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Original research article

Automating Production Process Data Acquisition Towards Spaghetti Chart 4.0

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ABSTRACT

Automation of logistics and production processes is one of the significant goals of the Industry 4.0 movement. Thus, this study uses the automatic data acquisition approach to automatically create Spaghetti Charts (SC), decrease the required time spent on collecting data, and provide a fast analysis (feedback). Smartphone technology used for drawing the automated spaghetti diagram has potential drawbacks related to safety, security, the privacy of organizations, and independency. So, Method Time Measurement 4.0 and RStudio software are used to collect the real data and draw the spaghetti chart, respectively, as an alternative solution. The experiment results for four scenarios (different Facility layouts and processes) prove that the approach is competitive, with cycle time reduction exceeding 40% less than the conventional facility layout and process plan. The proposed solution of the wearable device is promising for replacing smartphone technology with smart spaghetti chart systems.

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1. Introduction

Spaghetti chart is one of the monitoring and analysis tools that assist the practitioners in obtaining a comprehensive view of the work in process on the shopfloor. The application of Spaghetti chart illustrates the movement of the workers on the shopfloor in the course of performing the entrusted technological tasks. Spaghetti diagrams expose inefficient layouts and identify large distances traveled between key steps. Spaghetti diagrams can identify areas where time is wasted by visualizing the unnecessary movement of people, products, or materials [1]. But this tool does not work well without providing realistic data representing the accurate movement of the human and material between departments, workstations, and machines on the shopfloor [2].

Real-time data acquisition will assist the practitioners in speeding up building reliable Spaghetti charts instead of using traditional tools that take long time, may cause long-term mistakes, and affect the production performance, safety, and ergonomics, especially those related to humankind [3, 4]. So, this work proposes to use Method Time Measurement 4.0 (MTM4.0) system to gather real-time data, fast data gathering from the workers on the shopfloor *instead of using smartphone technology*; this system relies on three combined technologies: Wearable technology, Radio Frequency technology, and Internet of Things Technology; MTM4.0 is a wearable device

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and an automatic measurement tool to calculate the time, identify the place of the worker and the work in process. Furthermore, MTM4.0 could assist the engineers in knowing the path of the process through tracking the human movement by RFID tags installed on the workstations [5]. The usage of this system is reasonable in the dynamic industrial environment, especially in the reconfigurable manufacturing systems, which require relayout of the facilities from time to time, and even more nowadays in a context where the impact of COVID19 pandemic [6, 7].

One of the most important implications of real-time data acquisition is real-time response that plays an essential role in Digital Twin (DT) systems and simulation 4.0 due to fast and immediate prediction sending the command back to the physical assets and industrial environment; this property helps the practitioners and industrial engineer to integrate the information with other departments as soon as possible [8]. Furthermore, the automatic system and procedure are used to align the ergonomics and safety rules in regard to the comfortability of the worker and the technological influences on the safe work environment [6]. Experiments in different scenarios are conducted to test the validity of using this system in a work environment (mechanical workshop) that deals with manual material handling and drilling operations as main jobs.

The following sections will explain state of the art, including wearable technology and data acquisition, MTM4.0 for spaghetti chart data, COVID19 impact and facility layout\ Relayout, and Smart Spaghetti Chart Systems in these different fields. Later, the paper illustrates the research methodology and the experiments to demonstrate the concept of integration of MTM4.0 with automatic data acquisition. Finally, it shows results, discussion, conclusion, and future work.

2. State of the Art

2.1 Wearable Technology and Data Acquisition

Recently, wearable technologies and devices are highly related to data acquisition in different fields such as construction, medical monitoring, ergonomics, and human factors, forest tracking, and industrial sectors due to their ability to gathering real-time and reliable data; real-time data play an important role in supporting the practitioners for designing, monitoring or even taking immediate decisions and actions, especially in cyber-physical systems. However, wearable devices that are used to collect the data vary depending on the scope of work, human factors, environments, and used technologies [9, 10].

Wearable technology is a pervasive solution for improving efficiency of work, enhancing workers' performance, and creating interactions between users and the workplace anytime and anywhere. The majority of the available devices are sensing systems composed of different types and numbers of sensors located in diverse body parts [11].

There is a need to develop or select personalized Wearable Sensing Devices (WSD) systems that mutually have advantages to workers and management to ensure successful WSD integration for data acquisition, which relates to tracking, health, and safety [12].

A wearable device can be used while the worker is in motion and should not necessarily be attached to the body but could become an integral part of the person's clothing, allowing the user to manage control and be constantly available [13, 14].

2.2 MTM4.0 for Spaghetti Chart

The method of drawing a conventional Spaghetti chart requires recording the time data, workstations, worker movements, and destinations manually [15]. In this era, this methodology does not match with advanced technologies, especially in Industry 4.0 environment, due to many impacts such as the accuracy of the data, incorrectness of estimated data and human mistakes, shortage adoption of data transformation to the intelligent information systems, so it can be useful to use a wearable device such as Method Time Measurement 4.0 (MTM4.0) [6] to overcome the challenges and drawbacks above mentioned. MTM4.0 is a wearable technology tool used to gather the data such as the time and location of the worker on the shopfloor in real-time and to document them automatically, unlike the traditional MTM, which relies on using a stopwatch and human interaction and following the worker in its workplaces. Moreover, this device is lightweight, aesthetically pleasing, shape-conformable, multi-functional, and easily configurable for the desired end-use application. It relies on using Radio Frequency Identification (RFID) technology and the Internet of Things (IoT). The worker can wear the bracelet device (RFID reader-Antenna) to detect the RFID tags for important workstations and tools on the shopfloor [5].

MTM4.0 was used for manual assembly operations and proved its efficiency for calculating the average time of the operations instead of traditional MTM and other recent technological solutions [16].

2.3 COVID19 Impact and Facility Relayout

According to the conference of United Nations on Trade and Development (UNCTAD), COVID-19 outbreak may slash the global economy by $1-2 trillion in 2020, and it has the potential impact on the Indian economy; several sectors are already feeling the pain [17]. Industry is one of the most affected sectors in this pandemic due to the stop of production, change of policies and commitment to government rules against COVID-19 crisis. Human interaction during COVID-19 pandemic era is highly avoided, especially in the closed spaces and small areas, particularly the factories requiring manual activities and crowded aisles. So, Spaghetti Chart is a helpful tool that plays a significant role to identify the safest and risky areas to support the practitioners to relayout the facilities on the shopfloor, reducing the number of conflicts and crowded aisles aligning with safety and healthy rules issued against COVID19 for maintaining the required social distance [16].

It is difficult to trace the workers in the dynamic environment using the traditional methods for identifying the movement path during this pandemic era [18, 19], So, it is reasonable to use wearable devices (e.g., MTM4.0) to speed up the data acquisition process and update the management in real-time to take the responsibility and analyze the data for creating a new facility layout avoiding using the conventional tools that rely on human interaction [20, 21, 22]. So, it is useful to use MTM4.0 for producing new Spaghetti charts and acquiring production data automatically as an initial step towards Spaghetti 4.0.

2.4 Smart Spaghetti Chart System

Last decade, [23, 24] authors had firstly used the automated spaghetti chart or "spaghetti diagram," and they called it "Smart Spaghetti" relying on using smartphone technology, in the health and hospital sectors. The approach depends on the smart phones used by the staff (doctors, nurses, etc.) and patients. It was a good trial, but they mentioned that there were many gaps and challenges: Independency, accuracy (several errors had occurred), and security. This is in the health sector, but the challenges could be more in the industrial sector than the health sector, which concerns the company's privacy, especially for the production systems and work mechanism and progress; some companies do not allow using smart phone during working times [25]. The second and important challenge, Health and Safety standards prohibit using smartphone in some dangerous industry facilities and plants such as oil and gas industry fields due to the possibility of generating static charge and electrical sparks [26]. For the above reasons, the MTM.0 is really competitive and useful for collecting the data and shall substitute the smartphone technology for creating Spaghetti Chart 4.0

More recently in 2017, [27] also tried to automate the process of drawing the spaghetti chart for Workers' movement analysis, the limitation of the proposed application is that it does not produce a fast drawing of random movement of workers. While authors in [28] have been worked on an innovative and smart wearable tool relying on integration of many technologies and different sensors; the above-mentioned citation used RFID technology not for tracking the location of the worker, but they used RFID technology to detect the good and material while the worker is moving from destination to another. In this work, MTM4.0 depends on RFID technology to identify indirectly the location of the worker and calculate the time between two destinations instead of using accelerometer and gyroscope.

Last year in 2020, [2] mentioned that "Smart spaghetti" is a valuable decision support system that can recognize potential improvements in the warehouse system through changes in the layout or in the operations are performed, the past author applied this "smart spaghetti" on the movement of forklift in a pharmaceutical warehouse. Anyway, "Smart Spaghetti Chart" systems are beneficial for movement analysis and producing fast visualization and overview, but there is still challenges and gaps need to be overcome such as accuracy, privacy and safety.

That is why the main research questions are: Is smart phone a useful tool to automate the data acquisition towards spaghetti chart 4.0 in all industrial environments? or Why MTM4.0 is useful tool? And the second question is how to use MTM4.0 to assist the practitioners in creating Spaghetti Chart 4.0? this work could be a first attempt for using a wearable device instead of traditional and smartphone technologies towards smart spaghetti chart system.

3. Materials and Method

As we explained in the past sections, smart spaghetti chart system relies on smartphone technology for collecting the data. However, this technology has many drawbacks related to independency, accuracy, safety, and security. So, the proposed methodology shall overcome these gaps to get a reliable spaghetti chart system called "Spaghetti Chart 4.0".

The methodology of data acquisition is different in this work. Hence, the automatic data acquisition of production processes relies mainly on the wearable technology including Radio Frequency Identification (RFID), Internet of Things (IoT), and the approach of Method Time Measurement. The smart system (MTM4.0) immediately provides the practitioners with informative data that can support the analysis process deals with the movement of worker, the overloaded machines and destinations, and the time spent for each movement with high accuracy and independency.

Transferring the data starts from passive RFID tags installed on the shopfloor (e.g., machines, tables, indoor\outdoor, store, warehouse, etc.) to RFID reader (portable by human) that detect the tags during performing the operations, the date and timestamp for each tag detection. Then, these data (the data refers to the identified place\ position, etc.) transfer through Wi-Fi from the RFID-Reader to PC, computer, and the organization's entire system. The wearable device contains a microcontroller ESP32 by Espress if powered to Wi-Fi can connect it with the Internet, and it contains RFID reader (ID-20LA by ID-Innovations operating with a frequency of 125 kHz, with a maximum RFID tag reading range of 12 cm) is connected with the microcontroller and integrated into the gloves and belt of the operator, this RFID reader is able to detect the passive RFID tags installed on the shopfloor, which have long work life, no battery, and memory capacity 128 bits. After collecting the real data, the microprocessor proceeds to filter, analysis, and assort the data "information" exporting to Excel file including (From-TO Chart) and other important information. The File can be downloaded periodically depending on the nature of work shift and times. The practitioners will manipulate the information obtained from MTM4.0 by inserting the required data to RStudio software, which is popular and useful for drawing the graphs automatically. The human interaction is to insert the data and identify the Cartesian of the passive RFID tags (location of machines, destinations, etc.). Generally, the materials of the system consist of RFID readers, Antennas, passive RFID tags, Wi-Fi, and computer systems. Beside the human (worker, technician, engineer, etc.) who is fundamental in the whole framework and system as shown in Figure 1.

This approach can work well in the industrial shopfloor and environment, if the management follows the reflective practice and experimental procedure below:

(1) identifying the facility layout, including the equipment, machines, stores, workstations, etc.

(2) identifying the production activities, including the manual material handling, manufacturing processes, and other most important operations

(3) installing RFID tags for each usable equipment, machine, store, workstation, and other important places such as indoor. RFID tags must be attached to match the human being's behavior and levels. RFID tags have identified codes for each place,

(4) Make the worker (operator) wear the RFID reader-Antenna on his/her hands (at the wrist), on the belt too. Each RFID reader has an identified code to facilitate the data acquisition and analysis,

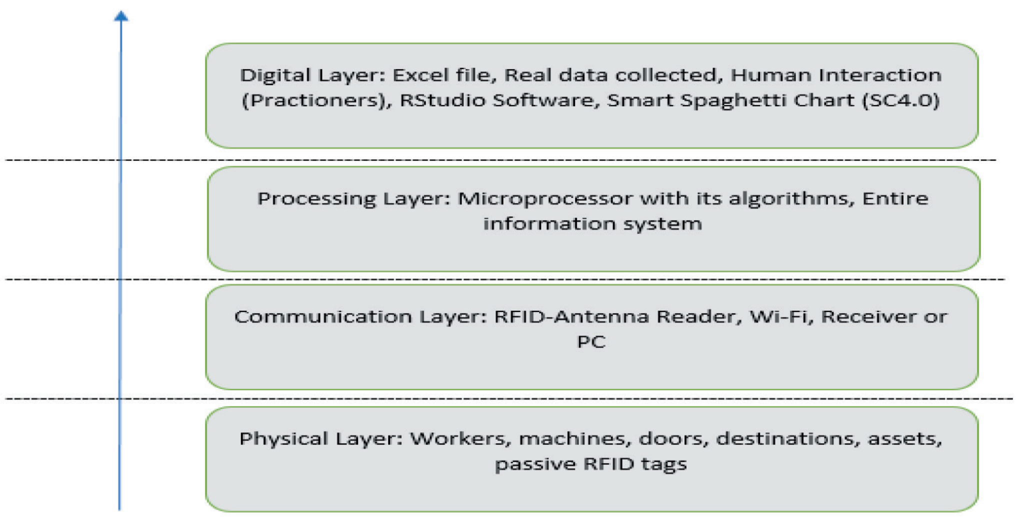

Figure 1. Spaghetti Chart 4.0 Framework

(5) connecting the RFID reader-Antenna to the PC using Wi-Fi to transfer the data as soon as the worker starts the activities (the worker detects the RFID tags by the RFID reader attached to the hands\belt while he is doing his\her job normally)

(6) Acquire and analyze data based on the current facility layout and activities to improve the route/productivity and produce a new spaghetti chart.

Figure 2 below explains the reflective practice procedure that can be applied for collecting the data towards Spaghetti Chart 4.0.

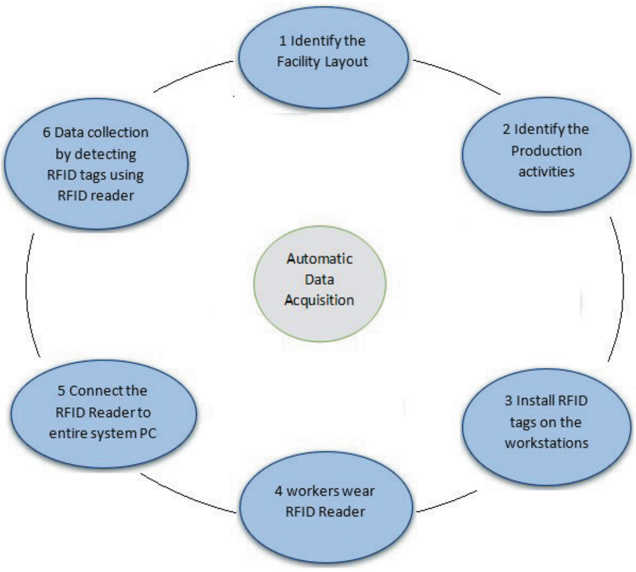

Figure 2. Reflective Practice Procedure of Automatic Data Acquisition

4. Case Study (Experiment)

In order to validate the methodology explained above towards automating the production data acquisition approaching Spaghetti chart 4.0, a series of experiments were carried out on a mechanical shopfloor; the goal is precisely to create a simple but significant experiment that can approach MTM4.0 towards Spaghetti Chart.

The starting idea consists of the configuration of an MTM4.0 system through the use of bracelets and a small number of RFID tags to monitor the sequences and durations of a certain number of activities: the main activity carried out in the experiment is drilling holes using two different drill machines available in the shopfloor and handling the material manually, documenting and storing the final pieces (Special Brackets).

The experiments were physically carried out by three people (two Ph.D. students and a mechanical technician). They work on two different machines available on the shopfloor. In order to validate the methodology and achieve the research goal, various scenarios with different sequences and cycle durations were carried out in four different scenarios for two different types of layouts, as described below (see 4.2 and 4.3).

4.1 RFID Tags Installation and experiment design

Passive RFID tags were installed on a mechanical shopfloor, in particular on the most important and useful places such as the two drilling machines, the measurement table, the store boxes, unused machines (error places can be detected while doing the activity; it can be excluded during the analysis stage and creating the process plan), etc.

The RFID tags were installed so that their positions matched with humankind behavior and positioning, while the workers wear the bracelet (RFID reader) in right hand, which is the main hand in this case study; the worker also wore an RFID reader on the belt to match the position of the tags on the tables. The distribution of RFID tags is shown in Table 1 and the facility layout of the mechanical shopfloor with RFID tags positions is shown in figure 3 below:

Table 1. RFID tags and their positions in the shopfloor

RFID Tag Number	RFID Tag Position
1	Indoor
2	Personal Protective Equipment Locker door
3	Raw Material Box
4	Measurement Table
5	Cutting Toolbox
6	**Machine 2**
7	Check and control table
8	Documentation/Record Book
9	Finished Product Box
10	**Machine 1**
11	Unused Machine (**Error Place**)

Then, we prepare the experiment design in order to test different hypotheses as:

(1) operations sequencing and related time
(2) old layout vs. optimized one
(3) expert vs. novice

To this end, we defined four variables on which the experiment design is based:

(1) Process plan, the sequence followed during the production process: job production (each item is finished before starting the next one) and batch production (a predefined number of items is produced together, and each group of items is finished before starting the next one). We do not consider mass production since it is not applicable in the context of our shop floor,

(2) Layout, the physical configuration of the shop floor: we hypothesized three different layouts shown in Figure 3 and Appendix A.

(3) Total number of pieces made by a novice (Ph.D. students),

(4) The total number of pieces made by an expert worker (Technician).

On the basis of these variables, we designed four different scenarios to be explored to test our hypotheses. The characteristics of each scenario are summarized in Table 2.

The following sections describe in detail the four scenarios we designed.

4.2 Scenario 1- Baseline

In the first scenario, the operator works without a process plan:
O1: enters the building (Tag 1),
O2: goes to the PPE cabinet (Tag 2) to take protective gloves and goggles,
O3: walks towards the raw material box (Tag 3) to get the material (1 piece),
O4: approaches the measurement table (Tag 4) to identify the position of the holes,
O5: after identifying the positions of the holes, the operator goes to the instrument panel (Tag 5) to take the tools necessary for cutting,
O6: goes to machine 2 (Tag 6): the operator fixes the piece, installs the cutting tool, makes the initial holes, changes the tool and makes the holes.

Table 2. Characteristics of the four scenarios for the experiment

	Scenario			
	1 - Baseline	2 - Efficient Process Plan	3 - Safe Layout	4 - Safe Layout with an Efficient Process Plan
Production method	Job production	Batch production	Job production	Batch production
Layout	Old layout (Figure 3)	Old layout (Figure 3)	Optimized layout version 1 Appendix A	Optimized layout version 2 Appendix B
Number of pieces made by a novice (Ph.D. students)	10	10	5	5
Number of pieces made by a specialist (Technician)	0	0	5	5

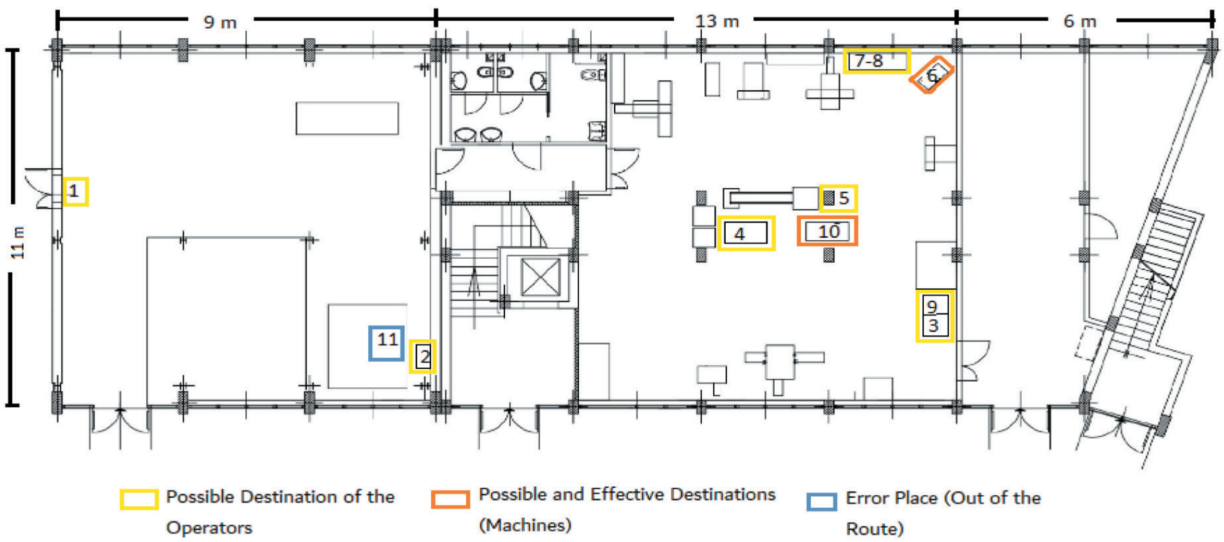

Figure 3. Facility layout of the mechanical workshop with RFID tags positions (for Scenario 1 and Scenario 2)

So, there is a change of cutting tools for each piece. After drilling the holes, the operator has to check the dimensions to approve the quality of the products, then he:
O7: goes to the control table (Tag 7),
O8: documents the finished products in the register (Tag 8),
O9: takes the finished product and places it in the finished product box (Tag 9).

The operator takes another piece and repeats the same procedure until he reaches the production of five pieces. This procedure was repeated twice by the same operator (Ph.D. student 1). This means that the final total number of pieces was ten.

4.3 Scenario 2- Efficient Process Plan

In the second scenario, the operator works with a process plan to reduce the time spent, for the first and second operations are the same as in the first scenario, so the operator:
O3: walks to the raw material box (Tag 3) to pick up the material (5 pieces),
O4: approaches the measurement table (Tag 4) to identify the position of the holes (1 piece only)
O5: after identifying the positions of the holes, the operator goes to the instrument panel (Tag 5) to take the cutting tools,
O6: goes to machine 1 (Tag 10), fixes the piece, installs the cutting tool, drills the initial holes for all five pieces, changes the cutting tool and drills the holes for all five pieces.

This means that the operator changes the cutting tool only once per cycle.

After making the holes, the operator has to check the dimensions of all five pieces to approve the quality of the products, then he:
O7: goes to the control table (Tag 7),
O8: documents the finished products in the register (Tag 8),
O9: takes the finished products and places them in the finished product box (Tag 9).

This procedure was repeated twice by the same operator (Ph.D. student 2). This means that the total number of pieces was 10.

4.4 Scenario 3- Safe Layout

In scenario 3, a new facility layout is set to avoid working together or close to each other on the shopfloor, aligning with health instructions against COVID-19 to maintain the social distance and safe job. On the other hand, the new facility layout could support activity time minimization.

In this case, we have the same scenario described in 4.2 (scenario 1), but the layout has changed at one point (Workstation): the operations are performed close to each other, as shown in Appendix A-1. The operator takes another piece to continue the same procedure until five pieces are completed.

This scenario was repeated twice (Ph.D. student 1 and Technician). This means that the total number of pieces was 10.

4.5 Scenario 4- Safe Layout with an Efficient Process Plan

In scenario 4, we have the same scenario described in 4.3 (scenario 2), but also, in this case, the layout is changed at one point: the operations are performed close to each other, as shown in appendix A-2. The operator takes another piece to continue the same procedure until finishing five pieces.

This scenario was repeated twice (Ph.D. student 2 and Technician). This means that the total number of pieces was 10.

5. Results and Data Analysis

The output of the research work can be summarized in three elements: (a) accurate real data acquisition from the shopfloor was done using MTM4.0 as shown in Figure 4, which has been exported to an Excel sheet for each scenario-cycle of the experiment., (b) The real data can be analyzed not only to draw the spaghetti chart, while it can be used to evaluate the efficiency of the workers, progress of the work and measure the cycle time of each scenario, and (c) the most important is the acquired data is coherent with the goal of the work, which is drawing spaghetti chart automatically.

The Excel sheet is structured as follows:

- column 1 - scanner_id deals with RFID reader, which are 2 in this case study
- column 2 - tag_id describes the code of RFID tag
- column 3 - tag_serial is the serial number of the manufacturer
- column 4 - tag position identify the workplace and destinations
- column 5 - server_ts contains the date of the work

scanner_id	tag_id	tag_serial	tag_position	server_ts	start_ts	end_ts	duration
24:0A:C4:1D:25:64	700489632	0004757042 072, 38450	Raw Material Box	11/5/2020 14:28	01:04:48.335	01:04:49.857	1522
24:0A:C4:1D:25:64	700489632	0004757042 072, 38450	Raw Material Box	11/5/2020 14:28	01:05:02.154	01:05:03.345	1191
24:0A:C4:1D:25:64	2D0071CAFC	0007457532 113, 51964	Finished Product Box	11/5/2020 14:28	01:05:36.426	01:05:37.807	1381
24:0A:C4:1D:25:64	4F0077BA47	-	Measurement Table	11/5/2020 14:29	01:06:58.593	01:07:00.175	1582
24:0A:C4:1D:25:64	4F0077BA47	-	Measurement Table	11/5/2020 14:29	01:07:51.836	01:07:52.804	968
24:0A:C4:1D:25:64	4F0077BA47	-	Measurement Table	11/5/2020 14:29	01:09:07.237	01:09:08.328	1091
24:0A:C4:1D:25:64	4F0077BA47	-	Measurement Table	11/5/2020 14:29	01:09:10.940	01:09:12.061	1121
B4:E6:2D:EB:08:81	2D0071CAFC	0007457532 113, 51964	Finished Product Box	11/5/2020 14:28	01:22:10.940	01:34:25.603	969
B4:E6:2D:EB:08:81	2D0071CAFC	0007457532 113, 51964	Finished Product Box	11/5/2020 14:28	01:34:28.476	01:34:29.573	1097
B4:E6:2D:EB:08:81	2D0071CAFC	0007457532 113, 51964	Finished Product Box	11/5/2020 14:28	01:34:39.604	01:34:40.575	971
B4:E6:2D:EB:08:81	700489632	0004757042 072, 38450	Raw Material Box	11/5/2020 14:28	01:35:06.172	01:35:07.144	972
24:0A:C4:1D:25:64	4F0077BA47	-	Measurement Table	11/5/2020 14:29	01:37:14.285	01:37:15.477	1192
B4:E6:2D:EB:08:81	700489632	0004757042 072, 38450	Raw Material Box	11/5/2020 14:28	01:39:34.085	01:39:35.056	971
B4:E6:2D:EB:08:81	700489632	0004757042 072, 38450	Raw Material Box	11/5/2020 14:28	01:39:36.077	01:39:37.055	978
B4:E6:2D:EB:08:81	2D0071CAFC	0007457532 113, 51964	Finished Product Box	11/5/2020 14:28	01:39:40.721	01:39:41.687	966

Figure 4. Data gathered from Method Time Measurement 4.0 (MTM4.0) System

- column 6 - start_ ts has the starting time of the event (start timestamp)
- column 7 - end_ts has the end time of the event (end timestamp)
- column 8 - duration contains the difference between the start and end timestamps.

So, the results of the experiments show acceptable outcomes that can enable the practitioners to create Spaghetti chart 4.0 starting from\ based on these data.

These data also can support the practitioners for different aspects such as safety analysis and risk assessment through identifying the time span for each cycle and operation; safety analysis and risk assessment can be identified through synchronizing the time stamp (Time of RFID tag Detection) and duration of two destinations, hence, doing the operation at the same time indicates that higher probability of incidents/accident and/or COVID19 infections. Relayout the facilities, besides the efficient process plan, the facilities have participated in cycle time reduction in the second, third and fourth scenarios, which is less than the existing traditional layout as follows: (45%, 44%, and 58%) respectively. Figure 5 shows the comparison between the cycle times of the four scenarios of the experiment.

ANOVA calculator has been used to show the variance level between cycle times for four scenarios (Group 1, Group 2, Group 3, and Group 4); each group has ten times for producing ten pieces. Hence, the analysis results show essential values,

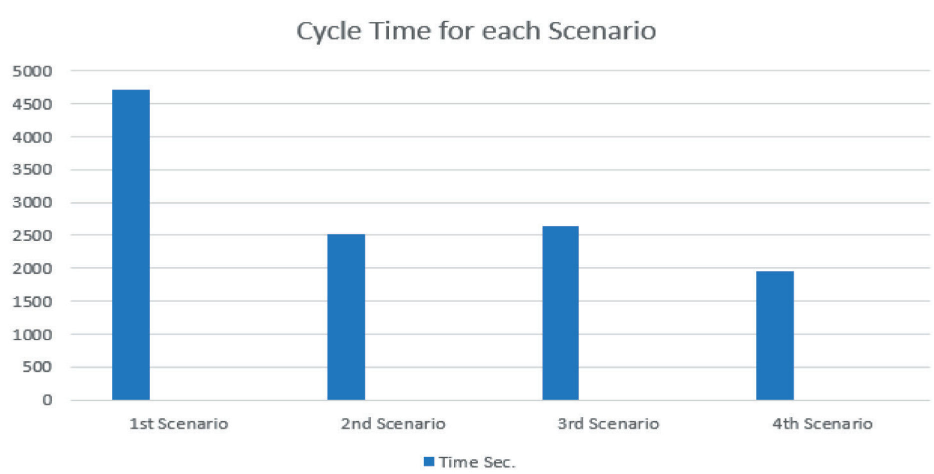

Figure 5. Cycle times of the four experiment scenarios

which prove the level of variance (P- Value= 0.00), F-Static Value=1301.17) and other details, as shown in the screenshot of the calculator in Appendix B. This Zero value of P confirms that the data collected are significantly acceptable and reflect the real scenarios of the case study. Therefore, the practitioners can use these data to identify the potential hazards, and determine the HSE (Health, Safety & Environment) supervisor movement to notify the workers during the work and other domains aligning with spaghetti chart goals.

To demonstrate the relevance of the tool in automating the process of building a Spaghetti Chart 4.0, we use the gathered data to draw a Spaghetti Chart with RStudio software[1], in particular, with the library igraph, widely used for creating and manipulating graphs and analyzing networks.

The Spaghetti Chart in Figure 6 above explores the differences between Scenario 1 (blue edges) and Scenario 2 (green edges) in terms of operator flows on the shopfloor. These layouts are interesting to be compared since they only differ by the production method adopted by the operator (job production vs. batch production). Nodes represent the RFID tags position as explained in Table 1. Edges represent the movement of the operator from one station to another (in both directions). The edge that has a thick line is the more frequent the movement. Nodes in orange are those related to RFID tags 6 and 10, respectively, to machine 2 (used in Scenario 1) and machine 1 (used in Scenario 2).

The software needs to be fed with some data automatically gathered by the MTM4.0 tool:

- links between RFID tags (a link between two RFID tags exists when the two tags are detected one after another)
- number of times each link occurs during the experiment (number of times two RFID tags are detected one after another)

The only human effort required is related to the positioning of the nodes within the graph to give the software cartesian coordinates of each tag able to show the real layout of the shop floor. Therefore, the MTM4.0 system proves to be useful in gathering data for automating the process of Spaghetti Chart drawing, leaving only a few tasks to the human expert. As expected, visually analyzing the Spaghetti Chart, the links are thicker in Scenario 1, where the job production logic that provides starting the production of one piece only after the production of the previous one is over is applied.

6. Discussion

The aim of setting four different scenarios is to find more relevant issues related to the use of the MTM4.0 automatic acquisition system. Our experiment shows two issues that we would like to point out: firstly, the presence of metallic materials in dif-

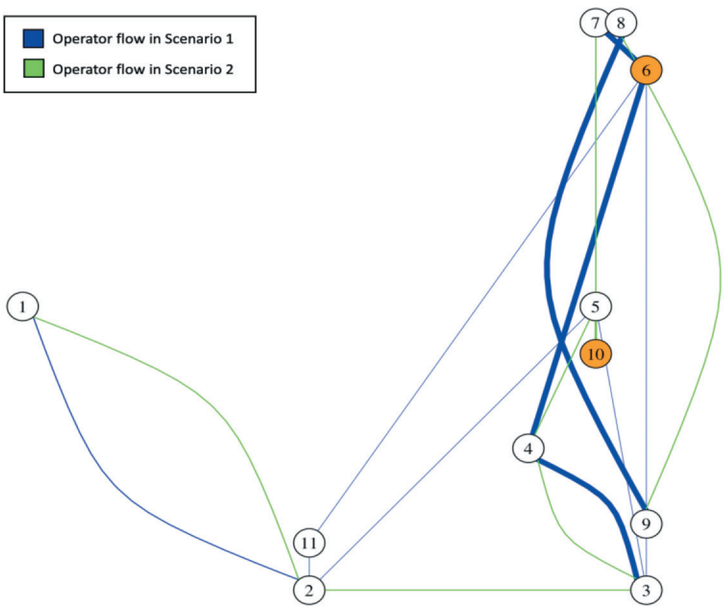

Figure 6. Spaghetti Chart 4.0 for Scenario 1 and Scenario 2

[1] https://www.rstudio.com

ferent places of the shopfloor; secondly, the different heights of the workers represent a challenge in placing the RFID tags in such a way the RFID readers can detect them on the belt. Despite these challenges, the tag positioning was easily performed and can be improved by using different types of antennas and RFID tags.

The problem linked to the metallic materials can be avoided by using non-conductive materials such as wood or sponge to separate the RFID tags from the metallic surfaces, obtaining the required connectivity between RFID tags and readers. The data could be gathered once or periodically, repeating the experiment; it depends on how much time the workers spend to achieve the jobs and how many cycles they perform in different cases. For sure, the proper choice could depend on the goal (facility layout vs. internal logistic analysis vs. 5S) or on the production (mass production vs. engineering to order vs. prototyping, etc.), or so on. As long as the final goal is to exploit a Spaghetti chart 4.0 system, we think that the best approach is collecting the data on a daily basis and use them to constantly support logistics, facility layout, ergonomics, and operation improvements.

From lean philosophy perspective, this effort is compared with significant research work related to FL redesign, which involves a case study of textile industry [31]. it is difficult to compare different scenarios, but it can refer to some important indications; hence, the new design reduces the cycle time to (45%, 44%, and 58%) respectively, considering the efficient process plans, while the research mentioned above reduces the cycle time to (46% and 34%), which is not considered the enhancement of process plan concurrently. So, it is useful to integrate the robust process plans with an efficient facility layout in Lean environment.

There are two challenges: Firstly, the positioning of the nodes in the graph by a system of Cartesian coordinates is difficult to manage the proportions of the graph. Improving this task could be crucial for superimposing the graph on the production layout map to provide an even more visually immediate output for users of Spaghetti Chart 4.0. Secondly, the software draws edges between nodes by following its algorithm based on graph theory; for this reason, it does not allow to easily manipulate the form of the edges to reflect the actual path of operators in case of obstacles and architectural barriers. If it is considered critical, this issue could be faced by putting "Dummy" nodes to make the edges follow the actual operators' flow in the Spaghetti Chart 4.0, even if this could be a time-consuming task.

7. Conclusions and Recommendations

MTM4.0 proves that it can substitute the smartphone for collecting real data towards Smart Spaghetti system/ Spaghetti Chart 4.0. The automatic system does not provide only the estimated logical path of the production process. However, it provides the duration of each performed task, the time spent moving from one point to another workstation, the manual material handling paths, and the destination points. The bracelet was comfortable and friendly for the Ph.D. students and the mechanical technician involved; they performed the work smoothly without claims.

To conclude, the MTM4.0 system is demonstrated to be a tool able to gather data for automating the process of Spaghetti Chart drawing, if supported by software able to manage this data. In our case study, we used RStudio software since it is a statistical tool easy to be adopted and used daily by the authors for research purposes. Real-time Data is a key element of Digital Twin DT [29, 30], so this effort based on automatic data acquisition can be considered as a baseline for building DT system concerns with the production environment, which is a part of our future work related to using Spaghetti Chart 4.0 for optimizing the work rather than redesign the facility layout. The proposed solution shall replace the smartphone technology in different fields and industrial sectors such as oil and gas plants, companies, shopfloors, and hospitals. So, it is highly recommended to practice and investigate more about MTM4.0 in the environments mentioned above.

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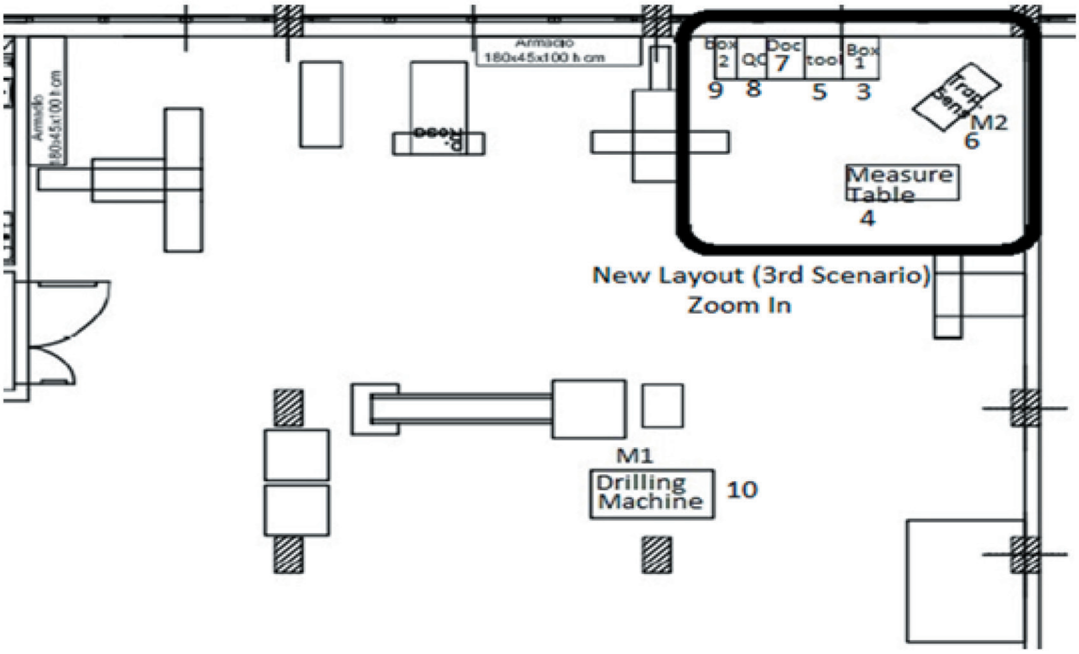
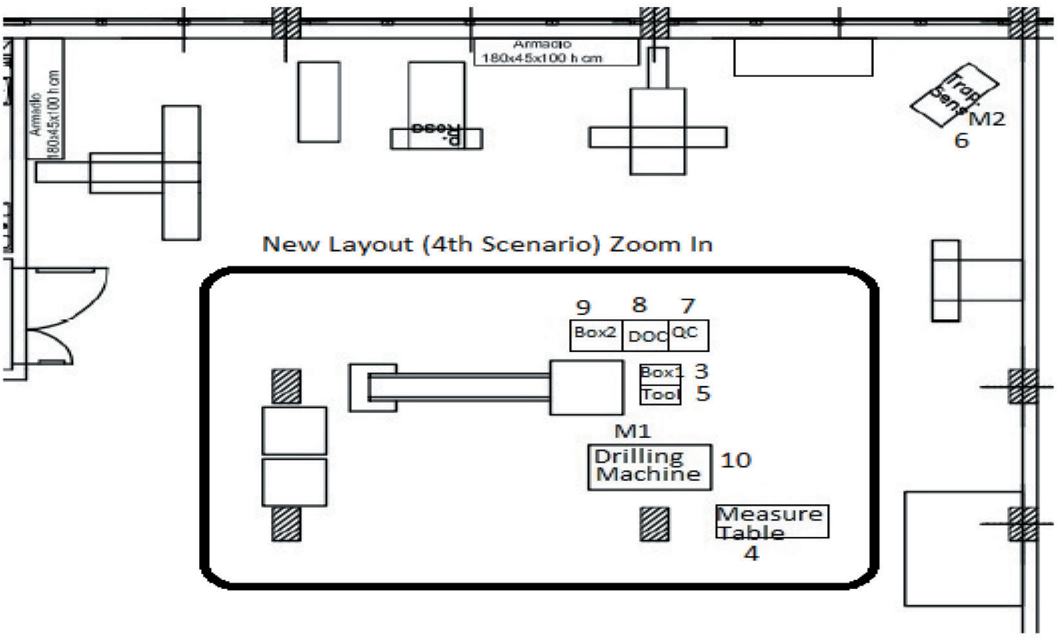
Appendix A (Figures of Facility Layout Scenarios)



1- Facility layout of the mechanical workshop with RFID tags positions (for Scenario 3)



2- Facility layout of the mechanical workshop with RFID tags positions (for Scenario 4)

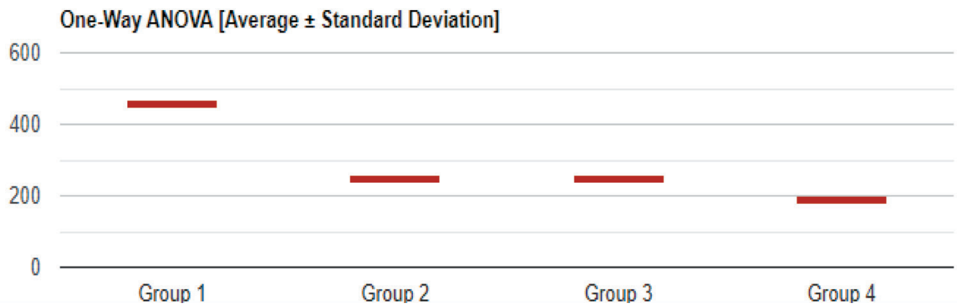
Appendix B (ANOVA Calculations)

F-statistic value = 1301.17

P-value = 0

Data Summary				
Groups	N	Mean	Std. Dev.	Std. Error
Group 1	10	457.6	10.4796	3.3139
Group 2	10	250	9.6839	3.0623
Group 3	10	250	8.8694	2.8048
Group 4	10	190	11.8509	3.7476

ANOVA Summary					
Source	Degrees of Freedom DF	Sum of Squares SS	Mean Square MS	F-Stat	P-Value
Between Groups	3	412513.2	137504.4	1301.17	0
Within Groups	36	3804.3902	105.6775		
Total:	39	416317.5902			



Appendix C (Acronyms/abbreviations)

Acronyms/abbreviations	Definitions
DT	Digital Twin
FL	Facility Layout
IoT	Internet of Things
MTM4.0	Method Time Measurement 4.0
O	Operation
PC	Personal Computer
RFID	Radio Frequency IDentification
SC	Spaghetti Chart
UNCTAD	United Nation Conference on Trade And Development
WSD	Wearable Sensing Device