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Towards Forklift Safety in a Warehouse: An Approach Based on the Automatic Analysis of Resource Flows

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Abstract: Warehouse management is a discipline that has gained importance in recent decades. In the era of the Digital Revolution and Industry 5.0, to enable a company to attain a competitive advantage, it is necessary to identify smart improvement tools that help search for warehouse problems and solutions. A good tool to highlight issues related to layout and resource flows is the spaghetti chart which, besides being used to minimize waste according to lean philosophy, can also be used to assess warehouse safety and reliability and improve the plant sustainability. This article shows how to exploit “smart spaghetti” (spaghetti chart automatically generated by smart tracking devices) to conceive improvements in the layout and work organization of a warehouse, reducing the risk of collision between forklifts and improving the operators’ safety. The methodology involves automatically mapping the spaghetti charts (searching for critical areas where the risk of collision is high) and identifying interventions to be carried out to avoid near misses. “Smart spaghetti” constitutes a valuable decision support tool to identify potential improvements in the system through changes in the layout or in the way activities are performed. This work shows an application of the proposed technique in a pharmaceutical warehouse.

Keywords: smart spaghetti chart; spaghetti diagram; warehouse sustainability; forklift movements; safety assessment; near miss detection; lean layout planning; strategy for improving layout

1. Introduction

In recent decades, the discipline of warehouse management has gained increasing importance [1,2]. Nevertheless, even today, sometimes the problems of the warehouse and the benefits that can be obtained from its optimization are still lost sight of [3]. To increase a company’s competitive advantage, it is necessary to identify continuous improvement tools that highlight critical inventory issues and facilitate the search for improvement solutions [4]. Among these tools, the spaghetti chart is useful to point out critical aspects related to layout and resource flows [5].

However, in the era of Industry 5.0 and digital manufacturing, it is essential to automate the construction of spaghetti charts, which would otherwise have to be created manually after long and numerous inspections at companies [6]. Using smart tracking devices to track the movement of resources within a system, it is possible to automatically generate spaghetti charts (that we will call, according to Uddin et al. [7,8], “smart spaghetti”). In this way, a valid integrated digital system can be obtained that supports decisions and helps to make a system more efficient by identifying possible improvements to its layout and work organization [7].

The literature shows how the spaghetti chart can be applied to any kind of field. Previous contributions show its use in mechanical industries [9], in electronics [10] and telecommunications industries [5], in hospitals [11,12], in healthcare laboratories [13], and even in

hotels and in the tourism sector [14]. Recently, a case study application has been shown to improve the management of warehouses and to visualize the critical issues related to their layout [15].

Even though the literature reports several applications of spaghetti charts, few authors show the advantages that can be achieved using smart tracking devices for automatic and smart flow [16,17]. Besides, the available case studies mention the spaghetti chart within broader studies focused on the application of lean approaches [18–20], and the introduction of the concept of “kaizen” in companies [15,21,22]. In such studies, a spaghetti chart is used to find layout solutions that minimize waste, distances covered, and handling times. However, in the case of warehouses, there is another well-known problem [23] that can be treated using the spaghetti chart: the assessment of the risk of collision due to means of transport and moving workers.

This article shows how to use smart spaghetti (spaghetti charts automatically build through smart tracking devices) to map the reliability of the warehouse and the risk of accidents between company workers (pedestrians or forklift drivers). The proposed methodology involves recording the movements of staff using smartphones. The flow maps are drawn automatically, then the “hot zones” of the layout (the most critical areas of the warehouse) are highlighted searching for near misses. In this way, the reliability of the warehouse is mapped, identifying the areas at high risk of collision, which negatively impacts the safety of the system. Based on the obtained results, observing the smart spaghetti and their critical areas, it is possible to identify potential interventions that should be made to improve the structure’s safety. The proposed approach is particularly interesting for the companies that are looking for a decision support system to improve the organization of their warehouses, pursuing as objectives the more sustainable development of a plant according to social aspects, greater safety in the workplace, and better interaction between humans and machines [24].

This paper shows an application of smart spaghetti to map the movements of forklifts and workers in a pharmaceutical material storage facility. The remainder of the present paper is as follows: Section 2 outlines the proposed approach; in Section 3, a case study is used to demonstrate its application; and finally, Section 4 provides a discussion on the results and some conclusions.

2. Materials and Methods

The spaghetti diagram (also known as a spaghetti chart) is a tool for mapping and visualizing physical flows of resources (materials, people, documents, or other) that pass through a predetermined volume of control [7]. It consists of drawing lines (called “spaghetti” because their shape recalls the pasta format) that represent the path taken by the entities moving in the system. To make the mapping of the flows more understandable, different colors can be used to draw the spaghetti by distinguishing the resources that move in the system or the time bands in which they move [25].

Typically, a spaghetti chart is used in the initial phase of planning improvement actions [26]. It is recognized as one of the tools to apply lean philosophy and it is useful to establish the optimal layout of a system based on the observation of distances traveled by resources and the quantification of material exchanges between departments [10].

The construction of a spaghetti chart is possible if inspections are carried out at the system under analysis and the movements of resources are recorded [11].

Traditionally, the spaghetti lines are manually drawn on a planimetry of the system [26]. However, some authors have recently proposed new software, sensors, and digital devices to automate the construction of maps according to the concepts of “digital transformation” and “Industry 5.0” [8,25].

During the construction of a spaghetti chart, tables called “from-to-chart” are often compiled, in which the following information is listed for each flow [10]: movements, duration, distance traveled, presence of intersection/overlap between flows, and any other information of a numerical nature. The combination of spaghetti chart and from-to-chart allows visualizing the company’s weaknesses and redesigning the layout and organization of the system to minimize waste, distances traveled, lead times, and all the non-value-added operations [27]. As stated by [26], the use of a spaghetti chart is indicated when looking for effective tools to achieve the following three objectives.

- Make the company manager and staff aware of the internal flows of a system;
- Highlight how much the behavior of individuals moving within a control volume can impact the well-being of the entire company;
- Give information on the critical areas of a system and seek the causes of these issues and possible solutions.

In this perspective, in the case of warehouses, the spaghetti chart can also be used to identify the safety level of the facility and the risks associated with the movement of forklift drivers and pedestrians. The following section shows how to achieve this goal and, therefore, how to plan possible solutions to improve the sustainability of a plant according to the social dimension.

2.1. How to Evaluate Warehouse Safety Through Smart Spaghetti

To assess the reliability of a warehouse by identifying the areas of the facility and the activities that generate collision risks, smart spaghetti should be built and analyzed by applying the following procedural steps.

Conduct interviews with warehouse staff to understand what activities are carried out in the facility, what products are contained in the inventory, how the shelves are loaded and unloaded, how forklifts are used, and how working days are organized [11]. During the interviews, the perceptions that staff members have of the advantages and disadvantages of the warehouse in terms of layout, management, and reliability can be asked. Once the spaghetti chart has been built, it will be possible to compare the visualization of real flows with the workers' perceptions, to confirm or not their impressions.

Define the control volume to be analyzed. It is possible to consider the entire warehouse or to focus only on the part of the facility that, according to the experience of the staff, is most critical [22]. The important thing is to make a choice so that the smart tracking devices and infrastructure needed to record the movement of resources are able to operate in these areas. Once the control volume has been defined, it is necessary to procure a planimetry that will be used to produce the spaghetti charts.

Choose the resources to monitor. To assess the adequacy of the warehouse layout in terms of safety and collision risks, it is necessary to map the movements of workers [25,28], whether they are moving on foot or using logistical means of transport.

Map staff movements using smart tracking devices. The mapping of movements must be carried out several times, on different working days at different hours, choosing the appropriate number of analyses to observe the performance of all warehouse activities (as if several inspections were being carried out) and analyze a sample of significant flows. During each inspection, smart tracking devices are used to localize forklifts and workers [29] and to trace on the planimetry the spaghetti corresponding to the observed movements. Aiming at objectively representing the flows of entities, it is preferable to use such devices rather than drawing diagrams manually. In fact, in this way, the staff is not disturbed and its work is not interfered with [30], flows are drawn in scale with respect to the layout planimetry, and the procedure for constructing reliability maps is automated. Moreover, to simplify the reading of the diagrams, the spaghetti should be traced using various colors to identify the different workers performing different types of tasks (palletizing, pallet labeling, loading onto the shelves, unloading stocks, etc.) [2,7].

Several devices can be used to automatically map resource movements in the system (cameras, smartwatches, position sensors, smartphones, etc.) [16,29,31]. However, using smartphones is particularly advantageous because it does not require large investments in IT technology to obtain a smart spaghetti mapping (nowadays, many companies already have company phones available) [7]. In the case of warehouses where workers can move either on foot or with forklifts, each forklift and each employee is equipped with a smartphone. Then, the smartphone's inertial sensors (accelerometer, gyroscope, magnetic field sensor, and orientation sensor) are leveraged to generate automatic spaghetti charts. When an operator is driving a forklift, the spaghetti related to the forklift

movements are mapped. Otherwise, the system plots the flow path related to the pedestrian worker. Uddin et al., in [7,8], describe in detail how to use smartphones to plot automatic flow paths, also explaining the system architecture, data acquisition, data fusion, accuracy, and functioning of the methodology. To implement a similar approach, it is also possible to rely on commercially available apps such as the one described in [32]. Again, readers are invited to consult [32] to obtain information about the system architecture, the accuracy of the approach, and its functioning.

Fill in a from-to-chart for each inspection carried out [33], recording for each flow which resource has moved (worker ID), the number of movements, duration of movement, and means of transport used (pedestrian or forklift driver). In the case of warehouses where the tasks performed are highly repetitive, by comparing the results of the smart spaghetti with information on the daily activities to be performed (known from the company's management systems), it is possible to associate each spaghetti with information on the type of task performed. Furthermore, it is possible to report in the from-to-chart the occurrence of "near misses", which are critical events not resulting in a crush but very close to that [34]. Near misses can then be used as indicators to estimate the safety of the system [35].

It is possible to detect near misses knowing that any tracking device records, for each instant of time, the position occupied by a resource within the planimetry. A generic tracker ID at instant t assumes coordinates:

$$A = (x_{A,t}, y_{A,t}), \quad (1)$$

By analyzing the consecutive positions assumed by each resource over time (smart spaghetti), the instantaneous speed ($v_{A,t}$) and the advancing direction ($\vartheta_{A,t}$) of each worker can be determined (Figure 1).

$$\vartheta_{A,t} = \arctg\left(\frac{y_{A,t} - y_{A,t-1}}{x_{A,t} - x_{A,t-1}}\right), \quad (2)$$

$$v_{A,t} = \frac{\sqrt{(x_{A,t} - x_{A,t-1})^2 + (y_{A,t} - y_{A,t-1})^2}}{\Delta t} \quad (3)$$

where Δt is empirically calibrated to be large enough to avoid the same near miss being detected multiple times.

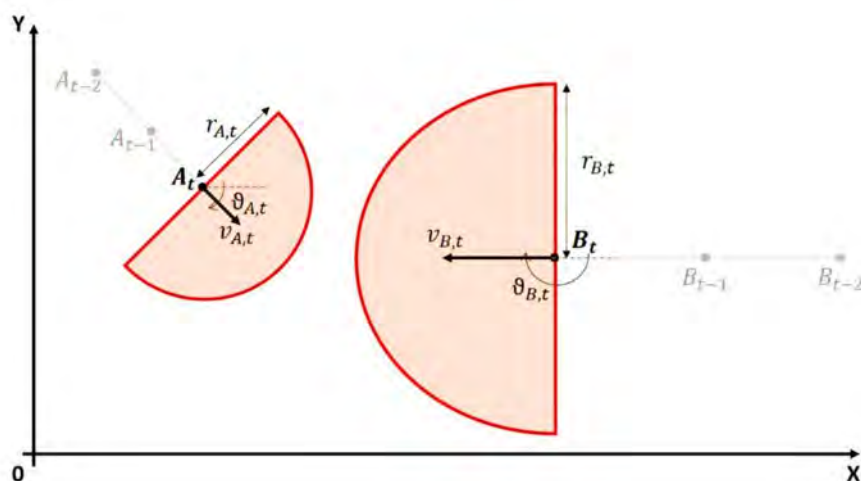


Figure 1. Representation of the risk spaces of two generic points (A and B) which, at the instant t , move with speed ($v_{A,t}$) and ($v_{B,t}$) in direction ($\vartheta_{A,t}$) and ($\vartheta_{B,t}$)

A generic near miss occurs if two or more resources get so close that there is not enough stopping distance. Although a near miss does not always result in a collision—one of the resources may suddenly change direction to avoid the impact—it is still considered a risky event. Depending on

the type of resource mapped by the tracker (pedestrian or forklift), a risk zone is calculated as a flat figure obtained from a closed semi-circle (red in Figure 1). In the case of resource A, this semi-circle will have a center given by Equation (1) and radius (4). When the closed semi-circumference of A intersects another closed semi-circumference (for example, that of B, Figure 1), the probability that A and B will collide in the following instants of time increases.

$$r_{A,t} = \begin{cases} l_{forklift} + s_{braking\ distance\ A,t} + t_{human\ reaction} \cdot v_{A,t} + c & \text{if ID forklift} \\ l_{average\ man\ stride\ length} + t_{human\ reaction} \cdot v_{A,t} + c & \text{if ID pedestrian} \end{cases} \quad (4)$$

where $l_{forklift}$ is shown in Figure 2, $t_{human\ reaction}$ is conventionally taken equal to 0.2 s, $s_{braking\ distance\ A,t}$ is proportional to the square of the speed $v_{A,t}$ [36], $l_{average\ man\ stride\ length}$ is conventionally taken equal to 0.75 m, and, finally, c is a corrective term taking into account the accuracy of the trackers.

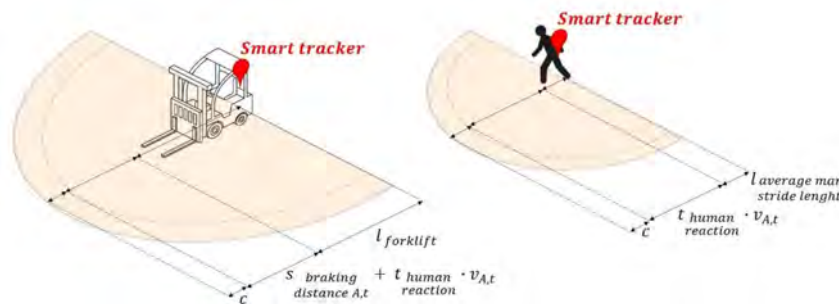


Figure 2. Calculation of the safety radius for forklifts (left) and pedestrians (right), based on the position of the resources detected by the trackers.

Before searching for the intersections between semi-circumferences of resources at instant t , it is useful to make an initial check to reduce the calculation power required by the methodology. In this perspective, we only search for pairs of points (A and B) whose Euclidean distance at instant t is less than or equal to the sum of the respective radii (r_A and r_B).

$$d_{AB,t} = \sqrt{(x_{A,t} - x_{B,t})^2 + (y_{A,t} - y_{B,t})^2} \leq r_{A,t} + r_{B,t}, \quad (5)$$

For the couples of points verifying condition (5), the presence of an actual near miss is then detected as follows. Given the equation of a semi-circumference centered in A (6a and 6b) and rotated by an angle $\vartheta_{A,t}$ (6c and 6d),

$$\begin{cases} (x' - x_{A,t})^2 + (y' - y_{A,t})^2 = r_{A,t}^2 & (6a) \\ x' \geq x_{A,t} & (6b) \\ x' = x'' \cos \vartheta_{A,t} + y'' \sin \vartheta_{A,t} - y_{A,t} \sin \vartheta_{A,t} - x_{A,t} (1 - \cos \vartheta_{A,t}) & (6c) \\ y' = y'' \cos \vartheta_{A,t} - x'' \sin \vartheta_{A,t} + x_{A,t} \sin \vartheta_{A,t} + y_{A,t} (1 - \cos \vartheta_{A,t}) & (6d) \end{cases} \quad ,$$

and given the equation of a line segment whose amplitude is $2 \cdot r_{A,t}$ (7a–7c), passing through point A (7d and 7e), and rotated by an angle $\vartheta_{A,t}$ (7f and 7g),

$$\begin{cases} x = 0 & (7a) \\ y \geq -r_{A,t} & (7b) \\ y \leq r_{A,t} & (7c) \\ x = x' - x_{A,t} & (7d) \\ y = y' - y_{A,t} & (7e) \\ x' = x'' \cos \vartheta_{A,t} + y'' \sin \vartheta_{A,t} - y_{A,t} \sin \vartheta_{A,t} - x_{A,t} (1 - \cos \vartheta_{A,t}) & (7f) \\ y' = y'' \cos \vartheta_{A,t} - x'' \sin \vartheta_{A,t} + x_{A,t} \sin \vartheta_{A,t} + y_{A,t} (1 - \cos \vartheta_{A,t}) & (7g) \end{cases} \quad ,$$

systems (6a–6d) and (7a–7g) characterize the closed semi-circumference relative to A. Similarly, systems (8a–8d) and (9a–9g) identify the closed semi-circumference of B.

$$\left\{ \begin{array}{l} (x' - x_{B,t})^2 + (y' - y_{B,t})^2 = r_{B,t}^2 \quad (8a) \\ x' \geq x_{B,t} \quad (8b) \\ x' = x'' \cos \vartheta_{B,t} + y'' \sin \vartheta_{B,t} - y_{B,t} \sin \vartheta_{B,t} - x_{B,t} (1 - \cos \vartheta_{B,t}) \quad (8c) \\ y' = y'' \cos \vartheta_{B,t} - x'' \sin \vartheta_{B,t} + x_{B,t} \sin \vartheta_{B,t} + y_{B,t} (1 - \cos \vartheta_{B,t}) \quad (8d) \end{array} \right. ,$$

$$\left\{ \begin{array}{l} x = 0 \quad (9a) \\ y \geq -r_{B,t} \quad (9b) \\ y \leq r_{B,t} \quad (9c) \\ x = x' - x_{B,t} \quad (9d) \\ y = y' - y_{B,t} \quad (9e) \\ x' = x'' \cos \vartheta_{B,t} + y'' \sin \vartheta_{B,t} - y_{B,t} \sin \vartheta_{B,t} - x_{B,t} (1 - \cos \vartheta_{B,t}) \quad (9f) \\ y' = y'' \cos \vartheta_{B,t} - x'' \sin \vartheta_{B,t} + x_{B,t} \sin \vartheta_{B,t} + y_{B,t} (1 - \cos \vartheta_{B,t}) \quad (9g) \end{array} \right. ,$$

A near miss is obtained when the closed semi-circumferences of A and B intersect according to one of the three scenarios shown in Figure 3, i.e., when at least one of the system pairs, (6a–6d)–(8a–8d), (6a–6d)–(9a–9g), and (7a–7g) and (8a–8d), admits a solution.

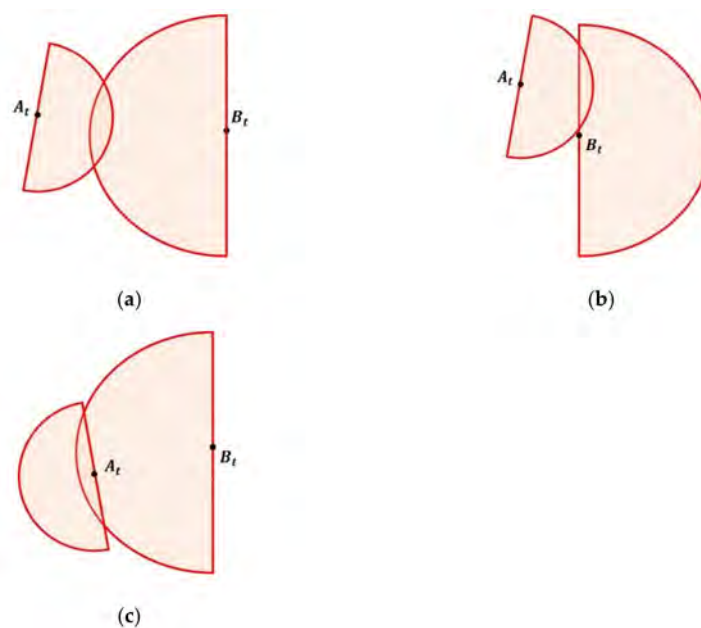


Figure 3. Possible scenarios of intersection between risk zones of two generic resources A and B. (a) Intersection between the semi-cumference of A and the semi-cumference of B. (b) Intersection between the semi-cumference of A and the straight line of B. (c) Intersection between the semi-cumference of B and the line of A. If at least one of these scenarios occurs, a near miss is detected. The scenario of intersection between two lines is not considered because the orientation of the closed semi-cumference always adapts to the advancing direction of the resources.

Analyze the spaghetti chart and from-to-chart results. At the end of this process, a smart spaghetti and a from-to-chart are produced for each time interval in which the tracking devices have recorded flows. The greater the number of analyses carried out, the more the diagrams will faithfully represent the real situation in the warehouse. According to a qualitative approach, the areas of the diagrams where there are more intersections between flows and near misses detected in the from-to-chart correspond to the “hot areas” of the structure, i.e., those on which it is good to operate to improve the reliability of the warehouse. In general, in fact, for the safety of a system, it is good to

avoid near misses and forklift trajectories at risk of an accident. Besides, the color of spaghetti gives information on the least reliable employees, while information on the tasks performed indicates which actions (or combinations of them) generate the greatest risk of collision.

Finally, where hot areas or risky tasks are detected, possible solutions can be devised to improve warehouse reliability both in terms of layout and organization of work activities. Thus, the diagram and the proposed methodology (Figure 4) correspond to a smart decision support system useful to

- Automatically obtain a visual and objective, although qualitative, mapping of the safety situation of the structure;
- Identify critical areas and tasks;
- Plan possible improvements.

Moreover, once the critical areas and activities are known, this approach allows comparing the results of the diagrams with the staff perceptions (emerged from the interviews) to verify the correspondence between initial impressions of the staff and the real situation. In this perspective, besides being useful as a design support tool (to identify possible solutions to reliability problems and to pursue greater sustainability of the warehouse at a social level), the proposed approach can be used as a description of the current situation of the warehouse, to make the staff and company manager more aware of the current safety level.

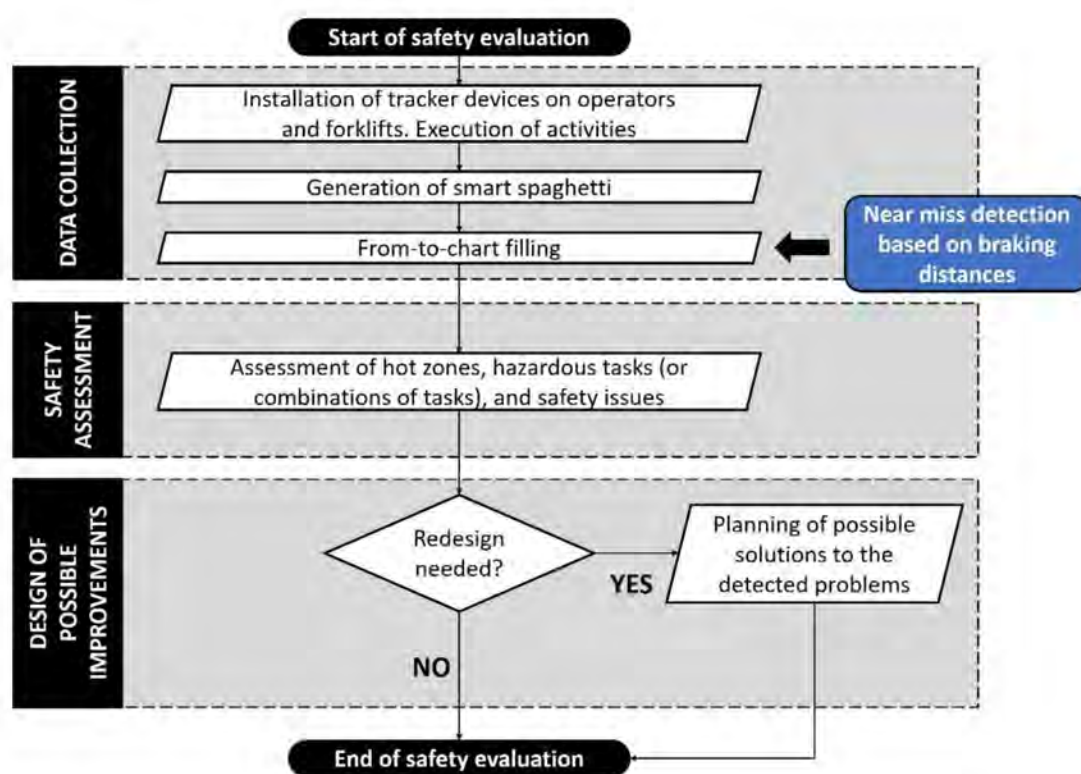


Figure 4. Procedural steps of the proposed approach to evaluate the safety of a warehouse and devise improvement solutions.

Below is a case study application of smart spaghetti to map the safety situation in a real warehouse and identify problems related to collision risks.

3. Results

The case study investigated took place in a large pharmaceutical company that owns a warehouse located 8.2 km away from the production plant. The warehouse is staffed by 30 warehousemen who

alternate with 6-h shifts. Although the warehouse has undergone improvements, the facility supervisor still detects issues related to reliability and the risk of collisions between forklifts. To increase the safety level and social sustainability, cameras, mirrors, and soft protections have already been installed at the aisle corners. Despite this, the supervisor reports that the staff is still at risk of accidents on a daily basis, especially in a particular area of the building: the goods unloading area. His claims are substantiated by camera footage, and scratches on the aisle walls and forklift corners. The supervisor is therefore looking for a structured strategy to show his boss that, despite the interventions made, the warehouse still has safety problems. Moreover, the supervisor seeks a way to detect which areas and tasks of the warehouse are critical and to devise reasonable solutions.

Evaluation of Warehouse Safety Through the Proposed Approach

First, the supervisor and staff members were interviewed. The interviews showed that the warehouse stores both drugs waiting to be sold and raw materials (syringes, bottles, needles, etc.) to feed the production plant.

The following tasks are carried out in the warehouse.

- **a. Unloading** of goods (finished products) to be delivered **by airplanes** to external customers. Due to the cost of air transport, only medicines that need to stay at a controlled temperature are shipped by air. In fact, they must be delivered quickly and immediately stored in the refrigerator.
- **b. Loading** of goods (raw materials) **from airplanes** sent by suppliers (replenishment of the warehouse). These goods are picked up at the airport by a truck, which then transports them to the warehouse. They are distinguished from other goods because they are always placed in cold stores and arrive in the form of large metal containers, each containing five pallets.
- **c. Unloading** of goods to be delivered **by ship** to external customers. The capacity of the trucks is finite, so the number of trips needed to bring the materials from the warehouse to the port changes according to the number of pallets to unload (customer orders).
- **d. Loading** of goods **from ships** sent by suppliers. These goods (some of which are destined for cold storage) are recovered at the ports and transported to the warehouse by truck.
- **e. Unloading** of goods to be delivered **by truck** to external customers. The capacity of the trucks is finite, so the number of trips needed to bring the materials from the warehouse to the customer changes according to the number of pallets to unload.
- **f. Loading** of goods sent by suppliers **by truck**.
- **g. Palletizing and labeling**. Before each shipment, boxes of medicines are palletized and labeled with descriptive stickers. These tasks take time to be completed because pallet formats and product labeling standards vary depending on whether goods are shipped in or out of Europe.
- **h. Unloading** of goods to be delivered **by truck to the internal customer** (production plant). Based on the production orders, the raw materials and semi-finished products needed to feed the production lines are shipped from the warehouse to the factory. Since the production plant has a small warehouse that can hold raw materials for only 4 h of work, this activity is repeated several times a day.
- **i. Preparation of pallets** to be shipped **to the internal customer**. Pallets of this type, waiting to be shipped, are stored in a waiting bay, where they remain until the trucks arrive.
- **j. Loading** of goods **in trucks from the internal customer**. The finished products are stored in the warehouse waiting to be sold to external customers. Loads are made several times a day.

All the loading and unloading tasks and the palletization are carried out using forklifts. The loading units to be transported are pallets and, since the trucks carrying out the distribution of goods have a known and limited capacity, the number of pallets needed to fill or empty a truck is known. As a result, knowing the number of pallets to be delivered to a certain customer (or the number of pallets arriving from a supplier), the number of movements (back and forth) that the forklifts have to make to load the

truck is known. The tasks of loading and unloading goods, therefore, are highly repetitive. Unlike the other tasks, the labeling activities are carried out by pedestrians who apply tags and labels directly on the pallets before they are loaded onto the trucks.

The area of the warehouse used for **unloading goods** to be shipped to external or internal customers has been set as the control volume (Figure 5). This area, as said, is where the supervisor detects critical points. For this reason, all the loading activities mentioned above were excluded from the analysis (b–d–f–j).

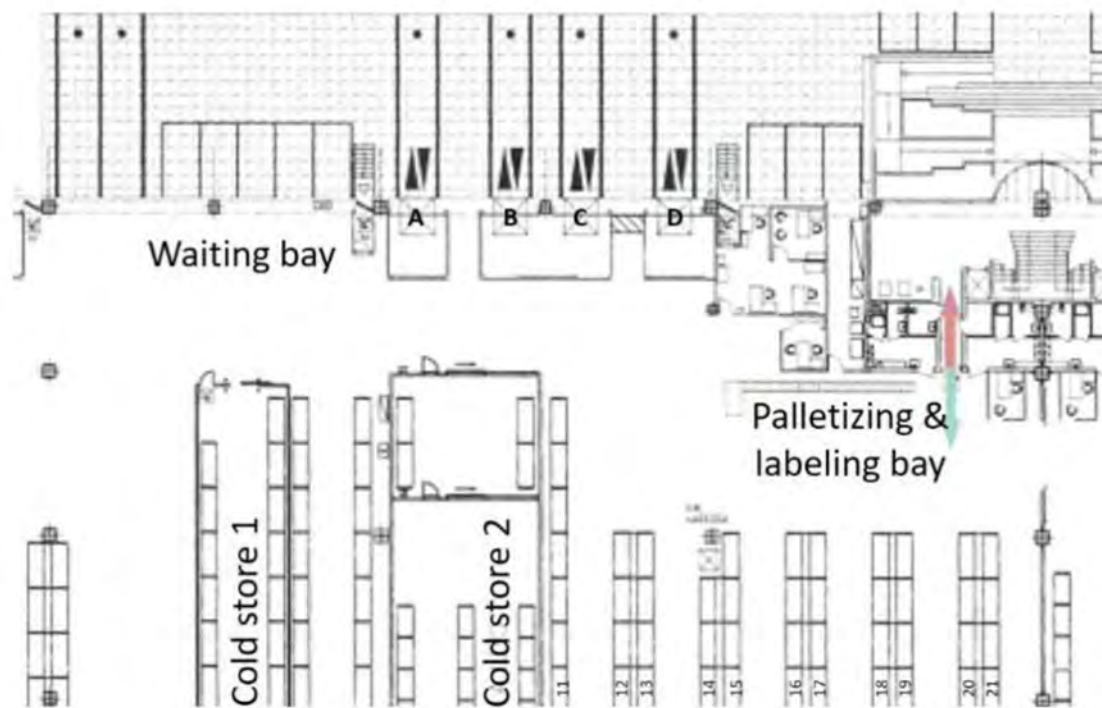


Figure 5. Planimetry of the control volume (warehouse area designated for unloading goods).

All operators and forklifts were equipped with smartphones. Then, their movements were observed. With the help of company IT technicians who installed a commercial app on their company phones [32] (see Section 2.1), following the suggestions by [7], smartphones worn by workers or placed on forklifts and their magnetic sensors were used to map flows. Three analyses were carried out—each lasting about 4 h—during which the devices recorded information on the flows. Different colors were used in tracing the spaghetti to distinguish the tracker IDs. Based on the flows recorded, a from-to-chart was created, of which an example is shown in Table 1. In order to associate with each flow path information related to the task performed, the focal points of the structure such as the labeling bay, the waiting bay, and the discharge doors (A, B, C, and D, Figure 5) were enclosed within rectangles. Then, the company’s IT technicians took information from the management systems regarding daily orders, scheduled activities, and the number of trips required to fill each truck. Subsequently, observing how many times the trackers were positioned within each focal rectangle and the duration of the movements, each route was associated with the task performed.

Table 1. Extract of a from-to-chart. The following information was provided for each flow: worker ID, working time, description of the task performed, number of movements, type of movement (“O” one way only, “R” return only, or both “O + R”), means of transport used (“P” pedestrian, or “F” forklift driver), and detection of criticalities (the symbol “x” is used to mark streams that generated a near miss). In the last column, some comments were added by authors to clarify the table content.

Worker ID	Start Time	End Time	Task	N° of Repetitions	Type of Movement	Means of Transport	Near Miss	Comments
9	10:50	11:10	Pallet loading on the truck (door C)	8	O + R	F		The first three activities of this table are simultaneous but do not cause collision risks
1	10:56	11:03	Thermal blankets are taken to cover medicines that need to be shipped while remaining at a controlled temperature	4	O + R	P		
1	10:57	11:04	Withdrawal of raw materials for internal customer	4	O + R	F		
5	11:41	11:09	Pallet preparation for internal customer	3	O + R	F	x	Workers 17 and 3 generated a near miss
3	11:42	11:06	Pallet preparation for internal customer	2	O + R	F	x	

By processing the content of the from-to-chart, it was checked that, during the inspections, all warehouse activities were analyzed several times (Table 2) to ensure that enough inspections were conducted.

Table 2. Through the from-to-chart, observing the dates and times of the flows, it was checked which combinations of activities were observed, then it was verified that each activity was observed several times. The symbol “✓” marks the activities observed on a specific date and time. If there are two or more ✓ on the same line, it means that activities were observed simultaneously.

Inspection Date	Start Time	End Time	Observed Scenarios					
			Transport to External Customer			Transport to Internal Customer		
			a. Unloading of Air Cargo	c. Unloading of Ship's Cargo	e. Unloading of Truck's Cargo	g. Palletizing and Labeling	h. Unloading of Truck's Cargo	i. Internal Order Preparation and Replenishment
Day 1	08:25	08:59					✓	
Day 1	09:37	10:23						✓
Day 1	10:45	11:03				✓	✓	✓
Day 1	11:37	11:54					✓	
Day 2	13:51	14:02					✓	✓
Day 2	14:38	14:48					✓	
Day 2	14:54	15:00				✓	✓	
Day 2	15:02	15:53	✓	✓		✓		
Day 2	15:54	16:04	✓		✓			✓
Day 2	16:12	15:19	✓			✓		
Day 2	16:21	16:24	✓		✓			
Day 2	16:24	16:34		✓				
Day 2	16:36	16:49	✓		✓			
Day 2	16:49	16:58	✓					
Day 2	16:57	17:18				✓		✓
Day 3	08:14	08:25	✓			✓		
Day 3	08:26	08:35						✓
Day 3	08:36	08:40					✓	
Day 3	08:40	08:53	✓	✓				
Day 3	08:55	09:02				✓		
Day 3	09:07	09:17		✓				
Day 3	09:19	10:08					✓	
Day 3	10:12	10:20					✓	
Day 3	11:23	11:26			✓			✓
Day 3	11:31	12:00		✓	✓			

Figure 6 shows the smart spaghetti charts obtained (one for each inspection carried out).

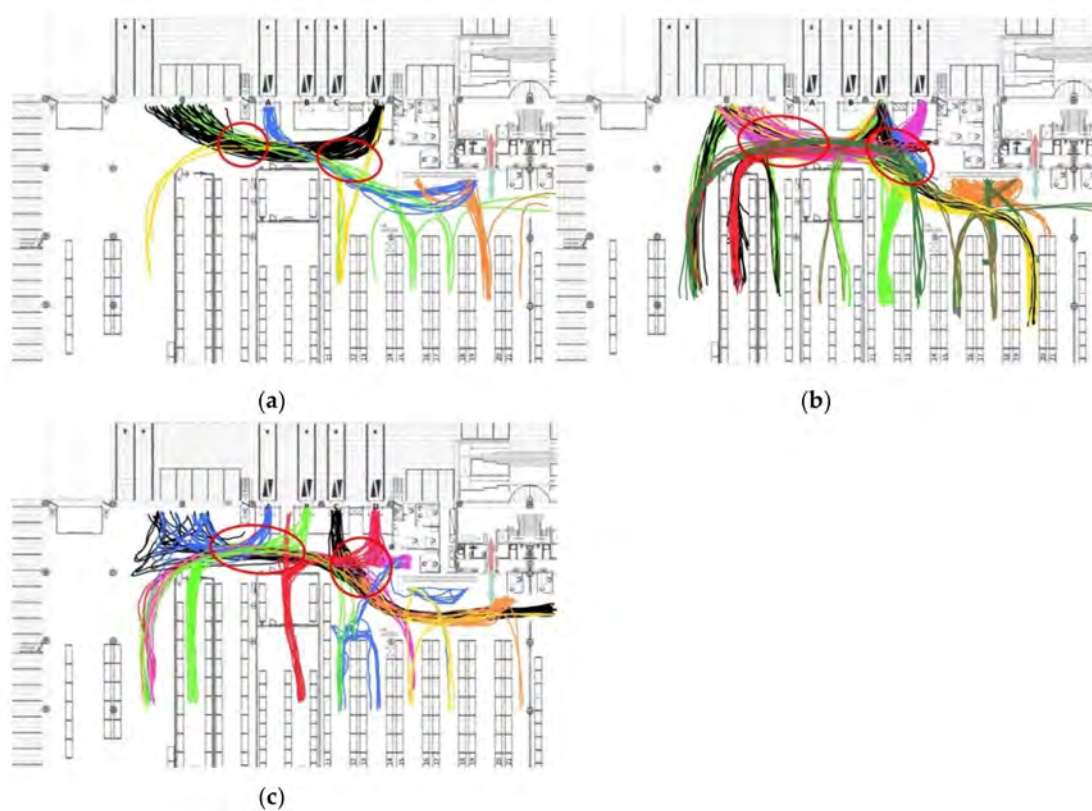


Figure 6. The Figure shows the Smart Spaghetti charts obtained respectively after carrying out the inspections on Day 1 (a), Day 2 (b), and Day 3 (c), whose information is detailed in Table 2. In each mapping, colors were used to distinguish the workers (forklift drivers or pedestrians) moving within the control volume. Red circles were added to highlight hot areas of the layout.

Red circles were added in the diagrams to highlight the “hot areas” of the layout, i.e., the areas where near misses were detected and where intense flows were recorded. It should be noted that the areas characterized by the most intense flows are those with reduced passage spaces and logistic surfaces. In particular, there are two regions with the highest number of near misses.

1. The area between the waiting bay and cold room 1 (left circles, Figure 6a–c). Here, the raw materials to be shipped to the internal customer accumulate, so they remain to occupy space and increase the probability of having a near miss. As stated by [5], the high volume of material on the ground is one of the causes of warehouse inefficiency and makes the processes unsafe and very time-consuming.
2. The area in front of the discharge doors C and D (right circles, Figure 6a–c). This is where palletizing and labeling operations and most truck transports are carried out. Even in this area, forklifts and personnel remain to occupy space, increasing the probability of collisions.

Based on the outcome of 12 h of analysis and considering $\Delta t = 1\text{ s}$ and $c = 0.50\text{ m}$ (see Section 2, Equations (3) and (4)), five near misses were detected in the from-to-chart. The first two near misses occurred when several workers were carrying out internal order preparation and replenishment activities simultaneously. In both cases, the palletizing and labeling bay (Figure 5) was occupied by pallets, and an operator moving around reduced the passage section. This forced the other operators directed to the waiting bay (Figure 5) to travel close or intersecting trajectories, leading them to risk collision on two occasions. Figure 7 illustrates one of the two near misses just described.

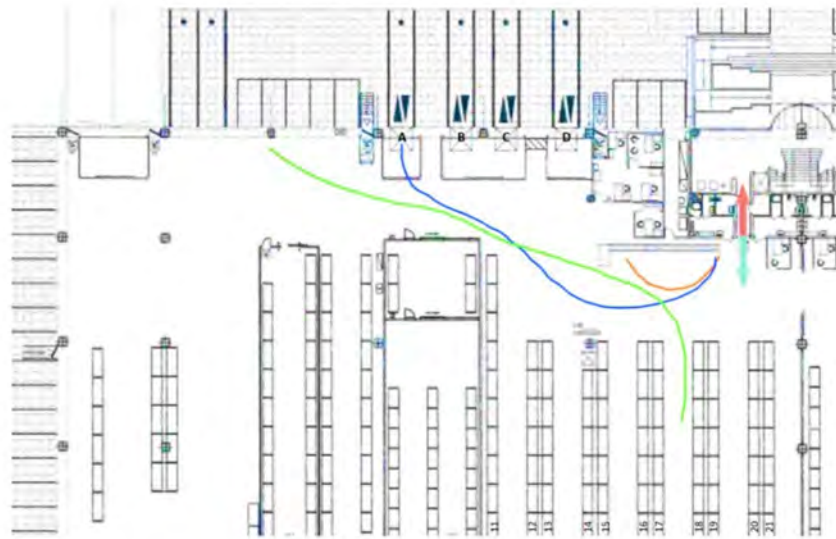


Figure 7. Near miss example. Each “spaghetti” corresponds to the trajectory of a different operator. The orange worker was performing the labeling operation, while the green and blue workers were performing internal order preparation and replenishment tasks. All the flows were detected at 10:45 a.m. during Day 1. Due to the obstruction in the labeling and palletizing bay (orange flow), the green and blue flows were forced to travel close trajectories and there was a near miss between forklifts.

In the case of the near miss shown in Figure 7, the intersection occurred when points A (blue low, Figure 7) and B (green flow, Figure 7) met the conditions shown in Table 3.

Table 3. Numerical data characterizing the first near miss (graphically illustrated in Figure 7).

	Resource A	Resource B	Measuring Unit
x_t	44.1	42.9	[m]
y_t	40.3	41.9	[m]
x_{t-1}	43.0	42.5	[m]
y_{t-1}	39.9	43.2	[m]
v_t	1.17	1.36	[m/s]
ϑ_t	19.98	-72.90	[°]
Means of Transport	Forklift	Forklift	[-]
r_t	2.36	2.68	[m]
Distance Between AB_t		2.00	[m]
Sum of Radii $_t$		5.03	[m]

Based on the data shown in Table 3, the circumference centered in A (6a–6d) and the straight line perpendicular to the advancing direction of B (9a–9g) intersected at two points (two solutions). The first solution is $x_1 = 42.19$ and $y_1 = 41.68$, while the second one is $x_2 = 44.91$ and $y_2 = 42.52$. Both solutions had a Euclidean distance from B smaller than $r_{B,t}$, therefore they belonged to the segment delimiting the risk zone of B. Finally, the solution $x_2 = 44.91$, $y_2 = 42.52$ also respected condition (10), thus belonging to the semi-plan where the semi-circumference delimiting the risk zone of A is situated.

$$\begin{aligned}
 & y_2 - y_{A,t} + \left(\frac{x_{A,t-1} - x_{A,t}}{y_{A,t-1} - y_{A,t}} \right) (x_2 - x_{A,t}) \\
 & = 42.52 - 40.30 + \left(\frac{43.0 - 44.10}{39.9 - 40.30} \right) (44.91 - 44.10) = 4.45 \geq 0,
 \end{aligned} \tag{10}$$

The third and fourth near misses also occurred in close instants of time, when several workers carrying out the internal order preparation and replenishment tasks almost collided. However, this time, the reduction in the passage section was caused by the presence of other operators carrying out air

cargo unloading activities and occupying the area in front of doors C and D. Finally, the fifth near miss occurred when some pallets containing refrigerated products, before being delivered by ship to the external customer, were temporarily stored in the middle of a lane to be covered with thermal blankets. In this situation, a forklift driver carrying out internal order preparation and replenishment, thinking he could cross the (usually free) lane, risked an accident with the pedestrian applying the thermal blankets.

As a result, the analysis performed using smart spaghetti and from-to-chart confirmed the initial impression of the supervisor: despite the presence of mirrors and guards, the reliability of the warehouse can be improved. The smart spaghetti and from-to-chart enabled the warehouse supervisor to describe the problems of the structure to his boss, highlighting graphically and through tabular charts the hot areas and the less reliable scenarios. Since, in the initial situation of the warehouse, several cameras had already been installed to observe the resource flows, watching the recorded footage, a verification of the effectiveness of the proposed approach was obtained, confirming the presence of the identified near misses and hot areas. Furthermore, confirmation was obtained of the near misses' causes and the nature of the risky tasks.

The proposed approach constituted a valuable (although qualitative) decision support system. Indeed, based on the information gathered, and by observing the flow and reliability maps, some possible interventions to improve the safety and sustainability of the system were devised. Below are listed, first, the problems encountered, then the possible solutions identified.

Hot areas and near misses occur in zones characterized by reduced passage spaces and logistical surfaces. Sometimes the forklifts risk collisions and resource flows are slowed down (or even blocked) by the presence of obstacles along their path. As shown in the company's database, currently, the static capacity of the warehouse is fully utilized, so a reduction in pallet places in the analysis area seems not possible. Based on these considerations, to overcome these problems, some ideas for improvement are as follows:

- To modify the warehouse layout by making more uniform use of the available surface, and gaining space in critical areas by relocating or eliminating some shelves (in this case, better stock management is necessary);
- To move the re-palletizing area to another area of the warehouse that is less frequented (not visible in Figure 5 for privacy reasons);
- To open a new bay for loading air cargo into another area of the warehouse and/or to relocate the bay for internal order preparation and replenishment;
- To establish one-way traffic directions (hypothesis to be evaluated by simulating the flows and obtaining automatic mapping of the warehouse also in the goods reception area, not only in the unloading area).

4. Discussion

The spaghetti chart, besides being a tool for implementing lean philosophy, can also be used to build safety maps, qualitatively define the risk of collision between forklift drivers and pedestrians in a warehouse, identify the less reliable tasks and areas of the layout, and, finally, devise potential measures to increase the safety and sustainability of the system.

For this purpose, by exploiting proper smart tracking devices, it is possible to automate the construction of spaghetti charts. Having performed a sufficient number of analyses (to obtain a significant sample of flows), a visual representation of the system safety is obtained. By processing the collected information, it is possible to fill in the from-to-chart, detecting near misses based on resource braking distances and human reaction times. Then, observing the spaghetti maps, the color of spaghetti, and the content of from-to-charts, the most critical warehouse areas and tasks (or combinations of them) are highlighted. Based on the type and number of near misses and the reasons for their occurrence, some possible improvements to the facility can be planned. In this perspective, the advantage of this approach is that of being a structured design strategy suitable for devising only solutions related to

the effective problems of the warehouse. Changes may involve, for example, modifying the layout of the system or work organization. The proposed approach allows remote examination of the near miss dynamics and their causes, thus avoiding the need to personally inspect the system and reducing analysis effort.

In the case study shown, the approach highlighted five near misses and two critical areas of the layout, both corresponding to areas of the warehouse where raw materials and pallets accumulate. In this sense, the results of the smart spaghetti and from-to-chart confirmed the statements by [5], demonstrating that the areas of a structure where materials remain to occupy space are the most critical. In the pharmaceutical warehouse, the accumulation of materials increases the probability of near misses and accidents between forklifts.

The approach also showed that internal order and replenishment are the most problematic activities (affecting four of the five near misses detected). The camera footage confirmed the presence of all the near misses, validating the effectiveness of the criticality detection approach based on staff speed and forklifts' braking distance. In addition, the camera confirmed the near miss causes and the presence of hot areas in the warehouse. The observation of critical events let us confirm that the labeling bay, the bay for preparing the products to be shipped to the internal customer, and the bay for loading the trucks (in front of the doors C and D) are the most hazardous areas of the warehouse. Due to the layout and conformation of the system, when one of these three bays is filled with pallets and forklifts moving inside it, the passage areas are restricted and, as a consequence, resource flows are slowed down due to obstacles along their path and near misses occur.

The case study confirmed the applicability of the method in real-life contexts and made it possible to hypothesize some improvements in the structure, including the elimination of some shelves, the opening of a new loading bay for trucks, the establishment of one-way traffic directions, or the shifting of the labeling and waiting bay.

Finally, the case study validated the claims by [26], showing that the spaghetti chart is a design support tool appreciated by company staff, such that its results constitute an "impulse to look for possibilities of implementing such improvements in other company areas". Indeed, after seeing the outcomes of the case study, and the speed and simplicity of the proposed qualitative approach, the head of the pharmaceutical company asked to repeat the investigation in two other company areas. The repetition of the analysis was facilitated by having automated the risk mapping procedure.

The proposed approach may be helpful as a support tool to assist companies in the design phases of the warehouse, especially in the early stages of collecting ideas for planning/modifying the layout and organization of the system. It allows representing the flows of a warehouse, highlighting unreliability, and, therefore, hypothesizing improvements based on the identified hot areas, critical tasks, and risky scenarios. Such an approach can be applied not only in warehouses but also in other structures where dangerous means of transport are moved. It is particularly effective in systems where work activities involve repetitive movements, as in the case study shown. In fact, in this case, a limited number of inspections is sufficient to observe a significant sample of flows and truly represent the reliability situation of the warehouse. However, it could also be applied in systems where many activities are performed. In this case, the approach requires to study many scenarios (many inspections) to obtain a faithful representation of the safety situation. However, this is not a significant problem, indeed, using tracking devices to plot operators' movements, the procedure for mapping the diagrams is automated [8]. As a result, it is easy to repeat the analysis several times and it is also possible, for example, to compare how the safety level changes before and after a certain intervention. Moreover, the proposed approach may help to check whether the impressions of the company staff in terms of structure reliability correspond to reality or not, making the operators and the company manager more aware of the risks they are daily exposed to.

The method, however, has some disadvantages. First, it is not a real-time analysis approach but rather is based on the study of offline information. Secondly, it is a qualitative approach, so it does not give a numerical estimate of the reliability of the structure, nor does it make a quantitative prediction

regarding whether possible warehouse changes will lead to an improvement in safety performance. Therefore, after having considered the possible corrective measures, it will be necessary to use other tools such as logistic simulation [37,38] to test their real goodness before making the economic investment.

In addition to the logistic simulation, other traditional tools [39–42] allow the performance of the layout to be quantitatively verified and, in this sense, are more accurate compared to the proposed approach. However, these tools do not consider risks connected to forklift collisions to plan possible improvements to the warehouse layout and organization. For this reason, aiming at increasing the sustainability of the warehouse and the operators' safety, the proposed approach may be preferable.

Possible future development of the present work could be as follows. First, to repeat the analysis in other areas of the pharmaceutical company and to verify with other application case studies the accuracy of the proposed approach. Secondly, to use the near miss detection model to prognosticate trajectories and forecast risky situations, instead of identifying them afterward. In fact, up to now, the smart spaghetti are traced and then the maps are analyzed offline, searching for the occurred near misses. In the future, on the other hand, workers' trajectories could be analyzed in real time, and possible near misses could be predicted knowing the instantaneous position of workers. Eventually, these results could be compared with those obtained through other forecasting methods [43]. Finally, to implement changes to the warehouse selecting one or more ideas from those that emerged and to verify their goodness with simulative or empirical methods [44,45]. The positive outcome of these scientific investigations would give greater value to the proposed approach, confirming its effectiveness as a smart design support tool. When using simulation or empirical models to confirm and refine the results provided by the proposed approach, further development of the model could be as follows. The data needed to feed the simulation or the empirical method could be collected automatically, thus making automatic also the process of data acquisition and validation of the final solution, as well as the process of designing ideas for improving the structure.

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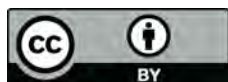
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