A 4.0 Automated Warehouse Storage and Picking System for Order Fulfillment

Lucia Cassettari, Fabio Currò, Marco Mosca, Roberto Mosca, Roberto Revetria, Stefano Saccaro, Gabriele Galli

***Abstract*— Despite the number of scientific contributions on the topic, there are still several challenges to be faced before the principles of Industry 4.0 become widely applicable. This study aims precisely to overcome some of the limitations of existing technologies and applications for material handling and picking. The current market solutions often require high investment costs being unsustainable by small and medium-sized enterprises and suitable exclusively for managing large volumes and a mix of highly diversified products. In this study, the authors aimed to conceptualize and design an automatic order fulfillment system applicable to small and medium-sized companies performing frequent shipments characterized by low volumes, variable product mix, reduced overall dimensions for products and products typically sold in bulk, such as those operating in the beauty and cosmetics sector. The proposed solution consists of a series of smart drawers, controlled by a communication architecture designed in 4.0 Logic, equipped with hardware and software interfaces that can be easily integrated with any existing management or departmental system. By the Cloud and WEB Portal, the warehouse thus conceived can be monitored and controlled in real-time from any part of the Globe. The solution is completely modular and easily adaptable to future changes in quantities and mixes in stock. The proposed system, as demonstrated by the cost vs. benefit analysis conducted on a real case, allows getting a significant saving in terms of manpower and space, as well as a strong increase in terms of precision, efficiency in order fulfillment and safety.**

***Index Terms*— Automated storage and retrieval system, Automated warehouse, Industry 4.0, Smart factories**

I. Introduction

COMPANIES characterized by frequent shipments to their customers, such as those operating in the beauty and cosmetics sector which are subject of the industrial case described in this study, share serious efficiency problems in warehouse management. These problems impact costs and delivery times and cause frequent shipping errors and continuous stock breaks.

The automated picking solutions available in the literature (already available on the market) enable to significantly improve warehouse performance, but they are offered at high costs and limited to specific uses, with large volumes and a vast mix of products.

The objective of this study was to develop an innovative picking system, structured in Industry 4.0 logic, which would allow Small and Medium-sized Enterprises (SMEs) to equip themselves with a smart management system, with an agile and flexible infrastructure, able to successfully overcome the aforementioned problems and consequently to increase their competitiveness on the market.

For this reason, during the conceptualization phase, particular attention was paid, to those engineering tools and methods belonging to Industry 4.0 that could help develop a high-efficiency system with low costs and, in any case, lower than those of other similar systems already existing on the market.

As a result, a measurable improvement in inventory management and operational efficiency is obtained. Each product in the warehouse becomes quickly accessible, without picking errors and in full compliance with the product mix relating to each order.

Each loading and picking activity (current or historical) and each operating parameter such as quantities in stock and rotation statistics are made available online monitor and on cloud, using innovative Industry 4.0 tools and methods, thus allowing managers to make monitoring, control, and management of warehouse stocks more effective.

In particular, the proposed system allows integrating the internal logistics, purchasing and marketing functions, exponentially improving the overall corporate performance and thus producing tangible savings.

This paper aims to provide the basis for a work started by the Department of Mechanical Engineering (D.I.M.E.) of the University of Genoa in 2020. The completed application is currently under development and it will be presented in a follow-up paper.

Manuscript received Mar 24, 2021; revised Apr 18, 2021.

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II. Fundamentals and Literature Review

In this section is presented an overview and the state of the art of the major areas illustrated in the paper. In particular, the areas are automated storage and retrieval system, automated warehouse, automated picking, and digital factories.

A. *Automated Storage and Retrieval Systems*

In the automated storage and retrieval systems area are highlighted eight works. Automated storage and retrieval systems have been widely used in distribution and production environments since their introduction in the 1950s. Automated storage and retrieval systems (AS/RS) usually consist of racks served by cranes running through aisles between the racks [1].

AS/RS are computer-controlled automated material handling systems that are widely used in industry and warehousing. They present several advantages, the most important are high throughput, efficient space use, and safety improvement [2].

Chandra et al. proposed a work about the widely used in warehouse management of AS/RS systems due to their high uptime reliability and effective management. The storage organizer detects the product on arrival and stores it automatically; retrieval is done by using a graphical user interface developed using LabVIEW software. The model has been created using CATIA software and fabricated by necessary actuators and sensors. This system has advantages over traditional systems in terms of time, cost, and layout management [3].

In traditional automated storage and retrieval (AS/R) systems, the storage and retrieval machine travel simultaneously in horizontal and vertical directions. The so-called split-platform AS/R (or SP-AS/R) system consists of platforms (or shuttles and lifts) that can move independently in horizontal (shuttles) and vertical (lifts) directions [4].

Dual-tray Vertical Lift Modules (VLMs) are relatively new systems not yet addressed in automated storage and retrieval (AS/R) systems research. In this regard, Dukic et al. proposed a model for single dual-tray Vertical Lift Module automated storage and retrieval system with a human order-picker is presented [5].

Another work is proposed by Kazemi et al. The authors showed the differences between Multi-shuttle automated storage/retrieval systems and automated storage/retrieval systems. The first typology can carry more than one load at a time and are able to perform storage immediately after retrieval at the same location in a storage rack. The authors address concurrent storage location assignment and storage and retrieval sequence scheduling under the shared storage policy and the modified 2n-command cycle pattern [6].

Brezovnik et al. in order to reduce space consumption and minimize investment costs proposed an AS/RS with no corridors and one single elevator for multiple products. Results showed that the expected distribution of products was reached and that ACO can be successfully used for planning automated storage systems. The study reported how to plan AS/RS using multiple objective ant colony optimization (ACO). The distribution of products in the AS/RS is based on the factor of inquiry (FOI), product height (PH), storage space usage (SSU), and path to dispatch (PD). The factor of inquiry for any product can be adjusted during the storage process concerning actual market requirements [7].

Chakravorty in order to improve the performance of distribution operations, found an implementation of material handling systems that involve both human and technical factors. These factors interact over time and go through three somewhat overlapping transitional stages. In the first stage, both human and technical problems exist; in the second stage, human problems improve, but technical problems persist, requiring formal problem-solving methods to resolve. In the third stage, both human and technical problems improve [8].

B. *Automated Warehouse*

With regard to the second area, the automated warehouse, six works were selected. In warehouses, order consolidation processes are inevitable whenever picking orders are assembled under zoning and/or batching policy. Boysen et al. (2018) carried out a specific warehouse setting, bins containing partial orders picked under a zoning and batching policy are intermediately stored in an automated storage/retrieval system (ASRS) and, afterward, released on a conveyor system supplying the consolidation area [9].

The vertical lift module is an automated storage and retrieval system widely used in warehouses. The performance of a warehouse with vertical lift modules is highly correlated with the efficiency of the order picking [10]. Order batching, namely regrouping customers' orders into batches to be collected from the module, constitutes a critical decision impacting the picking efficiency. The authors provide optimization models for order batching, intending to minimize total completion time, that is, the time required to collect a given set of customers' orders. First, the case of one vertical lift module was considered and then it has been extended to a warehouse with several modules.

Small items order picking is a very labor-intensive activity that is often performed in a dedicated area equipped with carton racks and with the operators walking within the aisles to pick the required products.

Calzavara et al. compared an automated system, called the dual-bay Vertical Lift Module (VLM) system, to a manual warehouse with carton racks. The comparison of the systems leads to the definition of a VLM area of application, which can be used to understand the suitability of the VLM concerning the warehouse with carton racks [11].

Lototsky et al. discussed a dynamic model of the automated warehouse management and forecasting system in the conditions of Industry 4.0. Usage of inductive knowledge base allows to predict the appearance of bottlenecks in advance and turns the warehouse management system into an expert with all the necessary integral experience, which helps to reduce significantly the financial costs of excessive inventory and to prevent certain components shortage possibility [12].

In modern, highly competitive markets, efficient warehousing is critical as it accounts for a great part of logistics costs. Mourtzis et al. proposed a warehouse design using augmented reality technology. The paper proposed a framework for warehouse design that minimizes inventory cost while keeping a high degree of service by supporting the integration of an AR warehousing system. Warehouse design and planning is an ever-existing challenge in manufacturing that highly affects the efficiency of the warehouse. The application used in the work aimed to facilitate warehouse management, supporting efficient navigation and product retrieval, which could be extended to logistics warehouses [13].

Logistics has assumed a determining position in the supply chain of each organization. Freitas et al. showed an application of work carried out in a manufacturing organization to improve efficiency in its hybrid warehouse. A hybrid warehouse could be considered as one that mixes several different activities (reception, storage area, picking, shipping, supply to production lines, and production preparation tasks) and brings together many different materials or raw materials and components. The combination of lean tools was implemented, and the results have been checked, showing a significant impact in the hybrid warehouse, with annual gains through the optimization of several activities: in particularly an important decrease of check and picking times [14].

C. Automated Picking

For this section, the authors selected six works. Order picking has long been identified as the most labor-intensive and costly activity for almost every warehouse; the cost of order picking is estimated to be as much as 55% of the total warehouse operating expense [15]**.**

Optimizing the order picking is effective for advancing the working efficiency of an automatic warehouse. Fa-Liang et al. according to the characters of picking in an automated warehouse proposed a new mathematic model with capacity constraints and multiple objectives [16].

One of the cost-intensive issues in managing warehouses is the order picking problem which deals with the retrieval of items from their storage locations to meet customer requests.

Azadnia et al. proposed a novel solution approach in order to minimize tardiness which consists of four phases [17]:

- Weighted association rule mining has been used to calculate associations between orders concerning their due date
- A batching model based on binary integer programming has been formulated to maximize the associations between orders within each batch
- The order picking phase will come up which used a Genetic Algorithm integrated with the Traveling Salesman Problem in order to identify the most suitable travel path
- The Genetic Algorithm has been applied for sequencing the constructed batches in order to minimize tardiness.

It became necessary to develop more innovative and efficient solutions to the constant diversity of challenges proposed by the market. In this sense, it was proposed to develop something innovative within the area of Automated Storage and Retrieval Systems (AS/RS), a technology increasingly sought after by today's manufacturing plants. As such, the goal was to improve the most emergent AS/RS in recent years: Pallet/Box Shuttle AS/RS.

Fernandes et al. analyzed all the existing solutions in the market and, mainly, to find the main systems to be improved and the direction to follow in order to create a novel solution based on the existing advanced solutions [18].

In most manual assembly settings, the picking of components before assembly is a task that often is performed with a high frequency by the assembly operator. In many assembly systems, components are manually repacked before being delivered to the assembly station. Calzavara et al. with their paper give insight into how both picking time and ergonomic effort relate to the storing configuration, considering whether parts are stored on pallets or in smaller boxes, and considering whether or not the containers are tilted towards the picker [19].

Warehouses can be characterized in many ways, including the number of items stored, the average number of cases per pallet, throughput and inventory requirements, and demand profile, to name a few. Thus, there is no one-size-fits-all design for case-picking warehouses, and hundreds of designs are possible. Moreover, the decision variables in warehouse design are interrelated and this further complicates the design process [20].

D. Industry 4.0 and Smart Factories

In the last decade, a new industrial revolution seems to be emerging, supported, once again, by the rapid advancements of Information Technology in the areas of Machine-to-Machine (M2M) communication permitting large numbers of intelligent devices, e.g., sensors to communicate with each other and take decisions without any or minimum indirect human intervention. The advent of these technologies has triggered the emergence of a new category of hybrid (cyber-physical) manufacturing systems, combining advanced manufacturing techniques with innovative M2M applications based on the Internet of Things (IoT), under the term Industry 4.0. Even though the topic of Industry 4.0 has attracted much attention during the last few years, the attempts of providing a systematic literature review of the subject are scarce.

Efthymiou et al. present their study of the field with a special focus on the use and applications of Industry 4.0 principles in material handling automation and in-house logistics. Research shows that despite the vivid discussion and attractiveness of the subject, there are still many challenges and issues that have to be addressed before Industry 4.0 becomes standardized and widely applicable [21].

In recent years, manufacturing companies have been faced with different challenges, in particular with an increasing level of variability. The variability implies a different set of dimensions such as demand, volume, process, manufacturing technology, customer behavior, and supplier attitude, transforming the industrial systems engineering domain.

Demartini et al. introduced technological concepts of Industry 4.0 and related enabling technologies such as the Internet of Things, and the Internet of Services that could support decentralization and manufacturing flexibility. The identified flexibility type in manufacturing systems is discussed and contrasted with the various reconfiguration use cases, which include specifically the planning, orchestration, and optimization of production processes within MES [22].

Gotthardt et al. showed a digitalized milk-run system in LEAD Factory. This system relies on RFID technology to automatically generate orders from a warehouse to a

ISBN: 978-988-14049-2-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

workstation. In the warehouse, a pick-to-light system is used to show the logistics employee on a screen which parts to pick. To efficiently deliver the order to the workstation, the shortest path is calculated using a path planning algorithm that is used in robotics [23].
Due to changing markets, new service opportunities have opened up, thus, to stay competitive innovative services are vital. The demand for practice-oriented training and education of customers is key to master upcoming challenges of warehousing facilities.

III. Problem Statement

After a careful analysis of the literature, a critical analysis of the picking methodology in place in some SMEs was conducted to assess where significant operational, functional, and managerial improvements could be made. Therefore, the extension of such analysis to a significant number of plants, allowed to identify of a series of recurring problems such as:

- Overall inefficiency
- Operational slowness
- Queues and long waits
- Stock breaks
- Picking and delivery errors
- Waste of Human Resources (warehouse and purchases)
- Improper use of existing departmental and management software

The problems identified to produce a 360° impact on the company:

- On management efficiency and performance
- On costs and order margins
- On customers (decisive aspect in a competitive regime)
- On the corporate image

In order to increase operational efficiency and to address the aforementioned problems, the market already offers multiple automated picking solutions, valid, but complex, vertical, and expensive, therefore inaccessible to most companies for small volumes (meaning for “small volumes” a few hundred product codes) and certain sectors (such as those under analysis: cosmetics and beauty).
Consequently, many SMEs tend to renounce the opportunity to acquire automated warehouse solutions, contenting themselves with manual management (picking operators), although inefficient and unreliable, therefore facing a set of common problems.

A. *Benchmarking with Existing Solutions*

A benchmark on the solutions already existing on the market was conducted by the proponents, with the aim of following an information and learning process, comparing their methods with those established by similar systems. The comparison of operating practices with the sector's best practices had the dual objective of drawing useful ideas for improvement and ascertaining the real level of innovation of the proposed solution. The authors wondered if the problems encountered in hardware development had been previously encountered by similar practices and, if so, how they had been overcome. In consideration of the above, it was decided to conduct the benchmark on technical solutions and warehouse processes, to avoid incurring the risk of operating simple copying activities, rather than learning and adapting the implemented solutions.
Unfortunately, the benchmark did not allow the development of applicable ideas since the market solutions analyzed proved to be extremely different from the solution proposed both from the hardware and architectural point of view and from the software point of view (warehouse logic); however, it made it possible to compare the competition solutions with that proposed to develop a clear differential (distinctive elements) with respect to the competition, thus identifying a completely new market segment, with vertical applications dedicated to some segments, such as beauty and cosmetics.

IV. The Proposed Solution

Following the benchmarking phase, which made it possible to analyze the strengths and limits of applicability of the most innovative solutions on the market, the sector's best practices, the authors tried to put in place a solution that would allow them to effectively solve all the business problems identified.

So, the proposed solution consists of conceptualizing, designing, and producing an automated picking warehouse specifically for the specific use, such as to be industrial, robust, and precise but, at the same time, accessible for small and medium businesses. The target was hypothesized under the binding condition of renouncing the possibility of fully generalizing its use, for example by extending its applicability to a mix of heterogeneous products in shape and size, characterizing Sectors different from those examined, but keeping the opportunity of identifying other Sectors being suitable for such application.

A. *Preliminary Technical Specifications*

The preliminary technical specifications aimed to start defining the system in terms of shape and nature to meet the technical requirements of the proposed automation. The results obtained in this phase were successful even if they only partially satisfied the final system requirements, while, in part, they were updated during the work.
The aspects maintained were:

- RTU (industrial PC for system integration)
- Drawers 4.0 (implementable on the logic of “replication of the core”)
- Column structure of stacked and put beside drawers
- Column lift
- Compartmented conveyor belt for the physical separation of orders
- End of line packing station (with operator and control monitor)

The main differences were found in:

- Abolition of column racks in favor of a rackless structure, initially, the drawers were housed in five-place racks, on runners. The racks consisted of steel box cages that could be stacked and consolidated using flanges that allowed the coupling between them and the ground. The rack columns were designed to be placed side by side and joined, again employing flanges. Those constituted a solid and robust infrastructure, with the possibility of replacing any damaged drawers simply, at the expense of a reduction in assembly flexibility and high costs. The rackless structure subsequently

ISBN: 978-988-14049-2-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

developed has made it possible to overcome all the problems described above, with a significant reduction in cost, an increase in flexibility, greater simplicity, and speed of installation (drawers stackable directly with interlocking coupling). The replacement of any damaged drawers was made possible through the development (at low cost) of a special hydraulic tool for vertical lifting of the column

- Introduction of column gateways for data management and integration: initially the RTU was designed to communicate directly with the individual drawers. However, there have been conflicts in the management of the data in the event of simultaneous access. The problem was solved by implementing a hierarchical information structure, or by introducing column gateways capable of consolidating the information coming from the RTU (downstream flow) and the drawers (upstream flow) in a bidirectional way. The cost-effectiveness of the system has not been compromised: considering an average of 30 column drawers and a cost of approximately € 200 per gateway, for a 1,000-drawer warehouse the cost would be less than € 7,000, with an impact on costs in the order of 1%.

B. Conceptualization

The conceptualization of the hypothesized solution required a preliminary study in terms of sizing the selected technologies, in order to generate a specific and functional application, limiting any type of waste of resources. Among the aspects considered the emerging were:

- Definition of type and characteristics of gateways
- Definition of type and characteristics of the RTU
- Evaluation and sizing of the actuators
- Study of the SW in use (ERP, MAG)
- Analysis for SW and tablet integration
- Definition of the main customizations of the drawers

C. Main Requirement and Selected Solution

The main requirements were therefore defined as the design of a simple and inexpensive, but robust, industrial system. To achieve this goal, a high level of IT integration was implemented, aimed at disintermediating human intervention as much as possible in the entire picking process, and at reducing the communication through the interconnection of systems to what is strictly necessary. For this purpose, the common market hardware has been completely redesigned, taking care to maintain exclusively the components required to carry out the process. The Operating System has also been rewritten, with proprietary logic, to make communication more direct, fast, and reliable (with great benefits also in terms of cybersecurity). Figure 1 shows the current flow and the new downstream flow, which allows the achievement of the set objectives, solving the problems of the current flow.

The new flow provides for the elimination of the MRP and of the picking Operators on the shelves, while maintains the current warehouse software (in communication with the company ERP) with the function of transmitting to the RTU (instead of to the picking Operators via tablet) the Purchase Orders queues to be processed. The RTU then communicates with the columns of drawers via the gateways, while the drawers require the intervention of the column lift, which synchronize with the compartmented conveyor belt. The drawers, lifts and conveyor belts perform the Operations required mechanically, using stepper motors driven directly by the electronics of the drawers, piloted by the system Software.

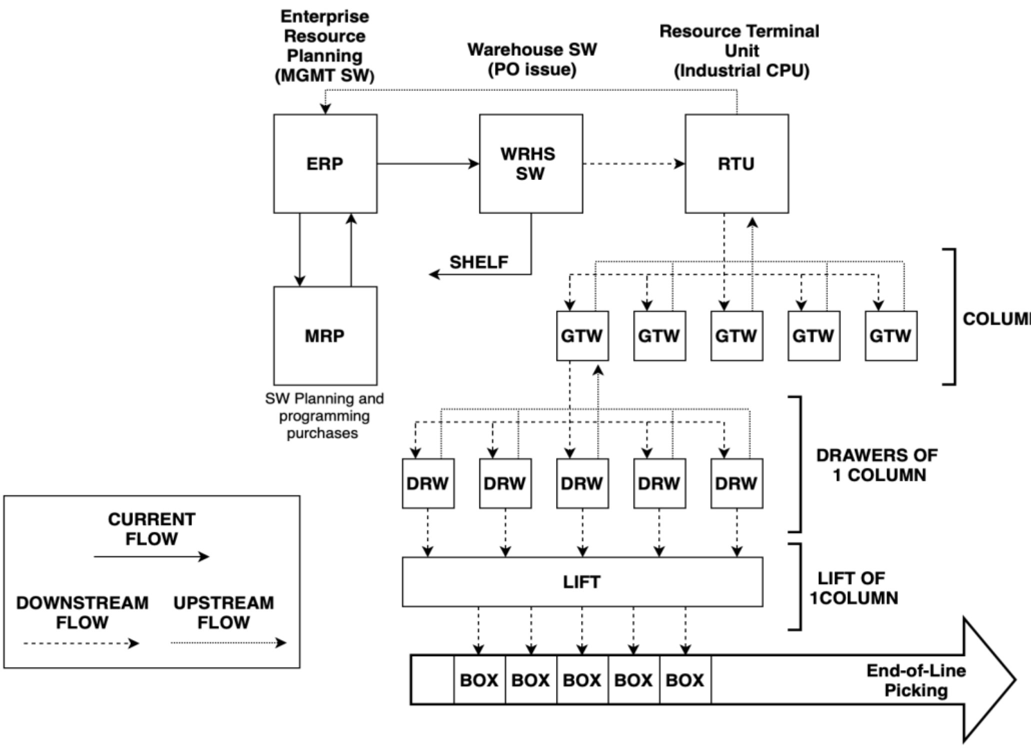

Fig. 1. ITS architecture (hardware, platforms, and software)

ISBN: 978-988-14049-2-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

V. DETAILED DESIGN

Following the first phase of the study, the Authors were able to build the knowledge base necessary to proceed with the design phase of a fully automated warehouse in Industry 4.0 logic for the storage, picking and shipping to the Customers of the order queues received.

A. Mechanical Design

The proposed solution consists of an in-line dispenser shelving, at the base of which a special sectioned conveyor belt runs.
The products belonging to the same order are collected in each section to transfer them to the end of the line, where they will be packaged for shipment by the Operator assigned to this task (see Fig. 2). The same Operator is responsible for loading the warehouse.
The line is made up of columns side by side with stacked multicell drawers, which are assembled on-site based on a project developed in relation to the needs and spaces available (see Fig. 3).
The drawers are independent from each other because they are equipped with local (peripheral) intelligence, they can be single or multi-product and are characterized by parallel slides adaptable in width and height to the shape of each product housed. The material used is AISI 304 stainless steel and dimensions: 500x1000x250 mm (see Fig. 4).
The structure, which allows the drawers to be horizontally side-by-side and stackable vertically, allows maximum adaptability to spaces and flexibility of use.

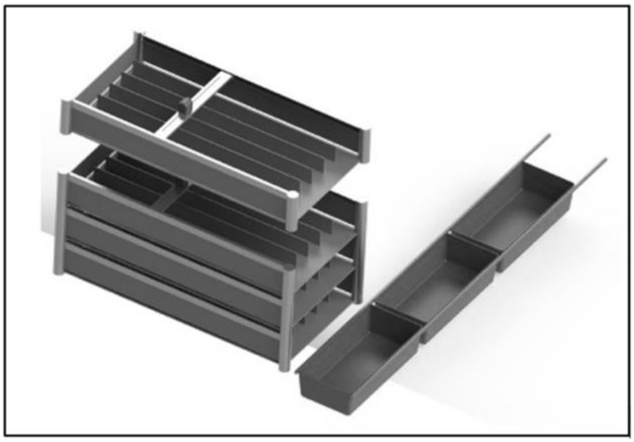

Fig. 3. Column of smart 4.0 drawers with conveyor belt (illustrative renders)

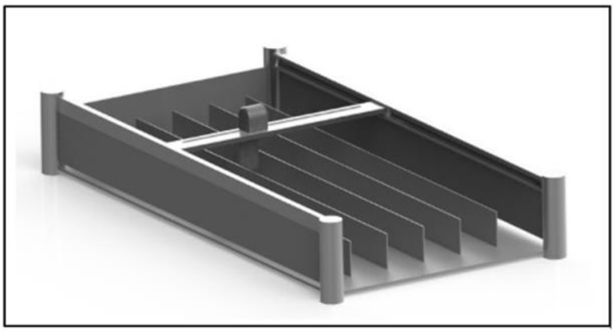

Fig. 4. Smart 4.0 drawer (illustrative renders)

The connection between the drawers is carried out through joints and anchored to the ground by bolting. This in order to be able to make any changes to the structure at any time of the life cycle (with a simple hydraulic lifting procedure) to adapt it to new needs, without compromising

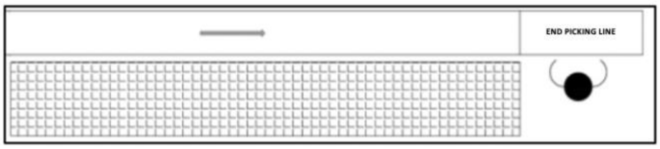

Fig. 2. Line of Picking (lean logic)

its functionality, with maximum speed and irrelevant intervention costs. The replacement of drawers approximates that of the new drawers, thanks to their "plug and play" design.
The structure, which allows the drawers to be horizontally side-by-side and stackable vertically, allows maximum adaptability to spaces and flexibility of use.

The connection between the drawers is carried out through jints and anchored to the ground by bolting with the purpose to be able to make any changes to the structure at any time of the life cycle (with a simple hydraulic lifting procedure) to adapt it to new needs, without compromising its functionality, with maximum speed and irrelevant intervention costs. The replacement of drawers approximates that of the new drawers, thanks to their "plug and play" design.

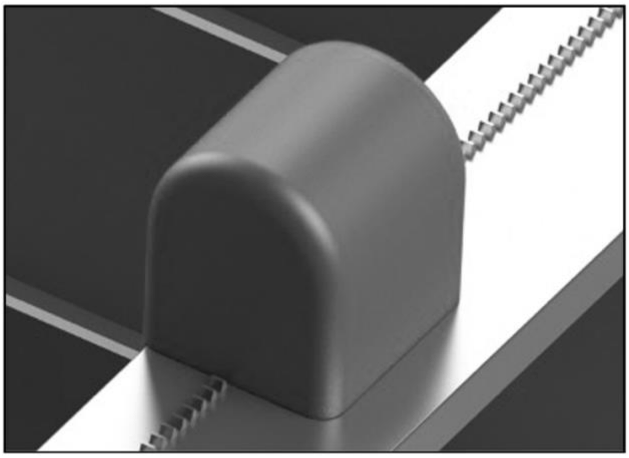

Fig. 5. Smart 4.0 drawer: detail of a pantograph

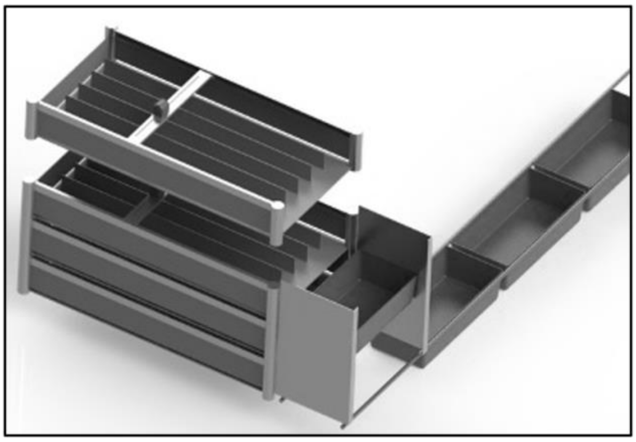

Fig. 6. Column of smart 4.0 drawers with conveyor belt and lift

B. Design of the Extraction System

The extraction system was designed in a simple way. Slides with variable distance are installed inside the drawers according to the size of the specific product code. The drawers are loaded at the rear, taking up all the space available in the slides. The system is ready for operation when the rear door of the drawer is closed. The extraction

ISBN: 978-988-14049-2-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

takes place through the advancement of a pallet which advances by gradually scaling the number of packages communicated by the column gateway according to the operating logic. The pallet is mounted on a pantograph system to be able to empty all the available slides sequentially. The pantograph is driven by two high-precision stepper motors. The pantograph mechanics consists of a steel bar that moves on guides (see Fig. 5). The movements along both axes take place by means of plastic racks studied in the technology of materials in order to be self-lubricating.

C. Design of the Picking System

The movement from the individual drawers to the conveyor belt is carried out by means of a high-speed and precision descent device called "lift". The lift positions

Fig. 7. Communication system (column gateway and RTU)

each product in the conveyor belt compartment corresponding to the order to be processed, thus eliminating that possibility of Human error, during the picking phase, which is anything but infrequent in manual handling (see Fig. 6).

D. Design of the interfaces and communication nodes

In order to be able to pilot the warehouse in terms of operations, monitoring, and control, it was necessary to design specific interfaces for the integration of the existing Software for manual picking with the warehouse hardware. These interfaces are configured both as hardware interfaces and as software interfaces.

Hardware interfaces are classified on three different levels in cascade:

- Drawer interface (Electronics PCB)
- Column interface (Gateway)
- Warehouse interface (RTU)

Communication is based on a bi-directional data transfer principle according to downstream flow (ERP-DRAWERS) and according to an upstream flow (DRAWERS-ERP) where the three hardware interfaces play the role of integrating the data and distributing/transmitting the obtained information according to the logic of the warehouse.

The three hardware interfaces were specially designed and developed, they consist of proprietary electronics with the specific purpose of containing everything is needed to run the process, but nothing more in terms of components (see Fig. 7).

The purpose of this approach is multiple and allows:

- to minimize the resources used, thus producing a significant saving of components, with a particularly appreciable return in terms of replicated electronics (drawers and gateways)

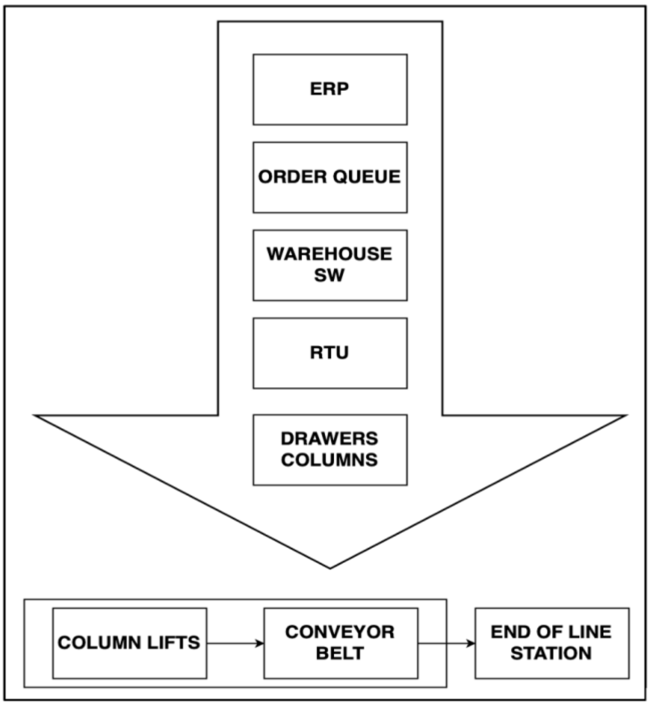

Fig. 8. Logical scheme of process phases

- to have essential, direct, and extremely fast electronics
- to have reliable and robust electronics (because it is based on a lower number of components)

The Software interface, as well, has been developed specifically to connect the RTU with the warehouse existing software and therefore allows INPUT and OUTPUT communication with the company functions of marketing (in terms of seasonality and trend) and purchasing (in terms of generating restocking proposals).

It is important to note that in 4.0 logic (and to further guarantee the security of operations and cybersecurity) the order is transferred electronically from the company ERP to the warehouse Software and then, again, to the local industrial computer RTU which presides over the picking phase thus eliminating a possible source of errors, again not infrequent when this phase is managed by an operator.

The author highlights the importance of the RTU (the centralized data management device) which has been specifically designed for the correct management of warehouse logic. The RTU can manage an unlimited number of columns of drawers and allows the integration of the data collected by the individual column gateways and the transformation of the same into usable information, by automatically producing analysis and statistics and communicating with the marketing and purchasing functions (see Fig. 8).

Among the outputs provided by the RTU, there are the fundamental elements for the management of the stocks of Class A materials, namely the EOQ (Economic Order

Quantity) and the RP (Reorder Point) corresponding, according to classical theory, respectively to the quantity to be ordered and when to order. These indicators are continually and automatically updated by the RTU according to seasonality and trend.

The results of these elaborations are then submitted to the decision makers for the necessary approval or modification (i.e., proposals for restocking aimed at the purchasing office, based on actual consumption trends and demand forecasting and demand planning algorithms).

VI. Final Technical Specifications

When finalizing the work done, the basic construction elements for the new Warehouse 4.0 were reduced to the essential:

- IIOT 4.0 drawers
- Columns gateways
- Columns lifts
- Compartmented conveyor belt
- RTU (Remote Terminal Unit)
- Line monitor for the Operator
- Software

A. *Warehouse Logic*

The warehouse logic (meaning for “logic” the system with which the new technology for product picking is piloted) is harmonized with the hardware and the software interfaces produced.

It is a logic designed in a deliberately simple and essential way, in order to optimize and speed up the downstream flow; it is based on only three parameters (X, Y, Z):

- IIOT 4.0 X: column reference
- Y: drawer reference
- Z: number of products for the specific location

The results obtained are again:

- Robustness
- Speed
- Reliability

B. *4.0 Features*

The warehouse is designed in strict 4.0 logic, with the specific aim of providing companies with the latest generation applied technology, which can be easily integrated into the existing system. Some examples of 4.0 design introduced in such technology can be found in:

- Plug and play drawers
- Self-configuring system for entering new codes
- Analytics (automatic reporting and statistical process control)

The architectural principles do focus on:

- Interconnection of machines, appliances, and sensors with the operator
- Treatment of a vast amount of data necessary to make the most appropriate decisions
- Ability to make decentralized and autonomous decisions (from drawers to RTU)

The value obtained from the 4.0 Design can be found in:

- Strong product customization
- Manageability of small batches (applicability to large and/or small stocks)
- High flexibility of installation and use
- Automated and interconnected technology
- Self-optimization and self-configuration methods

The effects produced mainly consist of:

- Intelligent networks of machines, systems, and operators
- Autonomously controlled value chains
- Human-machine collaboration in real-time
- Peripheral (drawer) and centralized (RTU) intelligence

Finally, the IoT (IIOT) aspects make the system particularly versatile and usable allowing the:

- System checks by authorized devices (desktop, laptop, tablet, smartphone) and by Cloud
- Respect of Cybersecurity (with different systems, by means of Hardware and Software keys, and a Proprietary Operating System)

No less important is the aspect of Maintenance 4.0:

- Intelligent support for operators
- Self-diagnostic systems to support Human intervention to accelerate problem-solving
    - Physical processes monitored continuously
    - Condition monitoring to decrease machinery downtime
- Machines that can autonomously predict breakages and automatically trigger maintenance processes

Other benefits can be found at Service 4.0 level, by allowing external companies to monitor and remotely control the warehouse in real-time and anticipating problems via alerts, thus transforming the service offered from reactive to proactive, limiting site visits to what is strictly necessary and significantly improving the offered level of customer service.

C. *The role of IIoT 4.0*

Following the distinctive features of a 4.0 Plant, an important role in its design has been assigned to the Industrial IoT. Through the Cloud, by a WEB Portal, the warehouse can now be real-time monitored and controlled from anywhere in the world with any authorized device.

The fundamental characteristics of how it was conceived are:

- Cybersecurity through access privileges, HW key, and proprietary Operating System
- The simplicity of use to make the system user friendly, by minimizing the training effort of the Staff
- The possibility to make queries
- Automated reporting
- Self-diagnostics and predictive 4.0 Maintenance, based on statistical process control

VII. Application to a Case Study

A. *Analysis of the Current Situation*

In order to evaluate the benefits deriving from the implementation of the proposed technological solution, the Authors describe the application to an SME operating in the cosmetics sector, highlighting the expected benefits both from an operational and logistical point of view, both from an economic-financial point of view. Below is a description of the business context, a sort of "360° photograph" of the system, concerning:

A. Infrastructure
B. Technologies in use
C. Human Resources currently engaged
D. Existing processes and methodologies

B. *Infrastructures*

The current layout consists of an area of 1,800 square meters, with an asymmetrical usable height of 5 to 6 linear meters and an average volume of 9,500 cubic meters. Shelves are 2.20 meters long and 1 meter wide (capable of housing 2 pallets each) and the distance between the shelves is fixed at 1.30 linear meters (see Fig. 9). The top floor of the shelving makes it possible to accommodate packages with a maximum height of 1 meter (equal to about 3 boxes on a pallet) except for 23 shelves (due to the available asymmetrical height). The shelves are placed, each other, at a distance of 2.20 meters away. 2 roller conveyors, divided into 54 columns per side (108 total), allow easier unloading of the bulky packages.

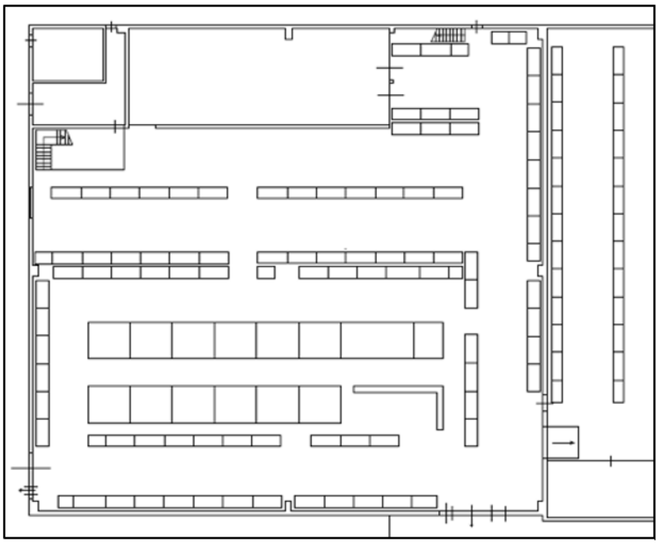

Fig. 9. Warehouse layout

C. *Technologies in use*

The technologies implemented were found to be inconsistent with actual business movement needs. They consist of:

- MRP (Material Requirement Planning). Indicated in literature as a technique that calculates the net needs of materials and plans production and purchase orders, in consideration of the market demand, of the bill of materials, of the production, of the purchase lead times, and the actual warehouse stocks. MRP systems are normally very useful for companies that have complex bills of materials and/or relatively long procurement lead times. Considering that the company in question operates a BTS (Buy To Sell) business, which by nature does not involve production (as it is a pure resale of cosmetics), it would normally not need MRP software. It is found that the company improperly uses MRP as a demand planning system which is unsuitable, inaccurate, and time-consuming.
- STOCKAGER (warehouse software). Stockager is a software with warehouse management function. It was implemented to manage individual or distributed warehouses in the area. It adapts to any warehouse layout, following its evolutions over time. The company uses this Software in connection with the corporate ERP to manage orders.
- WAREHOUSE TABLETS. The order queues produced by Stockager are displayed as job orders on the tablets supplied to the operators.

D. *Human Resources Currently Engaged*

Warehouse operators have the task of receiving products from couriers, loading products on the shelves according to warehouse logics, and performing picking operations. The number of warehouse operators varies according to seasonality; however, it is calculated on an average basis as seven FTE / month (Full Time Equivalent). Warehouse staff generates a significant cost that impacts the margins of the business. In addition, by the very nature of the work (high number of operations and limited time available), the picking operations thus conducted generate continuous Human errors, that worsen performance and damage the corporate image towards customers.

E. *Existing Processes and Methodologies*

In accordance with the activities carried out by the operators, the current warehouse processes are mainly three:

- Demand planning process through MRP
- Goods receiving process
- Product shipping process

A detailed mapping of each of the processes interconnected with the warehouse was carried out and a subsequent analysis to highlight any areas of potential improvement. The following critical issues emerged from this analysis:

- Improper use of the MRP system, which is used as a demand planning tool
- The "goods loading" on the shelves (associated with low added value activities that cause inefficiencies in the handling operations timing)
- The lack of process automation in the picking phase
- The use of the tablets significantly slows down the manual activity of picking and packaging the orders
- The ineffective stocking logic, which leads to excessive movement of goods between warehouses.

F. *Estimated Impact of Logistics and Operations*

The results produced by the introduction of an automated picking system have been in line with the initial hypotheses, producing significant benefits for the company on multiple levels, such as:

- Staff savings
- Space savings
- Increase in efficiency and speed
- Increase in precision and reliability (elimination of errors)
- Reduction of stock breaks

- The best level of service and customer satisfaction
- Greater safety for the operator

A brief description is provided below for each of the benefits listed above.

The automation introduced allowed to reduce the Human contribution to the picking phase, thus making it possible for a single operator to take charge of the total warehouse management (goods loading, surveillance, picking and packaging). Warehouse Staff was, therefore, reduced from an average of 7 Full-Time Equivalent (FTE) to 1 FTE with a consistent saving of the Human Resources engaged (over 85% saving).

The better use of the space has allowed a strong reduction in the facility volumes engaged; this was made possible by the introduction of sorting criteria, such as a better accommodation of the goods in the drawer's locations, than in the previous shelving ones. The space occupied went from 1,800 square meters to 400 square meters (over 75% saving).

The interconnection of the original warehouse software with the RTU, associated with the new warehouse automation, allows obtaining noncomparable performance in terms of efficiency and speed, with a 360° impact on picking operations.

The precision of the new operations is absolute, thus transforming the previously imprecise picking into a process phase with total reliability. The impact on performance is, again, significant, eliminating the possibility of error, which is statistically inevitable in manual activities.

The frequent stock breaks, to which the company was subject to the previous manual warehouse management logic, have significantly reduced. The reason for the improvement lies in having delegated the responsibility for the stock to the machine (which is based on counting down by each drawer 4.0, operated continuously) rather than the perception of the single operators (which is based on a repeated and expensive counting of residual stocks, as far as operating in discrete logic). The reduction in stock breaks, however significant, did not reach a “total zero” due to the variability of lead times by Suppliers.

A customer survey, conducted specifically afterward the implementation of the new technology, has allowed us to find an improved perception of the level of service in terms of speed in delivery and precision of the mix, thus producing a much better customer satisfaction and indirectly producing an increase in sales.

The traditional picking operations tend to expose the operators to risks such as fatigue, stress from alienation (repeated activities), and height (picking from the upper shelves). The automation of the warehouse produces a substantial change in the operator's tasks, by decoupling it from the picking and thus reducing the risk phase.

VIII. Economic Analysis

To give an idea of the economic and financial benefits associated with the introduction of the proposed solution, an overall investment analysis was also carried out. Before the implementation of the new 4.0 solution, 7 Operators were employed with a full cost of € 35K / year each (€ 245K / year in total). Following the introduction of the new picking system, 6 Operators could be “saved” with a lower cost of € 210K / year. At this point, 2 classic indicators of investment theory can be determined such as the Payback Period (PBP) and Net Present Value (NPV), bearing in mind the following data:

- The initial cost of the investment: € 300K (considering the normal design evolutions between the preliminary study and the executive project, it was decided to simplify the calculation, using a drawer evaluation, where each drawer “carries behind” a part of the cost structure of the entire warehouse implemented, installed, and tested. The drawers have a cost of € 1,000 / each for a volume equal to 300 drawers)
- Operations and Maintenance (O&M) Costs: the Authors considered an annual cost of maintenance equal to 6% of the total investment, while the cost of Energy was estimated of negligible impact as it uses renewable energy produced by a fully depreciated plant
- Disposal costs borne by the supplier company in exchange for the released property of the plant
- Annual income: intended as labor savings (7 Operators x € 35K – 1 Operator x € 35K = € 210K / year)

The PBP is calculated as the ratio between investment and profit, so: € 300K / € 190K = 1.57 years (certainly a favorable figure for a plant whose useful life is estimated at least ten years before requiring a possible revamping).

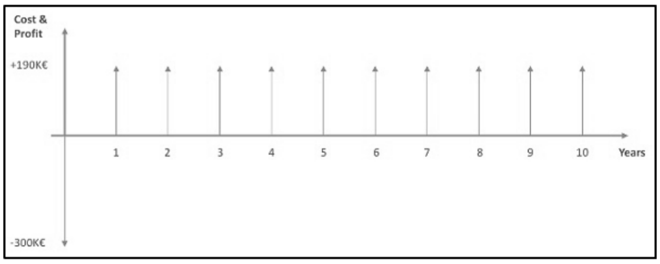

Fig. 10. Annual Cash flow diagram

A second test parameter of the economic validity of the investment is, as mentioned, the NPV.

$$NPV = \sum \frac{NCF_t}{(1+k)^t} - NCF_0$$

NCF_0 = initial cash outlay on the project
NCFt = net cash flow generated by project at time t
n = life of the project
k = required rate of return

Assuming a discount rate equal to 8% (according to the Sector average) the NPV is equal to € 1025 (see Fig.10). The NPV value is, again, significantly favorable to the investment, taking into account that only small maintenance requirements are fulfilled by the warehouse Staff during working hours, at a negligible cost.

IX. Results and Future Research

A significant effort during the conceptualization phase of this applied technology was paid to make it affordable by national SMEs, in order to give them better competitiveness on the reference market.

ISBN: 978-988-14049-2-3
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

For this reason, great attention has been paid to elements such as the cost of the first installation, flexibility over time, saving hours of labor for the picking operations, ...
This is in full contrast with other solutions already on the market which are inaccessible to small and medium-sized enterprises characterized by a limited volume movement and operating in specific product sectors due to their complexity and high price.

Consequently, the picking operations must be carried out manually with non-trivial times and costs, including the costs already mentioned of the errors made in the composition of individual orders, to remedy which it is necessary to recall from the customer the goods already delivered and provide for a new shipment.
All with inevitable disputes with the customer due to the delay in the arrival of the goods, the discomfort caused, and the associated costs.

The authors foresee in the implemented solution an unexpressed potential and define a new study area to introduce, in the second generation of such applied technology, other lines of innovation that can lead to the achievement of even higher efficiency levels, as:

- Management of a virtual warehouse
- Digital Twin (online and real-time warehouse simulator)
- Advanced analytics

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