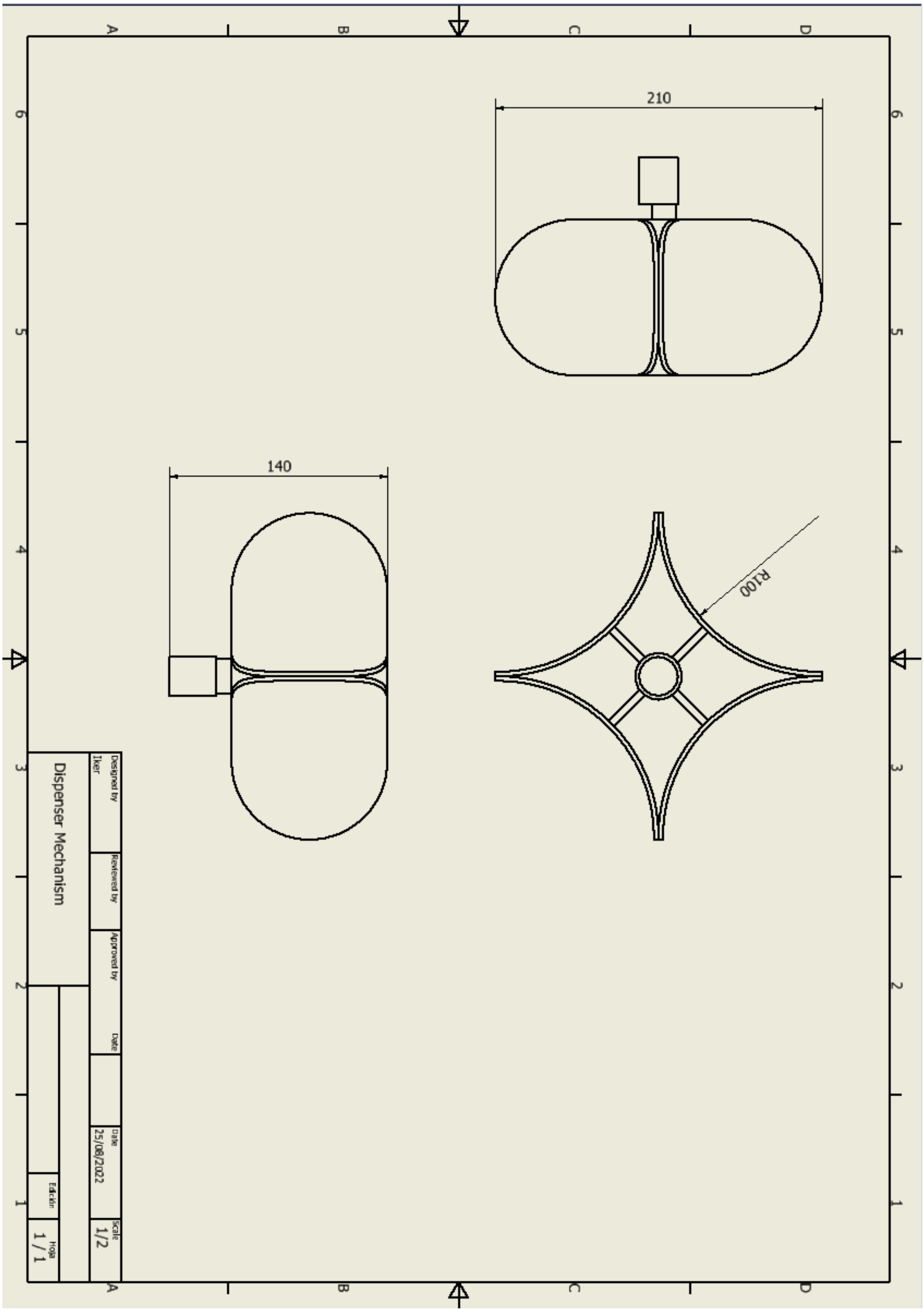
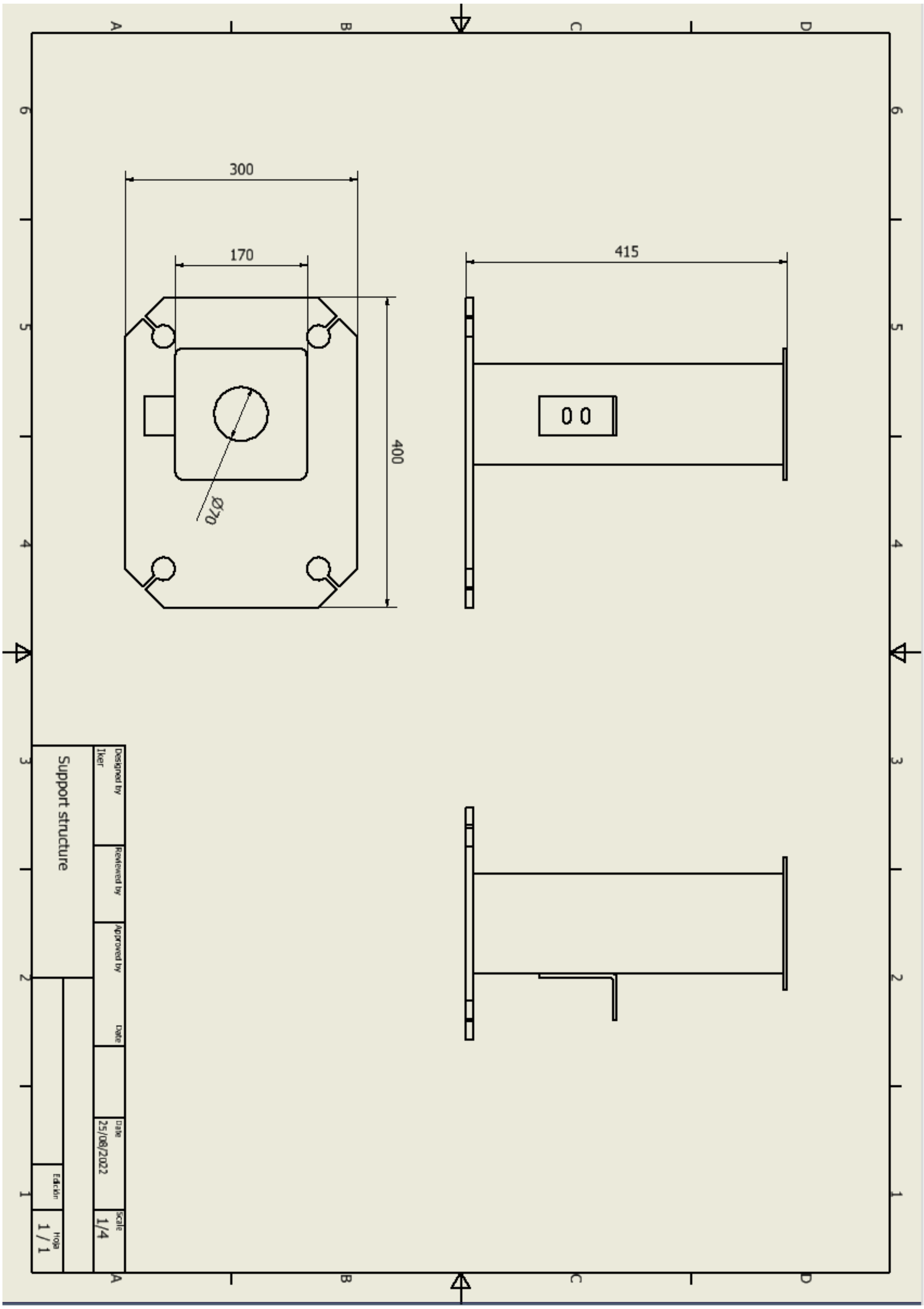
Dispenser Mechanism 2D



Support Structure 2D



Square distribution basic program (1/3)


```
clear

%Input variable collection (warehouse dimensions, distance
%between sensors and connectivity range)
distlong =20;
disttrans = 10;
distcent = 3;
range = 5;



%Values of the coordinates in  both directions. These first coordinates
% will be repeated to calculate the coordinates of all the sensors
x1 = (distcent/4:distcent:distlong);
y1 = (distcent/4:distcent:disttrans);
nspherx=length(x1);
nsphery=length(y1);

%The first sphere is placed half the distance between the sensors away from
%the wall. For example, If the distance between the sensors is 3 meters,
%the first sensor would be 1.5m away from the wall.
%The last sensor can be as close as possible to the wall, at the end the
%coordinates will be centered so it can be better distributed.


%With the coordinates of the first sensors as a reference, get the
%coordinates of all the sensors
x=repmat(x1,nsphery);
x=x(1,:);
y=repelem(y1,nspherx);

%Put the sensors more centered
diflong=(distcent/4+(distlong-x1(nspherx)))/2;
x=x-distcent/4+diflong;
diftrans=(distcent/4+(disttrans-y1(nsphery)))/2;
y=y-distcent/4+diftrans;

%Calculate the number of spheres and give value to the range to all of
%them.
nspher=length(x);
r=repelem(range,nspher) ;

%To calculate the number of spheres which a single sensor interferes with,
%it will be taken into account the distance between these, as the range
%will be constant. As an imaginary range depending on the distance between
%the spheres, it will be calculated a matrix that will give the
%superposition area and with that calculate if it exists a superposition.
%This way we will be able to calculate the number of sensors that interact
%together.

imar=repelem(range/2,nspher) ;

% Inputs are reshaped in columns
size_x = numel(x);
```

Square distribution basic program (2/3)


```
size_y = numel(y);
size_r = numel(r);
size_imar = numel(imar);

x = reshape(x,size_x,1);
y = reshape(y,size_y,1);
r = reshape(r,size_r,1);
imar=reshape(imar,size_imar,1);


% Calculation of distances between all spheres
[X,Y] = meshgrid(x,y);

D     = sqrt((X-X').^2+(Y-Y').^2);

% Since the matrix M for overlap computation is symmetric M(i,j)=M(j,i),
% calculations are performed only on the upper part of the matrix
D = triu(D,1);

[R1,R2] = meshgrid(imar);
sumR    = triu(R1+R2,1);
difR    = triu(abs(R1-R2),1);


% Creating the resulting vector
M = zeros(size_x*size_x,1);

% Partial intersection between circles i & j
C2 = (D>difR)&(D<sumR);

% Computation of the coordinates of one of the intersection points of the
% circles i & j
Xi(C2,1) = (R1(C2).^2-R2(C2).^2+D(C2).^2)./(2*D(C2));
Yi(C2,1) = sqrt(R1(C2).^2-Xi(C2).^2);

% Computation of the partial intersection area between circles i & j
M(C2,1) = R1(C2).^2.*atan2(Yi(C2,1),Xi(C2,1))+ ...
          R2(C2).^2.*atan2(Yi(C2,1),(D(C2)-Xi(C2,1)))- ...
          D(C2).*Yi(C2,1);

% Compute the area of each circle. Assign the results to the diagonal of M
M(1:size_x+1:size_x*size_x) = pi.*imar.^2;

% Conversion of vector M to matrix M
M = reshape(M,size_x,size_x);

% Creating the lower part of the matrix
M = M + tril(M',-1);


% Display results

    f1 = figure;
    hAxs = axes('Parent',f1);
```

Square distribution basic program (3/3)


```
    hold on, box on, axis equal
    xlabel('x')
    ylabel('y','Rotation',0)
    title('Distribution of the sensors on the warehouse' )
    text(-5,-5,'Intersection between the ranges of the sphere sensors' )
    text(-5,-6,sprintf( 'Number of sensors needed: %f' , nspher))
    axis([-8 40 -8 20]) ;
    colour = rand(size_x,3);
    rectangle('Position',[0 0 distlong disttrans])
    for t = 1: size_x
        plot(x(t)+r(t).*cos(0:2*pi/100:2*pi), ...
             y(t)+r(t).*sin(0:2*pi/100:2*pi), 'color',colour(t,:),'parent',hAxs)
        plot(x(t),y(t),'+','color',colour(t,:),'parent',hAxs)
    end


%HISTOGRAM calculation
istoaxis=zeros(1,max(size(M)));

for i=1:1:length(istoaxis)
    for k=1:1:length(istoaxis)
        if M(i,k)~=0
            istoaxis(i)=istoaxis(i)+1;
        end
    end
end
%Subtract the intersection with its own
istoaxis=istoaxis-1;

%Plot the histogram
figure;

    hold on, box on, axis equal
    xlabel('Number of interaction with other sensors' )
    ylabel('Quantity of spheres','Rotation',90)
    title('Histogram of the number of intersections between the sensors' )

    HG=histogram(istoaxis);
    HG.FaceColor = [0.3010 0.7450 0.9330];
    HG.EdgeColor = [0 0.4470 0.7410];
    HG.BinWidth = 0.1;
```

Diamond distribution basic program (1/6)


```
%Input questions and variable collection (warehouse dimentions, distance
%between sensors and connectivity range)
distlong = 20;
disttrans = 10;
distcent = 4;
range = 5;

%Calculate some parameters for the limit values to fill the whole area of
%the warehouse
catet=range/(sqrt(2));

%%%%%%%%%%%%%
%this is the distance between 2 sensors in the same axis!! (long distance)
distsph=2*distcent/sqrt(2);


%definition of x1 and x2
x1 = (distcent/4:distsph:distlong);
nspherx1=length(x1);

x2 = (distcent/4+distsph/2:distsph:distlong);
nspherx2=length(x2);

if x1(nspherx1) > x2(nspherx2)
    %These operations are needed to assure that the whole area is filled
    %with the range of the sensors: If the whole area is not filled, a new
    %sensor is added in that direction.
    if x1(nspherx1)+catet<distlong
           x2(nspherx2+1)=x2(nspherx2)+distsph;
    end
    %Update the number of sensors in their direction
    nspherx2=length(x2);
    %Check that the sensors will not be otside the warehouse, if not,
    %put them on the edge
    if x2(nspherx2)>distlong
       x2(nspherx2)=distlong;
    end
    %Update the number of sensors in their direction
    nspherx2=length(x2);
else
    %These operations are needed to assure that the whole area is filled
    %with the range of the sensors: If the whole area is not filled, a new
    %sensor is added in that direction.
    if x2(nspherx2)+catet<distlong
           x1(nspherx1+1)=x1(nspherx1)+distsph;
    end
    %Update the number of sensors in their direction
    nspherx1=length(x1);
    %Check that the sensors will not be otside the warehouse, if not,
    %put them on the edge
    if x1(nspherx1)>distlong
       x1(nspherx1)=distlong;
    end
```

Diamond distribution basic program (2/6)


```
    %Update the number of sensors in their direction
    nspherx1=length(x1);
end

nspherx=nspherx1+nspherx2;

%Definition of y1 and y2
y1 = (distcent/4:distsph:disttrans);
nsphery1=length(y1);
y2 = (distcent/4+distsph/2:distsph:disttrans);
nsphery2=length(y2);

if y1(nsphery1) > y2(nsphery2)
    %These operations are needed to assure that the whole area is filled
    %with the range of the sensors: If the whole area is not filled, a new
    %sensor is added in that direction.
    if y1(nsphery1)+catet<disttrans
           y2(nsphery2+1)=y2(nsphery2)+distsph;
    end
    %Update the number of sensors in their direction
    nsphery2=length(y2);
    %Check that the sensors will not be otside the warehouse, if not,
    %put them on the edge
    if y2(nsphery2)>disttrans
       y2(nsphery2)=disttrans;
    end
    %Update the number of sensors in their direction
    nsphery2=length(y2);
else
    %These operations are needed to assure that the whole area is filled
    %with the range of the sensors: If the whole area is not filled, a new
    %sensor is added in that direction.
    if y2(nsphery2)+catet<disttrans
           y1(nsphery1+1)=y1(nsphery1)+distsph;
    end
    %Update the number of sensors in their direction
    nsphery1=length(y1);
    %Check that the sensors will not be otside the warehouse, if not,
    %put them on the edge
    if y1(nsphery1)>disttrans
       y1(nsphery1)=disttrans;
    end
    %Update the number of sensors in their direction
    nsphery1=length(y1);
end
nsphery=nsphery1+nsphery2;

%Creating x
x=[];
ny1=0;
ny2=0;
for i=0:1:nsphery1
    if ny1<nsphery1
        a=length(x);
```

Diamond distribution basic program (3/6)


```
        for j=1:1:nspherx1
            x(a+j)=x1(j);
        end
        ny1=ny1+1;
    end
    if ny2<nsphery2
        b=length(x);
        for k=1:1:nspherx2
            x(b+k)=x2(k);
        end
        ny2=ny2+1;
    end
end

%Creating y

y=[];
ny1=0;
ny2=0;
for i=0:1:nspherx1
    if ny1<nsphery1
        a=length(y);
        for j=1:1:nspherx1
            y(a+j)=y1(i+1);
        end
        ny1=ny1+1;
    end
    if ny2<nsphery2
        b=length(y);
        for k=1:1:nspherx2
            y(b+k)=y2(i+1);
        end
        ny2=ny2+1;
    end
end


%Calculate the number of spheres and give value to the range to all of
%them.
nspher=length(x);
r=repelem(range,length(x))   ;

%Put the sensors more centered
if x1(nspherx1) > x2(nspherx2)
    diflong=(distcent/4+(distlong-x1(nspherx1)))/2;
    x=x-distcent/4+diflong;
else
    diflong=(distcent/4+(distlong-x2(nspherx2)))/2;
    x=x-distcent/4+diflong;
end
if y1(nsphery1) > y2(nsphery2)
    diftrans=(distcent/4+(disttrans-y1(nsphery1)))/2;
    y=y-distcent/4+diftrans;
else
```

Diamond distribution basic program (4/6)


```
    diftrans=(distcent/4+(disttrans-y2(nsphery2)))/2;
    y=y-distcent/4+diftrans;
end

%To calculate the number of spheres which a single sensor interferes with,
%it will be taken into account the distance between these, as the range
%will be constant. As an imaginary range depending on the distance between
%the spheres, it will be calculated a matrix that will give the
%superposition area and with that calculate if it exists a superposition.
%This way we will be able to calculate the number of sensors that interact
%together.

imar=repelem(range/2,nspher) ;

% Inputs are reshaped in
size_x = numel(x);
size_y = numel(y);
size_r = numel(r);
size_imar = numel(imar);

x = reshape(x,size_x,1);
y = reshape(y,size_y,1);
r = reshape(r,size_r,1);
imar=reshape(imar,size_imar,1);


% Calculation of distances between all spheres
[X,Y] = meshgrid(x,y);

D     = sqrt((X-X').^2+(Y-Y').^2);

% Since the matrix M for overlap computation is symmetric M(i,j)=M(j,i),
% calculations are performed only on the upper part of the matrix
D = triu(D,1);

[R1,R2] = meshgrid(imar);
sumR    = triu(R1+R2,1);
difR    = triu(abs(R1-R2),1);


% Creating the resulting vector
M = zeros(size_x*size_x,1);

% Partial intersection between circles i & j
C2 = (D>difR)&(D<sumR);
% Computation of the coordinates of one of the intersection points of the
% circles i & j

Xi(C2,1) = (R1(C2).^2-R2(C2).^2+D(C2).^2)./(2*D(C2));
Yi(C2,1) = sqrt(R1(C2).^2-Xi(C2).^2);

% Computation of the partial intersection area between circles i & j
M(C2,1) = R1(C2).^2.*atan2(Yi(C2,1),Xi(C2,1))+ ...
          R2(C2).^2.*atan2(Yi(C2,1),(D(C2)-Xi(C2,1)))- ...
```

Diamond distribution basic program (5/6)

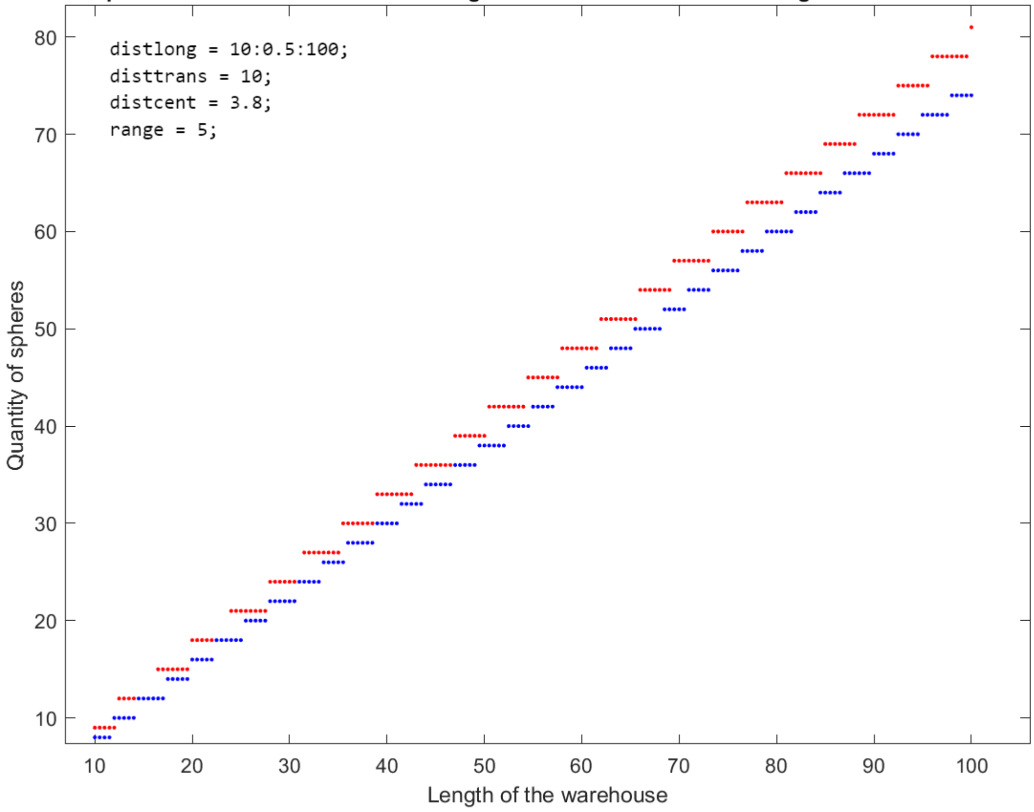

```
        D(C2).*Yi(C2,1);

% Compute the area of each circle. Assign the results to the diagonal of M
M(1:size_x+1:size_x*size_x) = pi.*imar.^2;

% Conversion of vector M to matrix M
M = reshape(M,size_x,size_x);

% Creating the lower part of the matrix
M = M + tril(M',-1);


% Display results

    f = figure;
    hAxs = axes('Parent',f);
    hold on, box on, axis equal
    xlabel('x')
    ylabel('y','Rotation',0)
    title('Distribution of the sensors on the warehouse' )
    text(-5,-5,'Intersection between the ranges of the sphere sensors' )
    text(-5,-6,sprintf('Number of sensors needed: %f' , nspher))

    axis([-8 40 -8 20]) ;
    colour = rand(nspher,3);
    rectangle('Position',[0 0 distlong disttrans])
    for t = 1: nspher
        plot(x(t)+r(t).*cos(0:2*pi/100:2*pi), ...
             y(t)+r(t).*sin(0:2*pi/100:2*pi), 'color',colour(t,:),'parent',hAxs)
        plot(x(t),y(t), '+','color',colour(t,:),'parent',hAxs)
    end


%HISTOGRAM calculation
istoaxis=zeros(1,max(size(M)));

for i=1:1:length(istoaxis)
    for k=1:1:length(istoaxis)
        if M(i,k)~=0
            istoaxis(i)=istoaxis(i)+1;
        end
    end
end
%Subtract the intersection with its own
istoaxis=istoaxis-1;

%Plot the histogram
f2 = figure;
    hAxs = axes('Parent',f2);
    hold on, box on, axis equal
    xlabel('Number of interaction with other sensors' )
    ylabel('Quantity of spheres','Rotation',90)
    title('Histogram of the number of intersections between the sensors' )
```

Diamond distribution basic program (6/6)

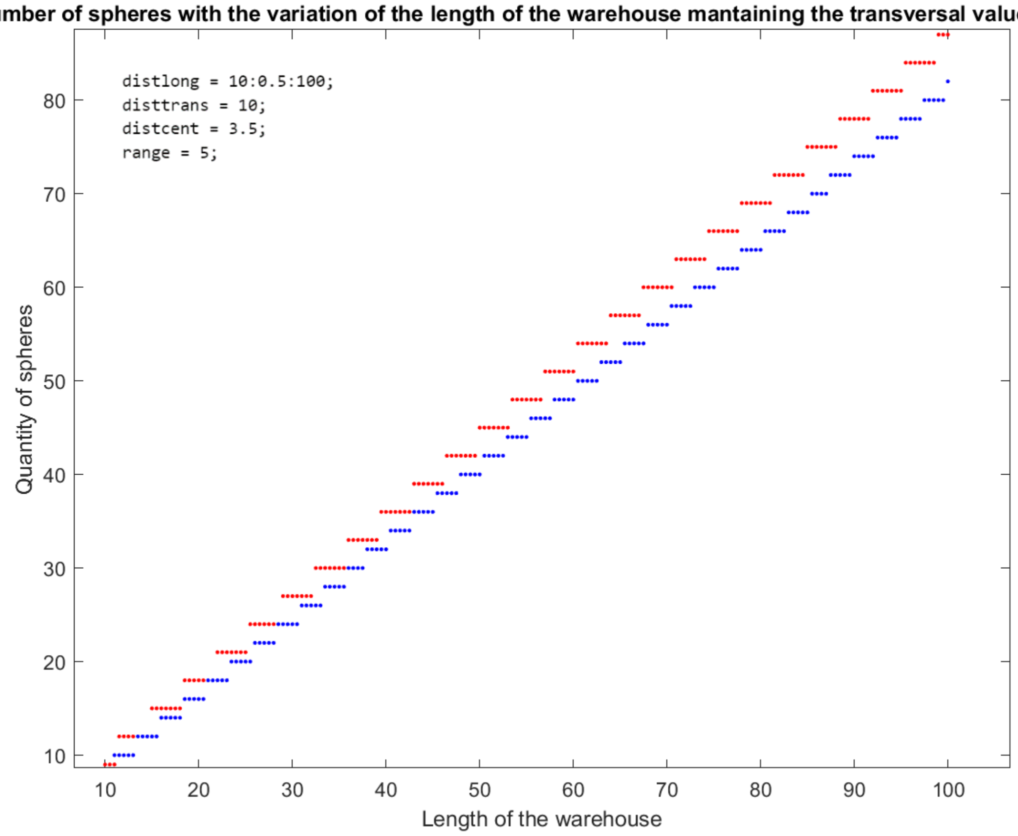

```
HG=histogram(istoaxis);
HG.FaceColor = [0.3010 0.7450 0.9330];
HG.EdgeColor = [0 0.4470 0.7410];
HG.BinWidth = 0.2;
```

Results for *longitudinal_variable*

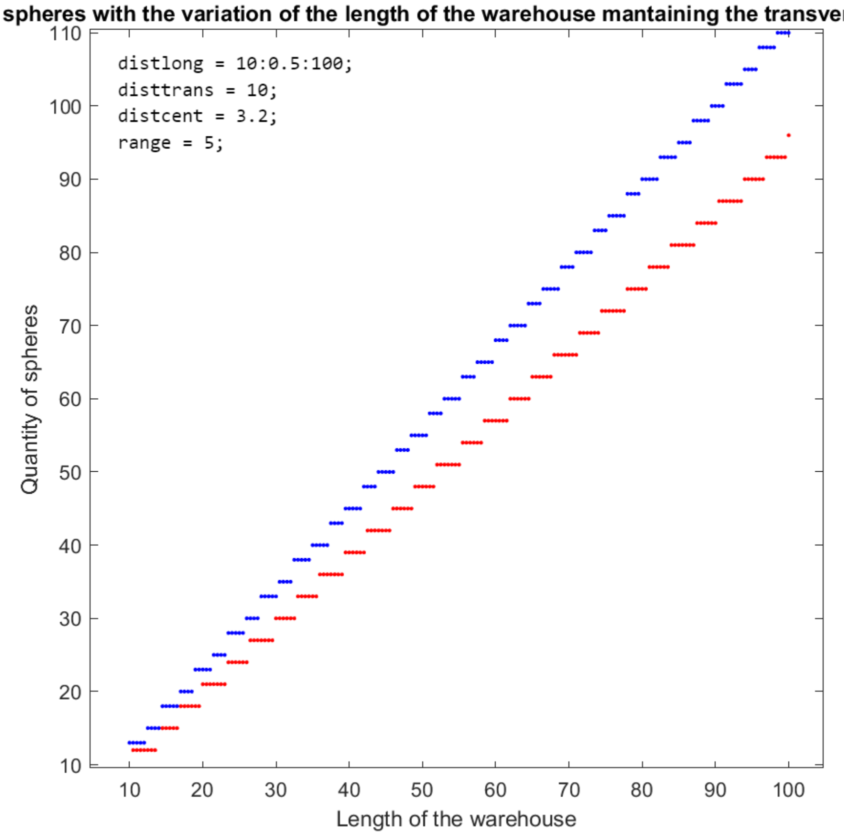
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m



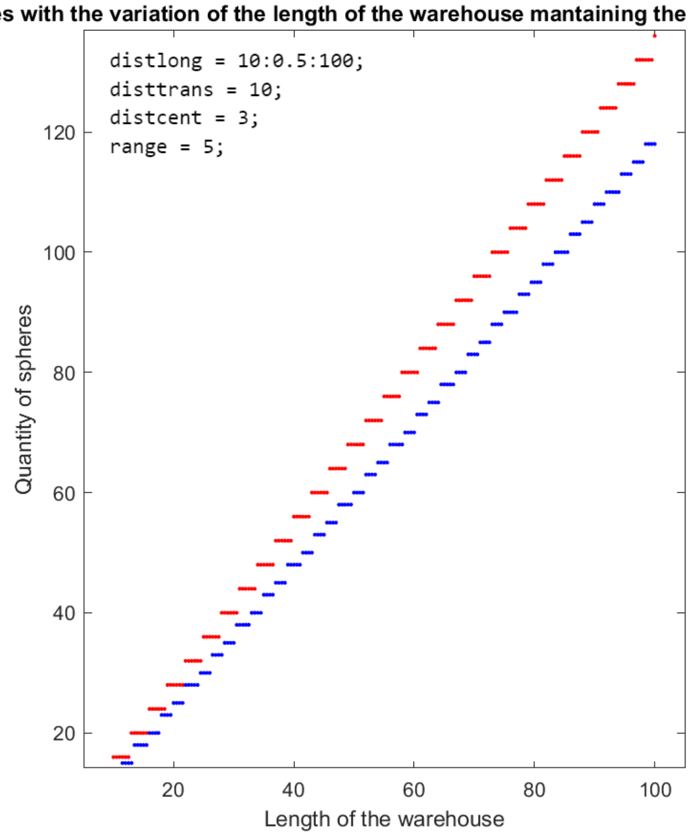
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m



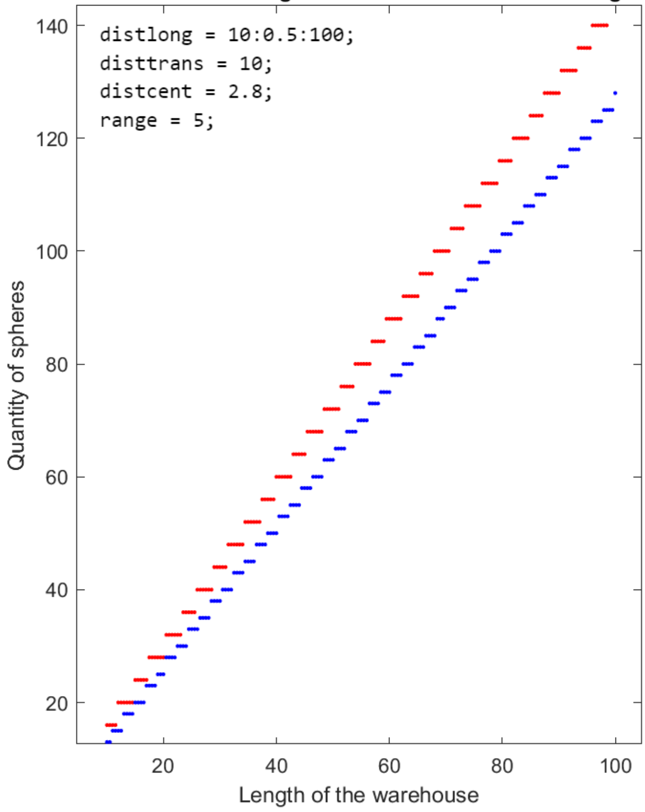
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m



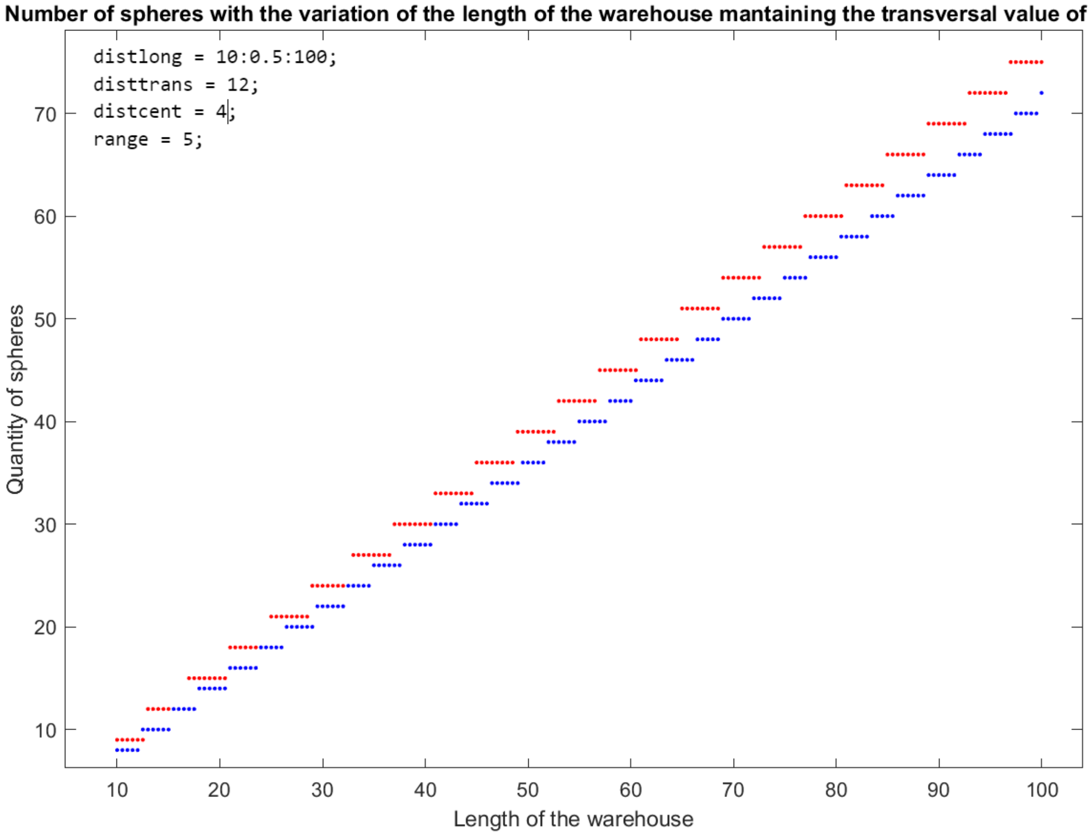
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m



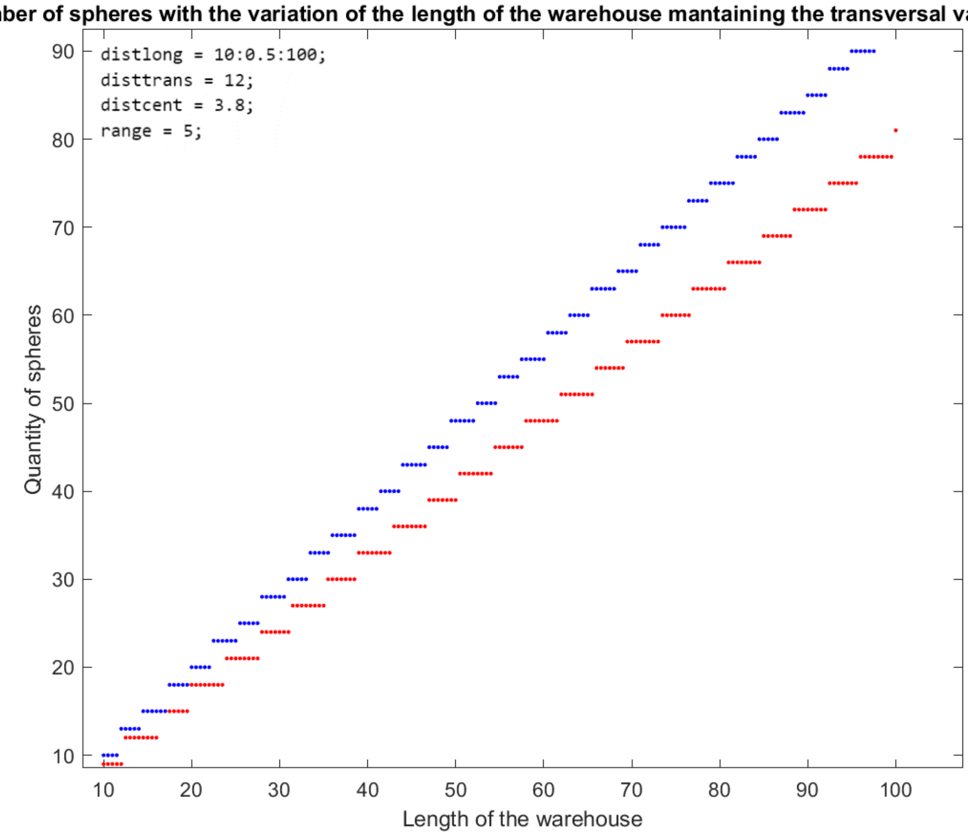
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m



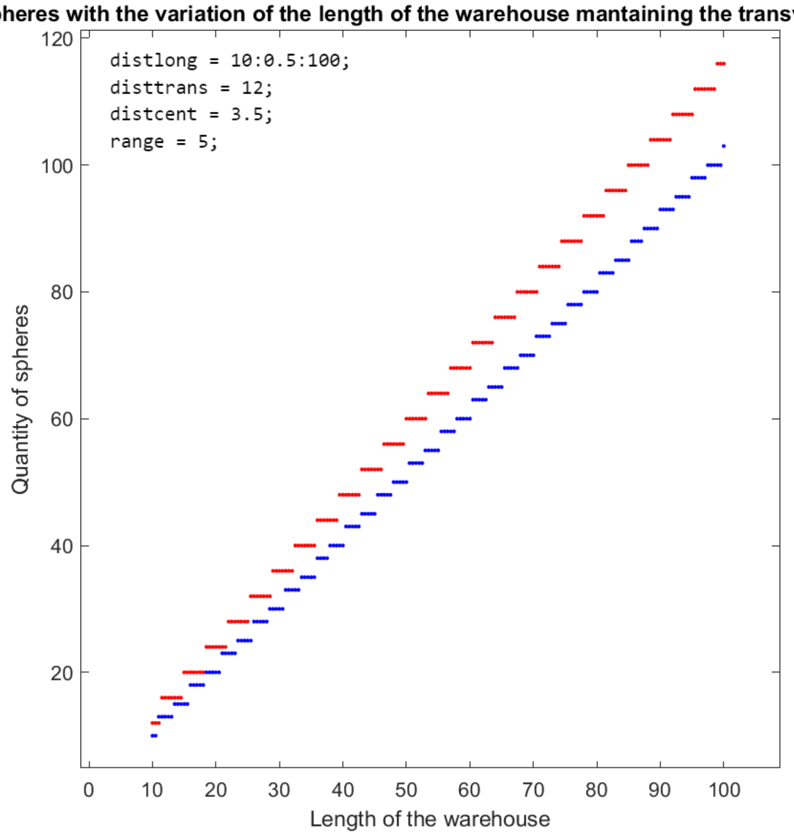
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m



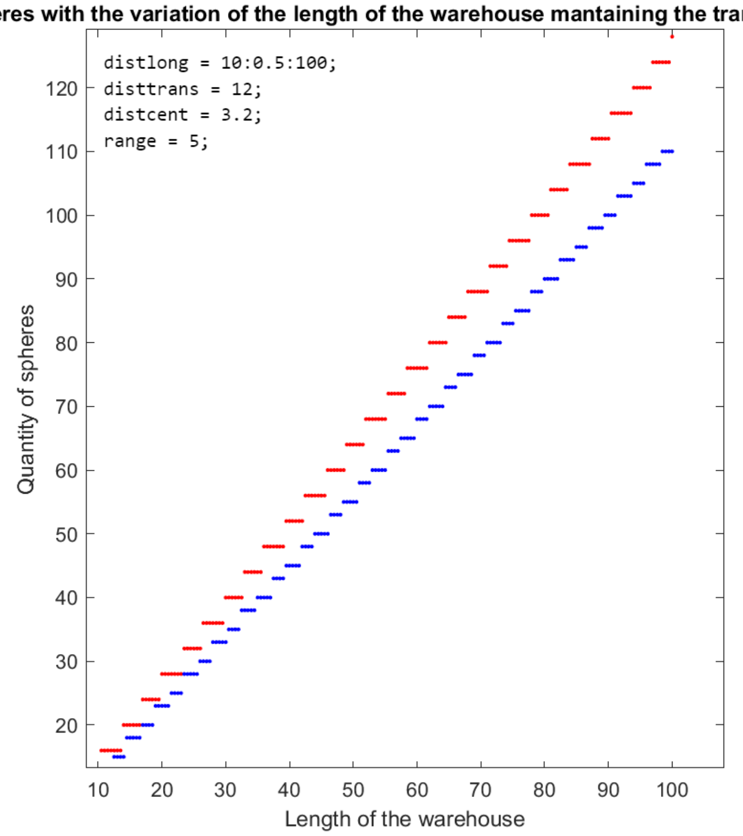
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m



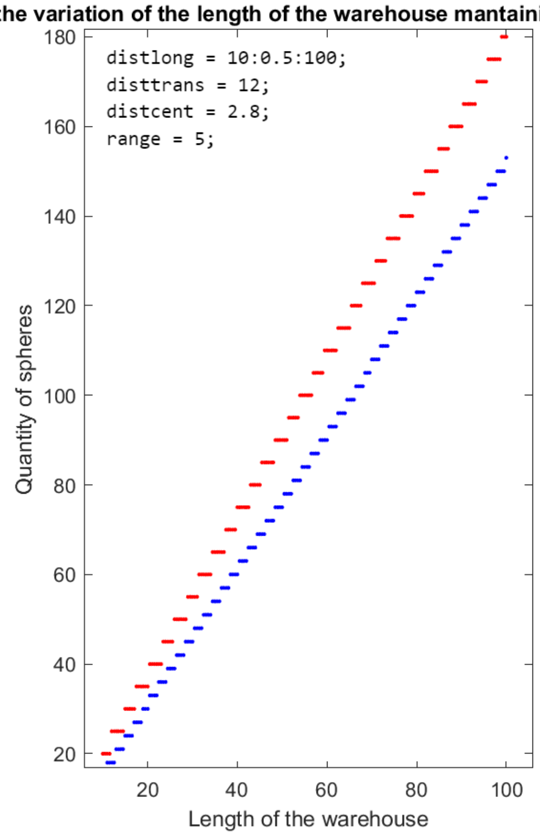
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m



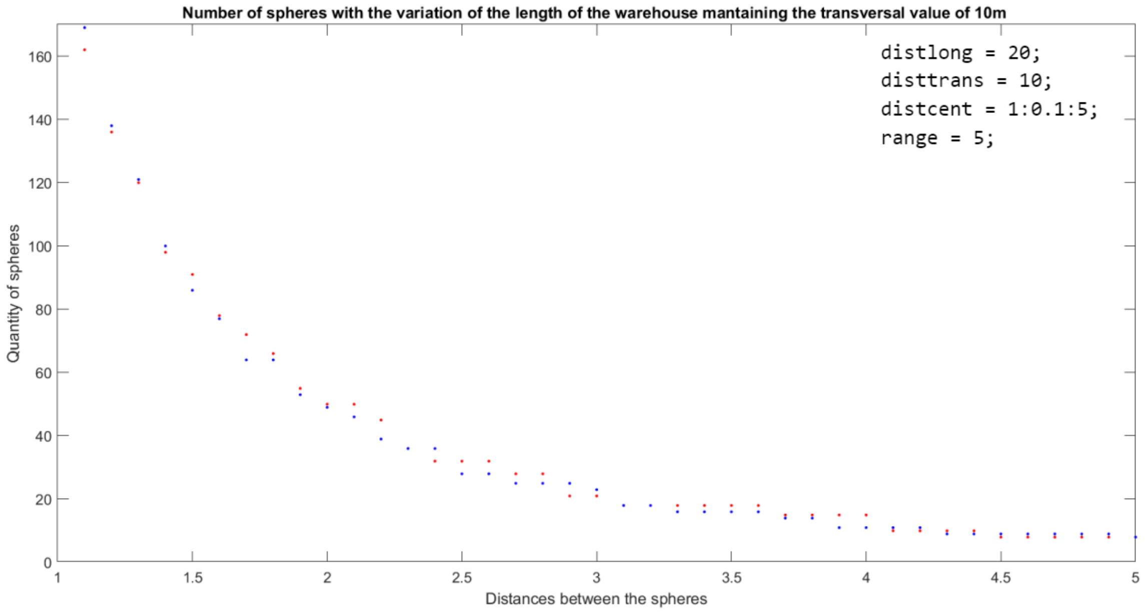
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m

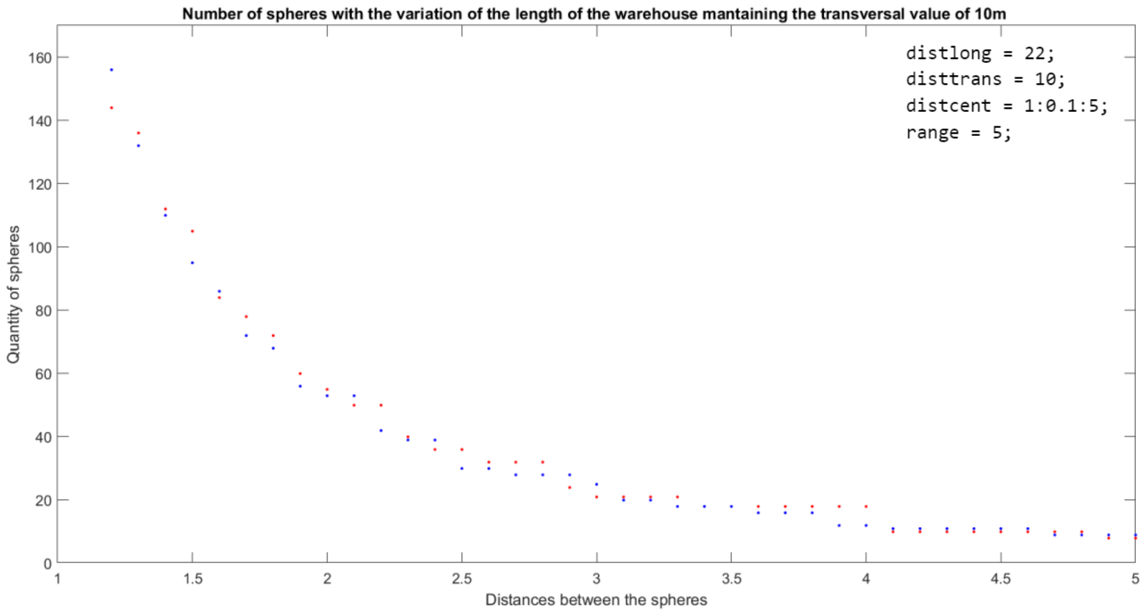


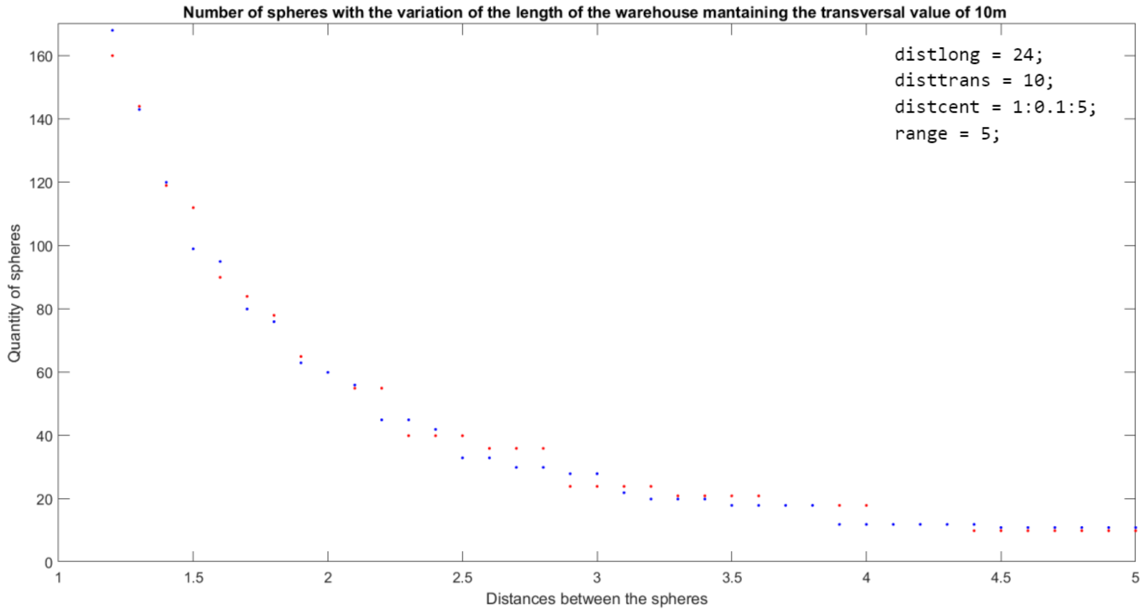
Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m

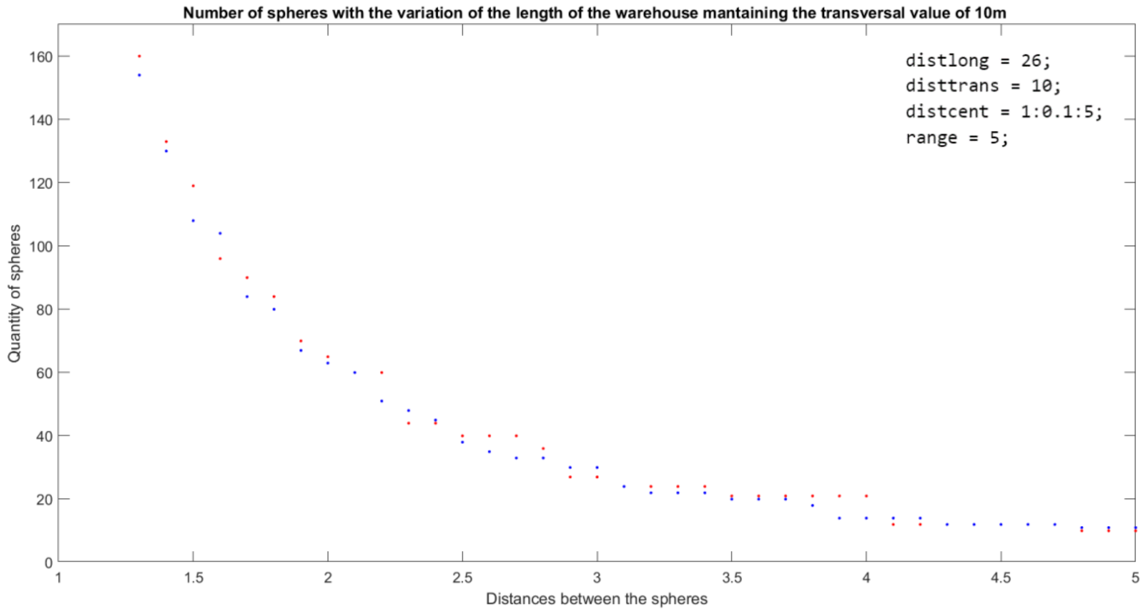


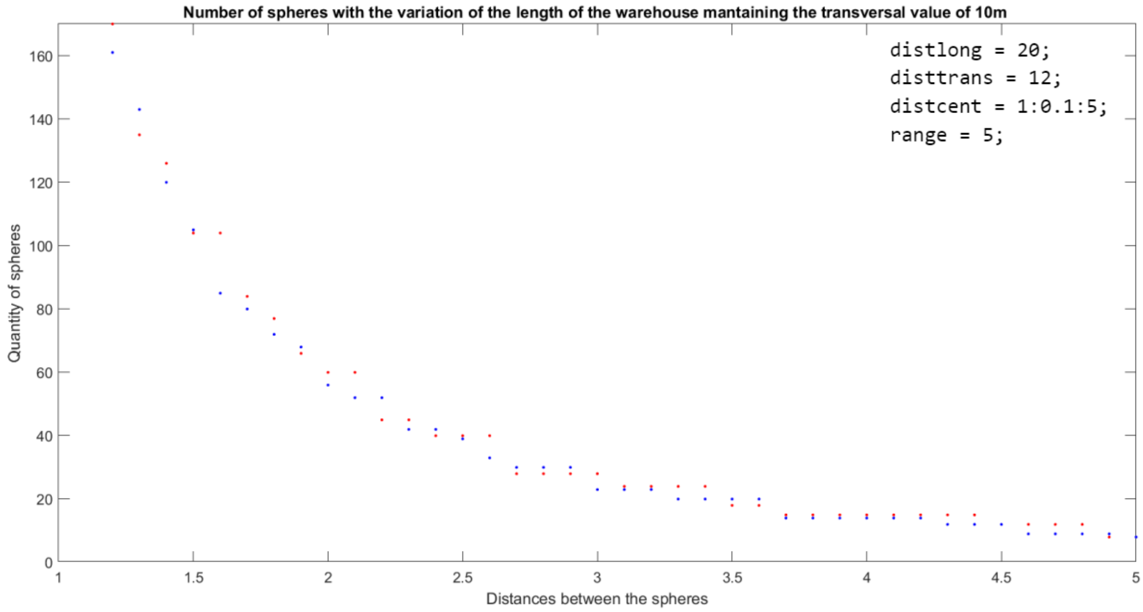
Results for *diset_sensor_variable*

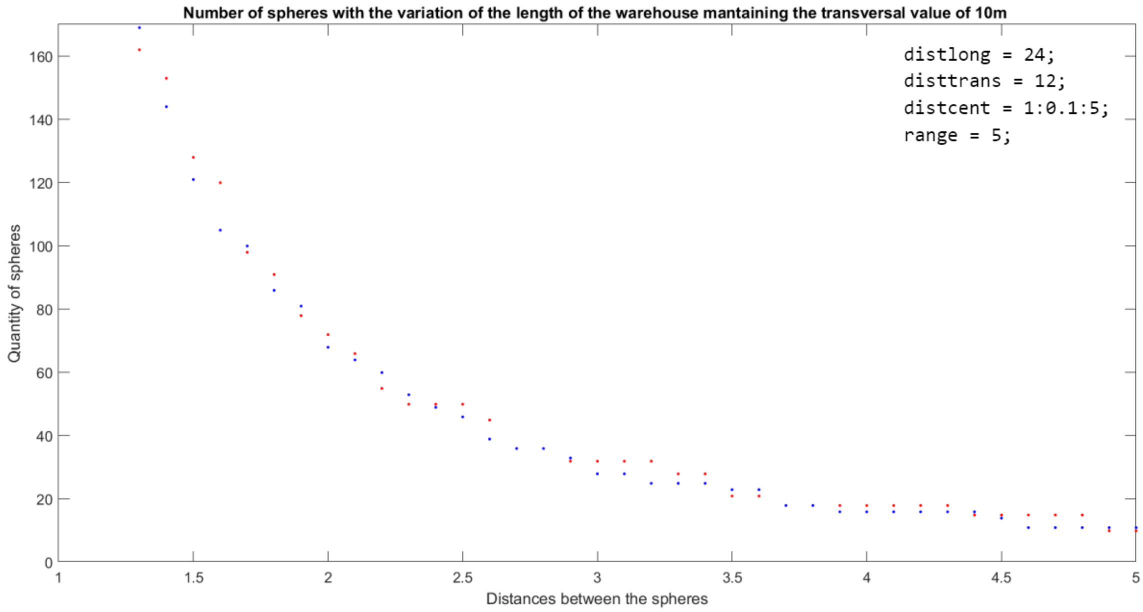





Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m
distlong = 24;
disttrans = 10;
distcent = 1:0.1:5;
range = 5;
Quantity of spheres
Distances between the spheres

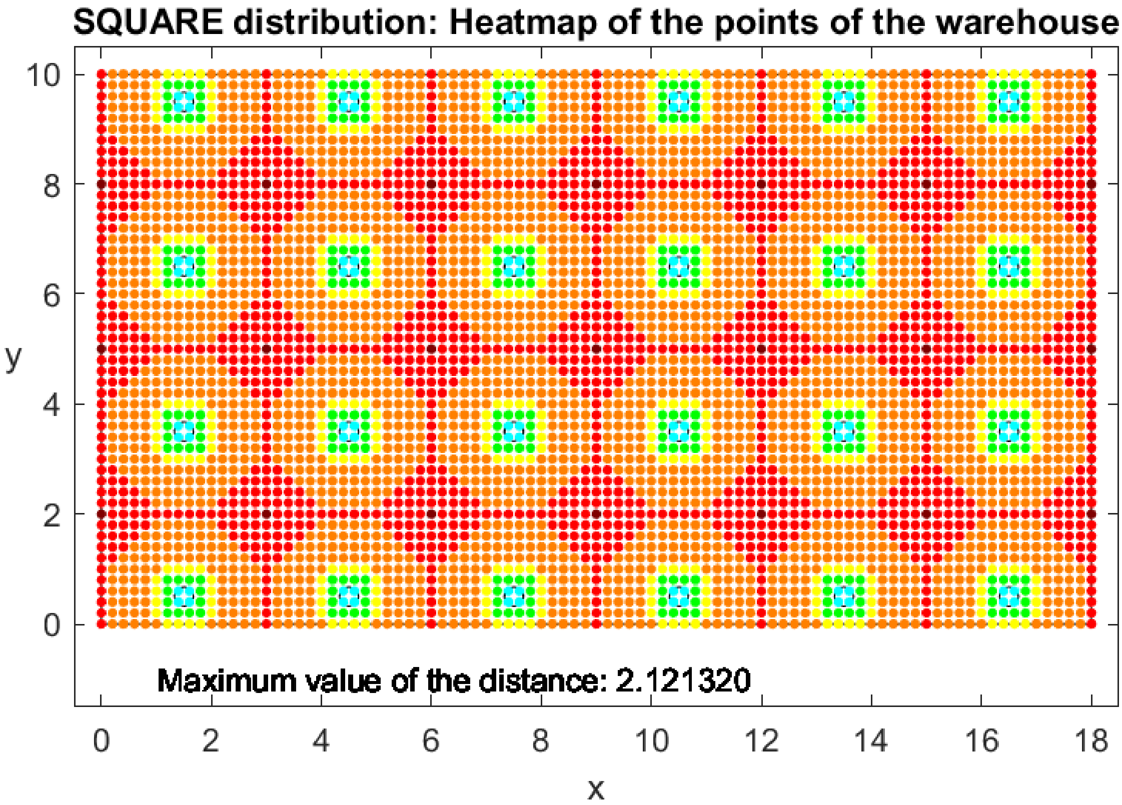

Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m
distlong = 26;
disttrans = 10;
distcent = 1:0.1:5;
range = 5;
Quantity of spheres
Distances between the spheres

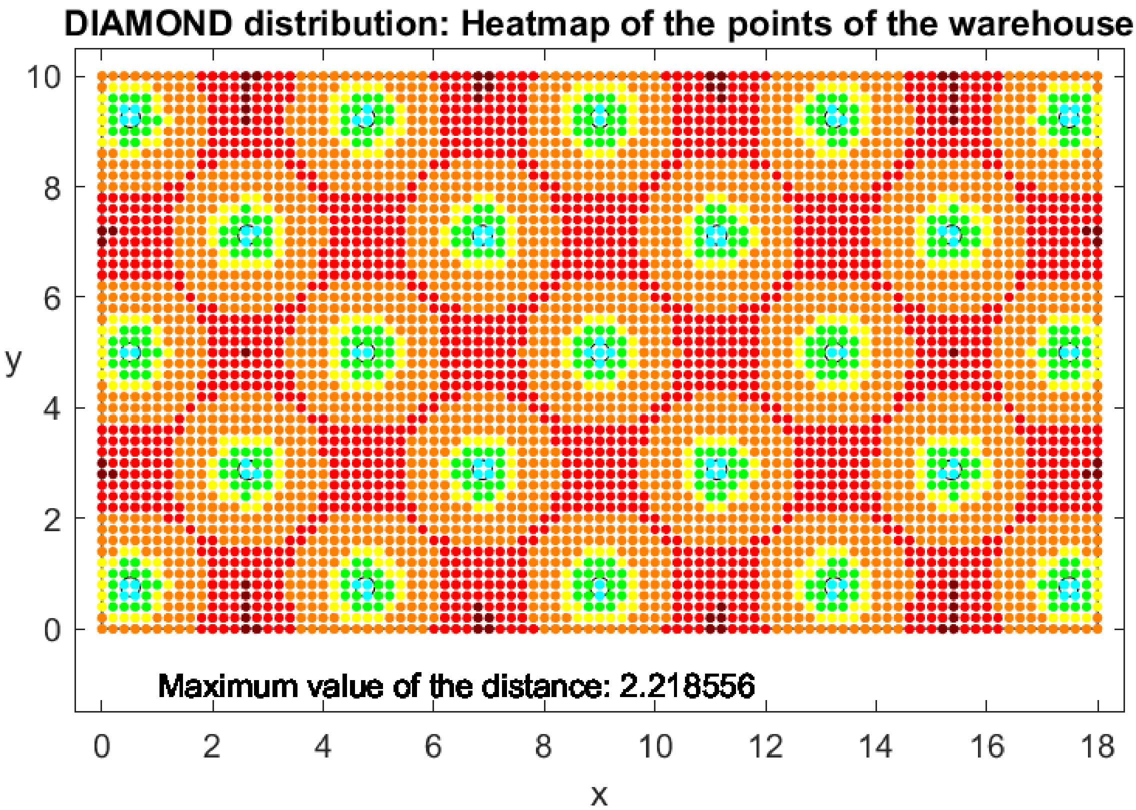

Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m
distlong = 20;
disttrans = 12;
distcent = 1:0.1:5;
range = 5;
Quantity of spheres
Distances between the spheres


Number of spheres with the variation of the length of the warehouse mantaining the transversal value of 10m
distlong = 24;
disttrans = 12;
distcent = 1:0.1:5;
range = 5;
Quantity of spheres
Distances between the spheres

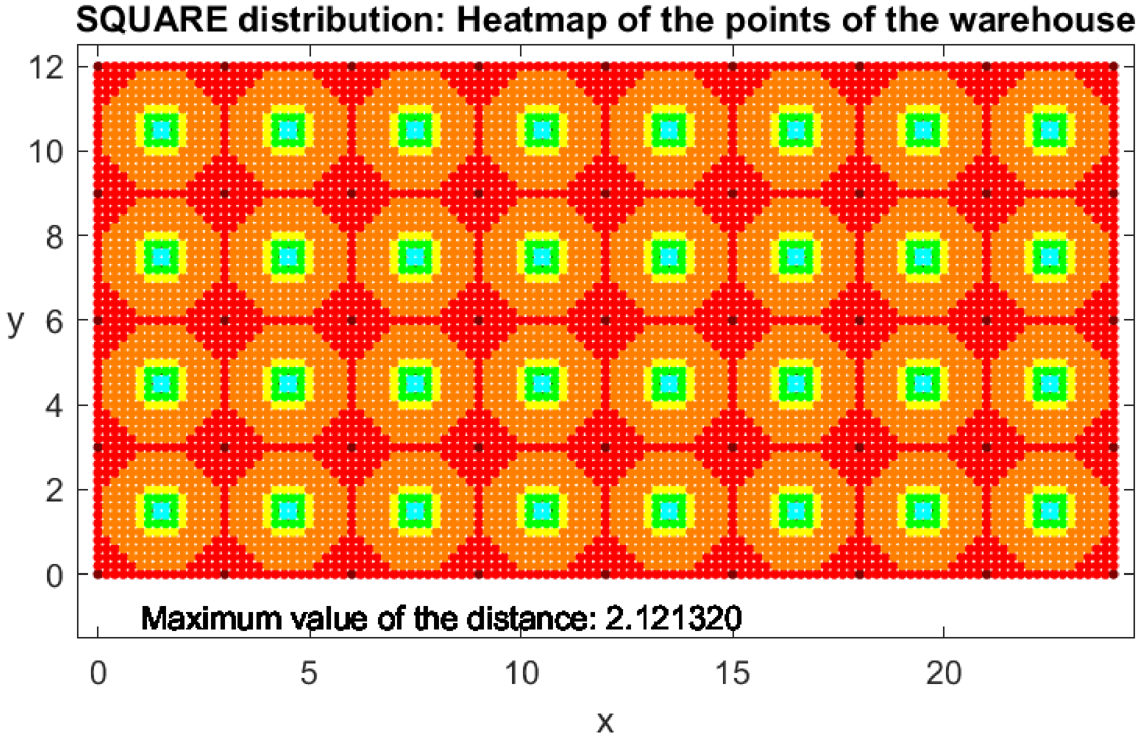
Results for *programs mesh_square* and *mesh_diamond*

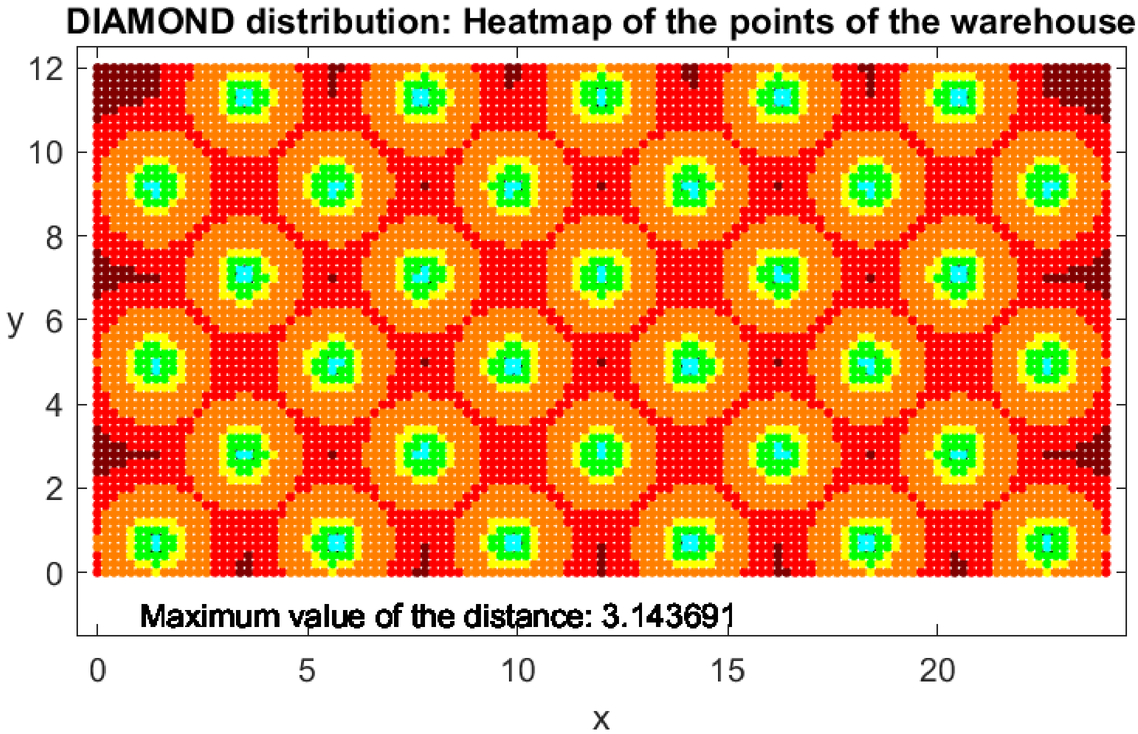
```
distlong = 18;
disttrans = 10;
distcent = 3;
range = 5;
```



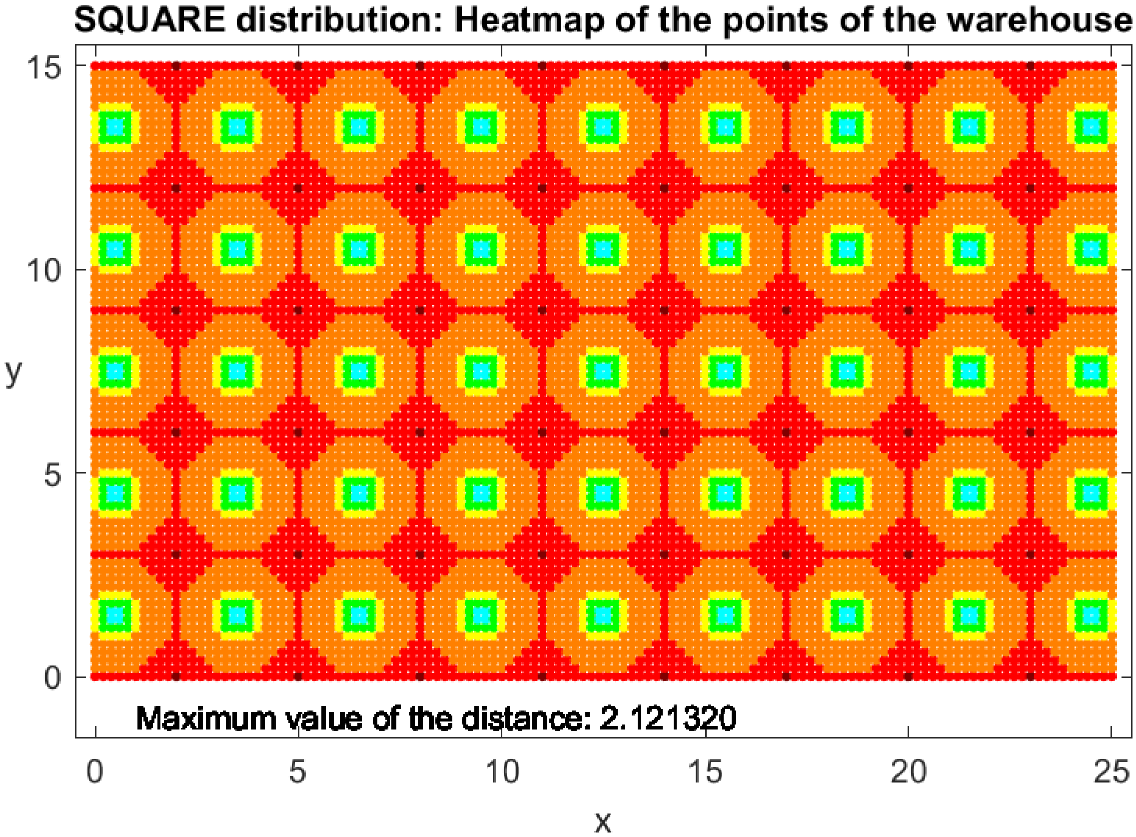


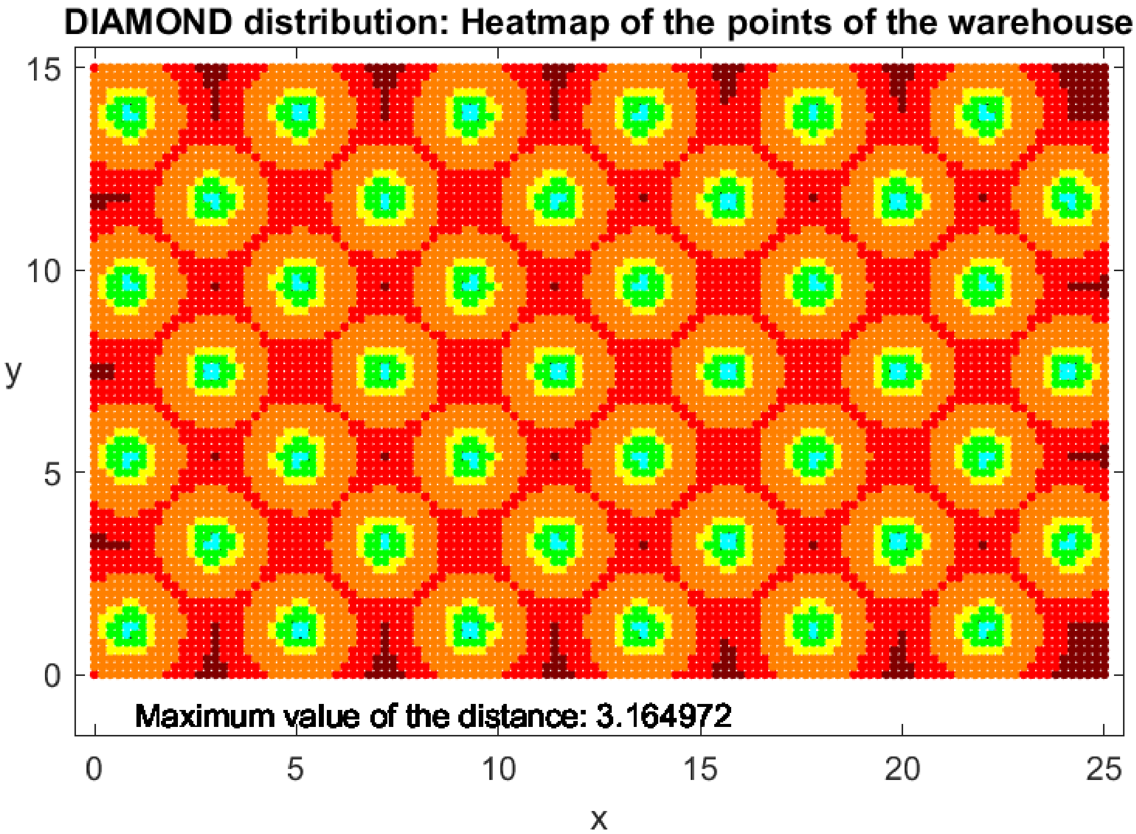
```
distlong = 24;
disttrans = 12;
distcent = 3;
range = 5;
```



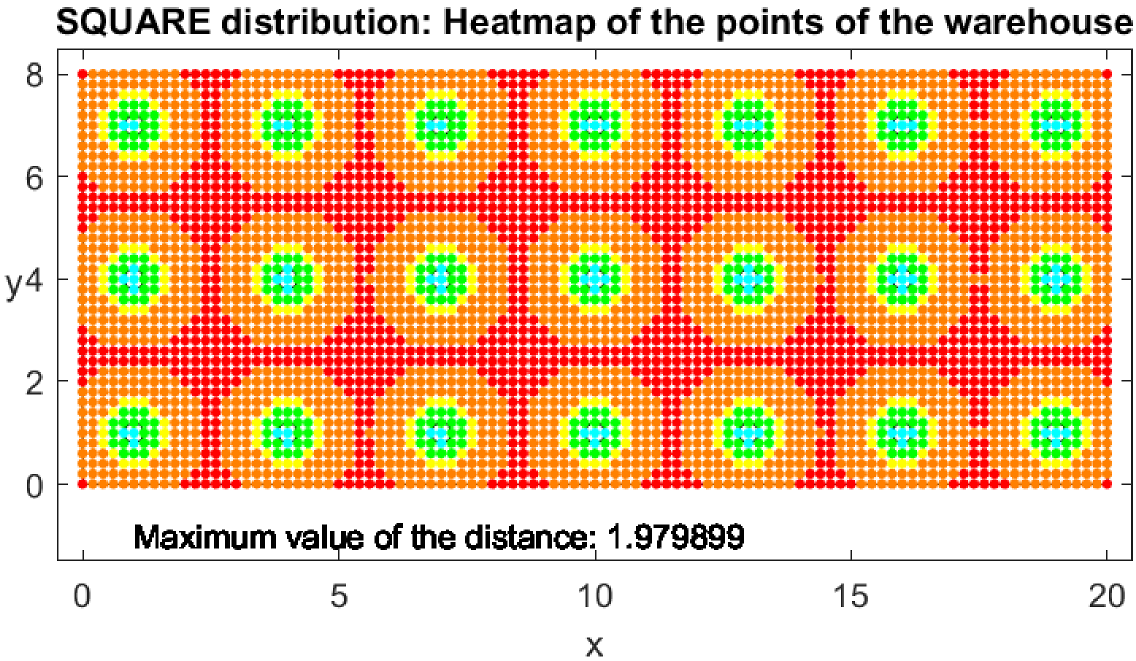


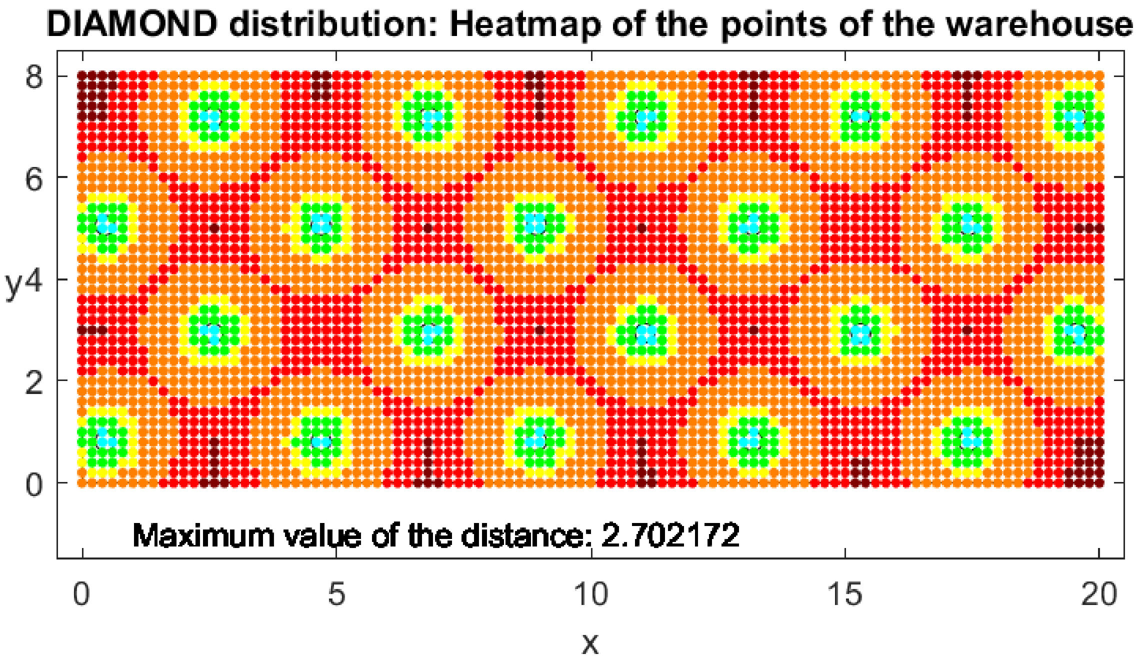
```
distlong = 25;
disttrans = 15;
distcent = 3;
range = 5;
```





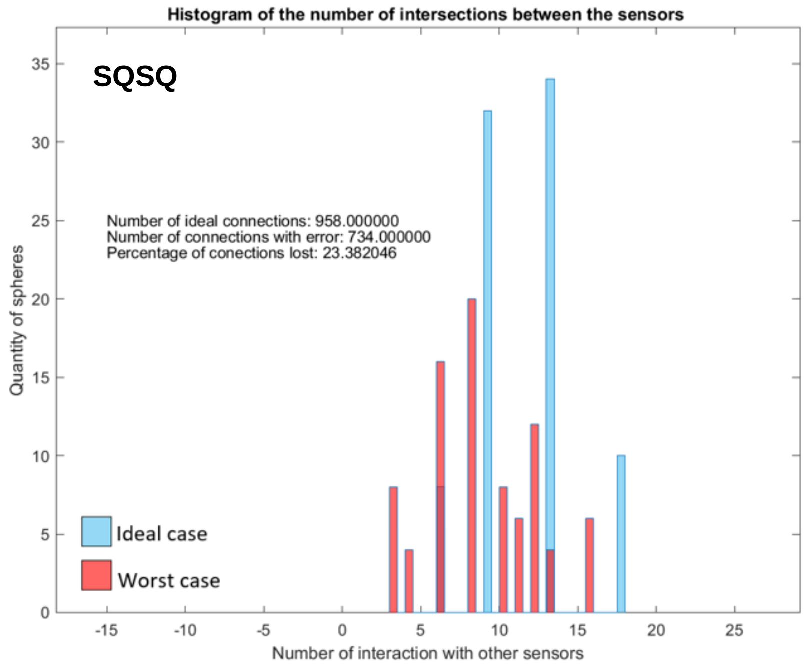
```
distlong = 20;
disttrans = 8;
distcent = 3;
range = 5;
```

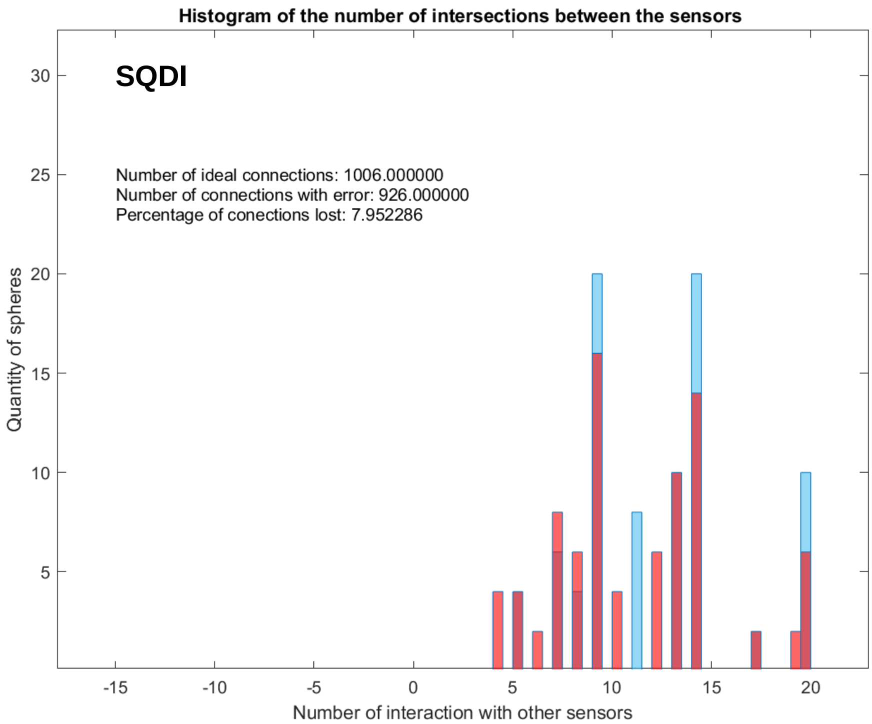


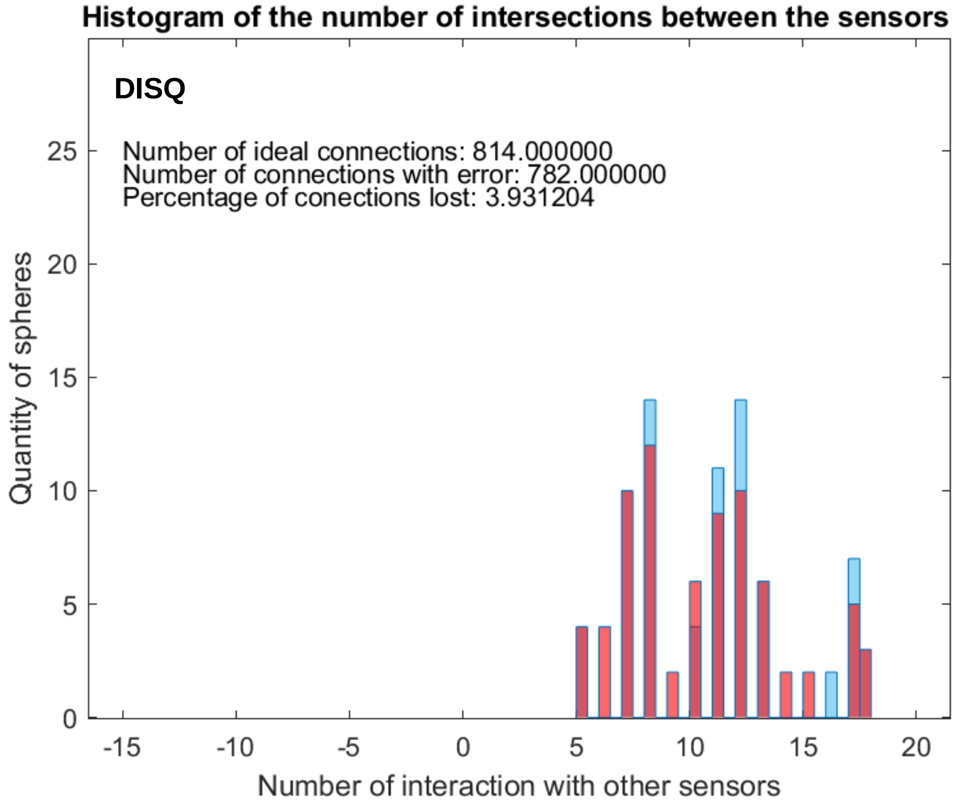


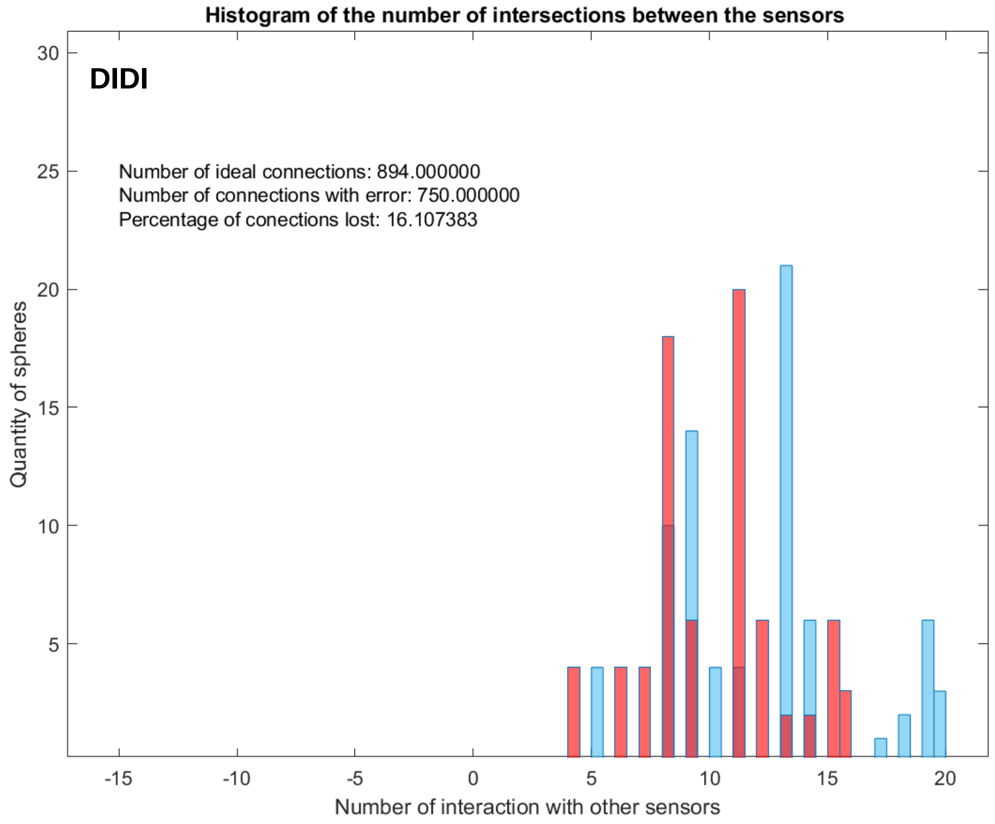
Results for histograms dropping error

```
distlong =20;
disttrans = 10;
distcent = 3;
distware = 10;
distgra = 7;
range = 5;
error = 0.55;
```

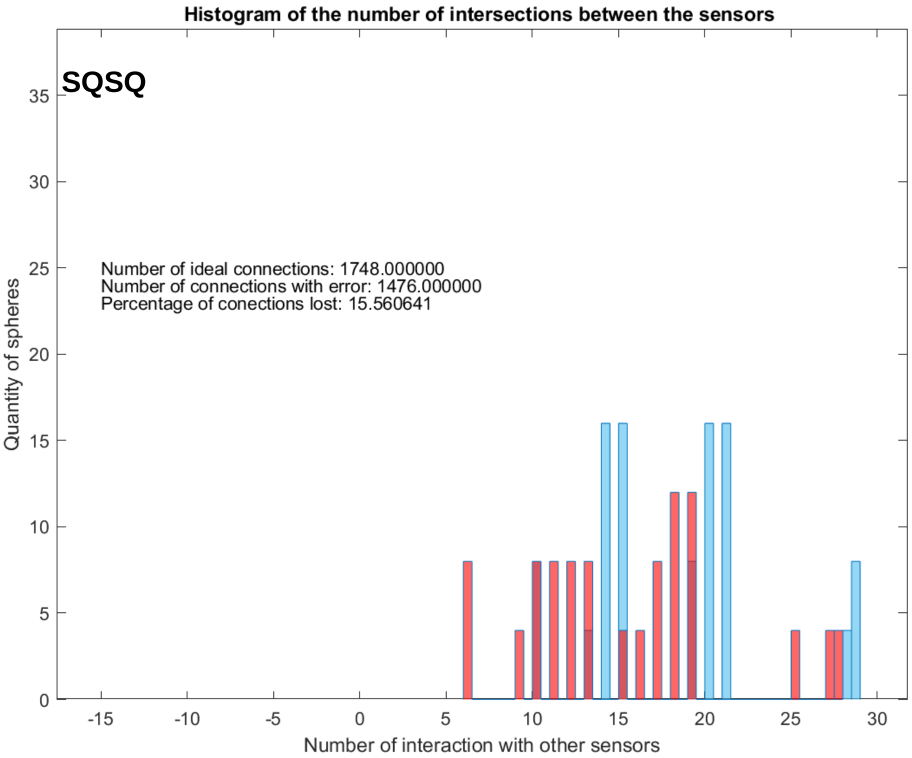


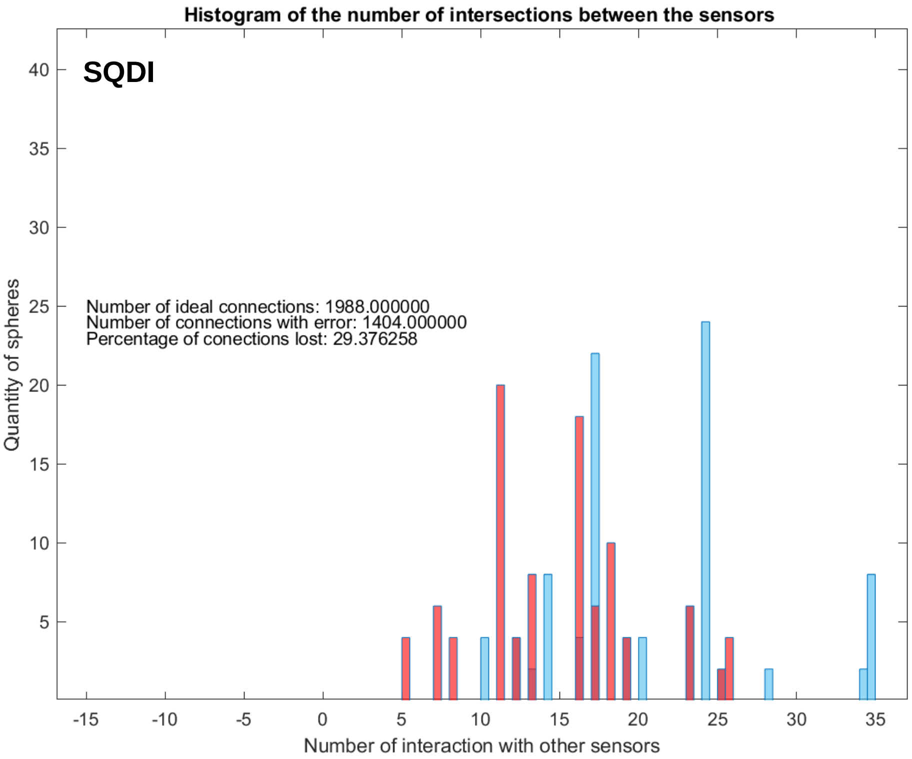


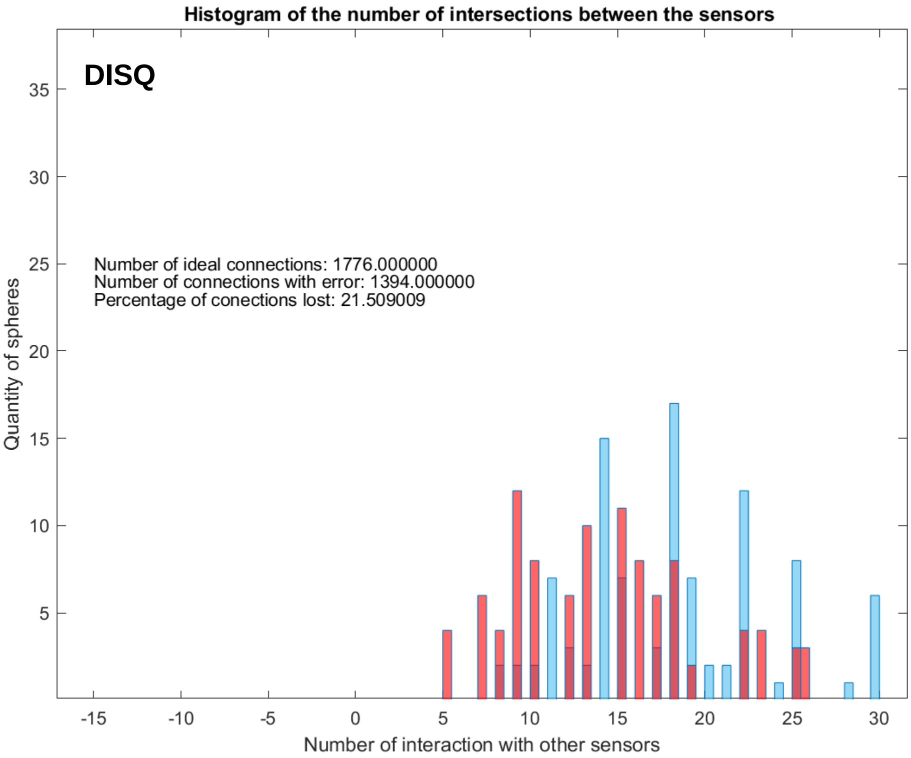

Histogram of the number of intersections between the sensors
DISQ
Number of ideal connections: 814.000000
Number of connections with error: 782.000000
Percentage of conections lost: 3.931204
Quantity of spheres
Number of interaction with other sensors

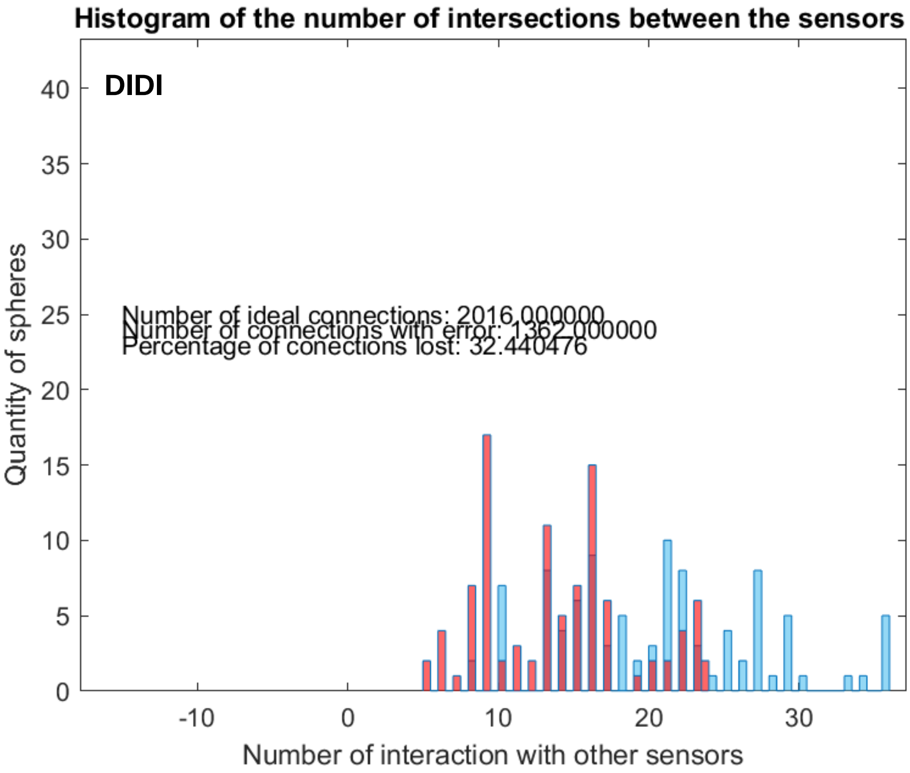

Histogram of the number of intersections between the sensors
DIDI
Number of ideal connections: 894.000000
Number of connections with error: 750.000000
Percentage of conections lost: 16.107383
Quantity of spheres
Number of interaction with other sensors

```
distlong =20;
disttrans = 10;
distcent = 2.5;
distware = 10;
distgra = 7;
range = 5;
error = 0.55;
```

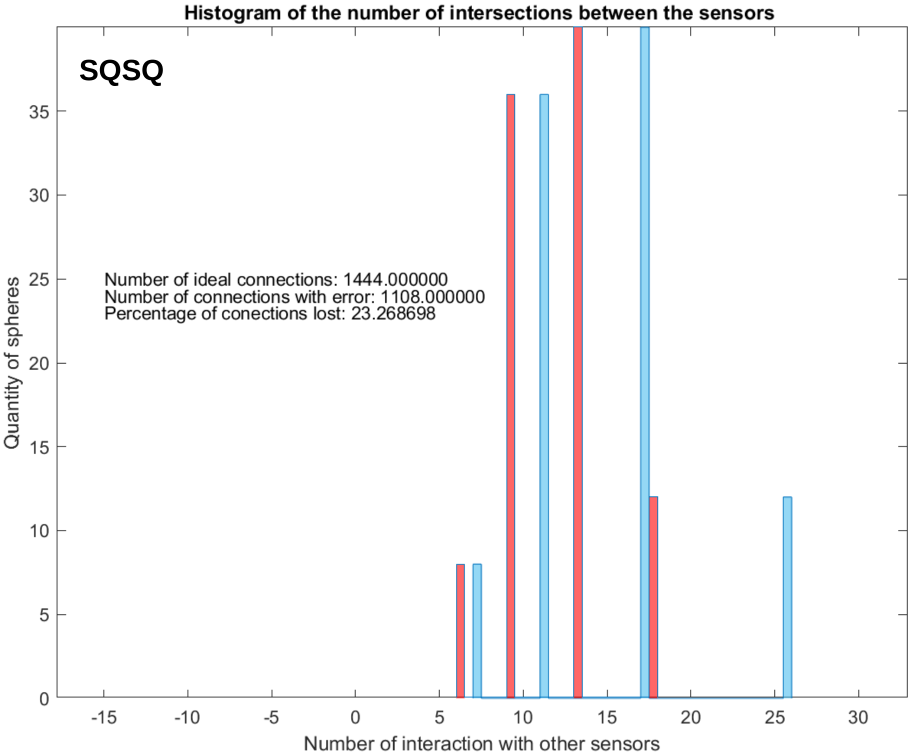


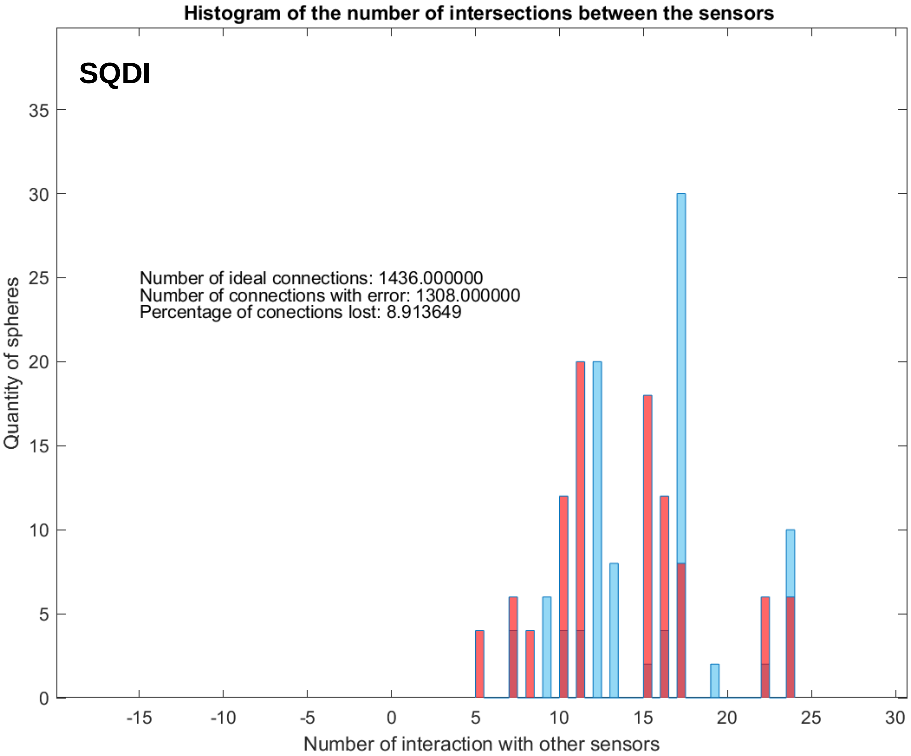


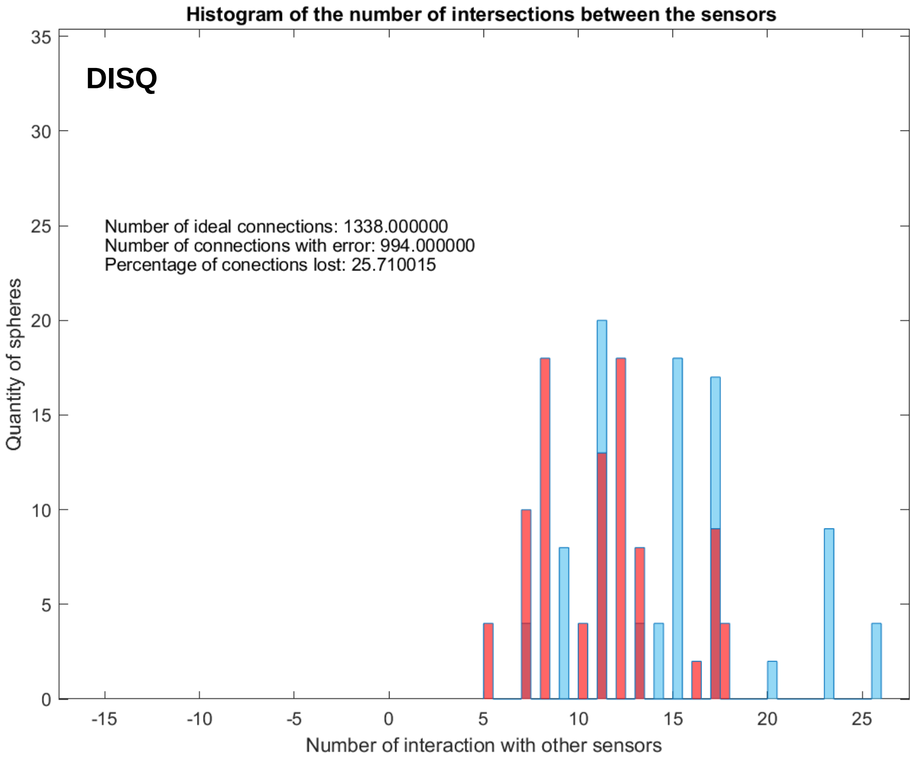

Histogram of the number of intersections between the sensors
DISQ
Number of ideal connections: 1776.000000
Number of connections with error: 1394.000000
Percentage of conections lost: 21.509009
Quantity of spheres
Number of interaction with other sensors
35
30
25
20
15
10
5
-15
-10
-5
0
5
10
15
20
25
30

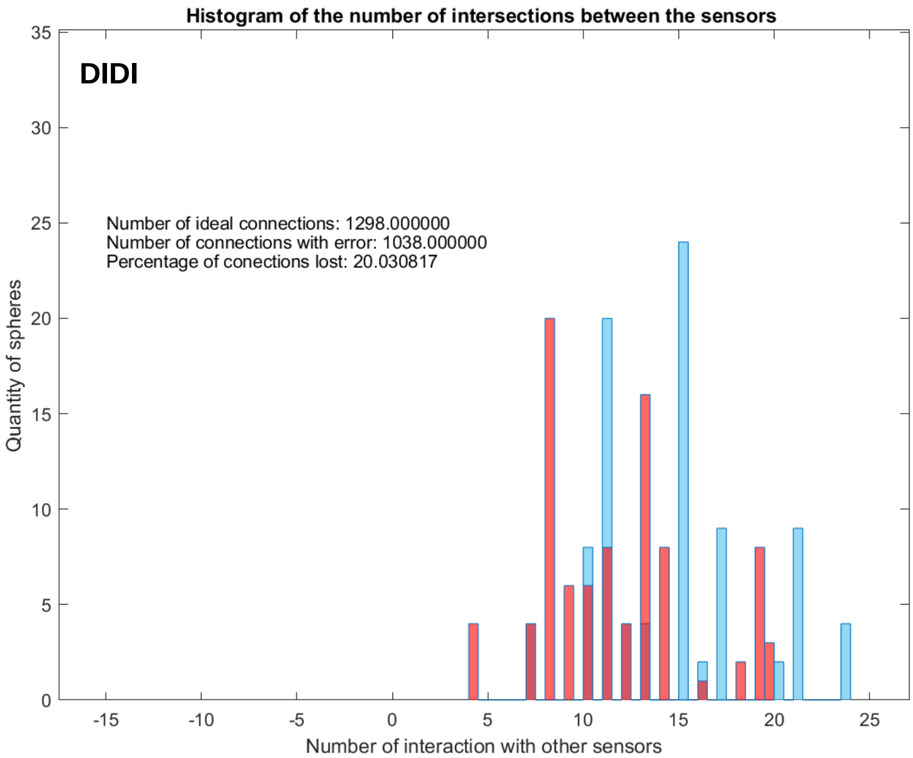

Histogram of the number of intersections between the sensors
DIDI
Number of ideal connections: 2016.000000
Number of connections with error: 1362.000000
Percentage of conections lost: 32.440476
Quantity of spheres
Number of interaction with other sensors
40
35
30
25
20
15
10
5
0
-10
0
10
20
30

```
distlong =22;
disttrans = 10;
distcent = 2.7;
distware = 10;
distgra = 7;
range = 5;
error = 0.55;
```






Histogram of the number of intersections between the sensors
DISQ
Number of ideal connections: 1338.000000
Number of connections with error: 994.000000
Percentage of conections lost: 25.710015
Quantity of spheres
Number of interaction with other sensors


Histogram of the number of intersections between the sensors
DIDI
Number of ideal connections: 1298.000000
Number of connections with error: 1038.000000
Percentage of conections lost: 20.030817
Quantity of spheres
Number of interaction with other sensors