Design of drone fleet management model in a production system of customized products

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***Abstract*— In many manufacturing plants, there is a major problem in the internal logistics due to the high number of products, machines, and routes, especially in those manufacturing plants that produce low weight products. For example, many industries such as footwear, toys, plastic household goods and industrial products, among others, require assemblage products in small assembly lines, in small and customized lots according to customer requirements. In general, in this stage of the process, it is not available an efficient logistics system and an adequate level of automation in the transport of supplies, either for collecting materials or for distributing them.**

Transporting materials and semi-finished products into a plant using a fleet of drones, involves to take over the tasks associated to the size of the fleet of drones, routing decisions, and drone selection to perform a particular task.

The aim of this paper is to propose a fleet managing model for VTOL-UAV drones (Vertical TakeOff and Landing - Unmanned Aerial Vehicle) that perform the delivery or pickup of supplies and materials in a production plant, also incorporating alternation in drone operations for an efficient use of energy in their batteries.

When calculating the size of a fleet, the model determines that, in order to bear the peak demand of final products, it will be required a drone fleet of a certain amount of units (drones) depending on the load capacity, cycle time of the transport operation, and the demand of units to be manufactured. This amount of drones is able to meet the demand of products covering all the deviations in the parameters. Furthermore, it is incorporated the use of coefficients which involve deviations in the estimated demand, cycle time, load capacity and availability of the drone fleet. In this context, a computational tool has been developed in order to determine the amount of drones that comprise a fleet to perform certain logistical operations under diverse operating conditions, some of which can include the product demand for turn; volume, weight and shape of the products, power and speed of the drones, covered distance and finally warehouse and plant layout.

A manufacturer of plastic is used as a reference model. In this situation, the final product, storage boxes for home of various sizes, are assembled by performing “pickup” of parts in warehouses and performing “delivery” to the assembly lines at the plant. This work is aimed to simulate and evaluate a model which represents the operation of a fleet of drones in the process of transporting materials. The model also includes the manufacture of semi-finished materials and parts in their respective workstations and final assembly of the products in their respective lines, incorporating the activity of replacing flat batteries for charged batteries. This model allows to evaluate the impact on production due to battery changes, especially the drones used for transport.

Index Terms- Drones; Inventory; Matlab; Batery Changes

I. INTRODUCTION

A growing interest has been evidenced in the UAV (Unmanned Aerial Vehicle) especially in those with vertical takeoff and landing (VTOL) They allow to perform horizontal flight avoiding obstacles, with characteristics of low speed and high precision in flight. Several structures and configurations have been developed with 4, 6 and 8 rotors; they all meet the necessary requirements for the operation proposed by this work, but with the limitation of high energy consumption required for operating.

In many industries such as footwear, toys, plastic products for home and industry, etc. there is a major problem in the internal logistics of the assembly plant or customization of products [1-2-3-4-5]. To study this situation, a manufacturer of plastic products for home has been taken as a reference model. In this case, it is shown the proposal for the manufacture of semi-finished and finished products, and the transport of these through a fleet of quadcopter drones.

Operating a fleet of drones for pickup or delivery of materials into the plant requires a significant consumption of energy extracted from the batteries. It is therefore necessary a battery replacement, extracting the flat batteries and inserting fully charged ones; this activity takes time, consumes resources and causes interruptions in the operation of the drones. In this paper we want to reduce the impact on plant productivity by performing this activity.

In order to estimate the impact caused by the battery replacement in drones on plant productivity, computer simulation will be employed using queuing systems [6]. This queuing system will be applied to the current production plant, which has servers that would be the work stations; these servers work on two families of products, plastic boxes and coolers, each product family will have its own service time on each server, the demand system is manufacturing to order.

The operational planning has many variables [7-8-9-10], some of these can be used as optimization criterion. These variables are: lead time, cycle time, waiting time, utilization, inventory levels, inventory turnover and in-process inventory. These do not indicate how they relate to each other, not being able to be aware of how one affects each other, neither being able to assess their impact. However these theories converge in emphasizing the management and control of the in-process inventory [11-12-13]. In-process inventory is the inventory between the starting point and end point of the line production. In-process inventory control is performed by controlling the overproduction, controlling waiting queues and reducing stopping times. With this, lead time of manufacture will be controlled and reduced, improving the level of service and customer satisfaction.

The interruption of the supply of materials as a result of battery replacement in the drones produces highly unbalanced flows. This asynchrony between arrival of materials and processing times is one of the reasons of queues. That is why it is important to control and manage it.

High and variable levels of inventory and lead time cause not only high operating costs, but also cause difficulty to see how the plant can be operated in "Just in time" mode [14-15]. A key ingredient of "Just in time" mode is to have lead times consistent and reliable and low inventories.

The variability in lead time is especially a problem when parts arrive and must be coordinated for assembly. Other consequences of the variability in lead time are that "safety time" tends to cause the early arrival of parts to in-process inventory, adding to the inventory queues [5-6]. High lead time also means to have high levels of finished products in security stock, which are requested to ensure the delivery deadline, causing loss of traceability in the information, production must be commenced on demand in further periods, which are more uncertain, with long periods of time between production and final use of the product, creating difficulties for detecting and correcting quality problems. It is also impossible to react to short-term problems or changes in demand [6].

Operating a fleet of drones in the transport of materials when manufacturing plastic products in the plant will be evaluated by computer simulation. It is designed a model that represents the manufacture and transport of materials and semi-finished products, and the final assembly of the product in mini-assembly lines. This model will permit to evaluate the impact on production due to the time used for battery replacement in drones.

The use of the results obtained will provide better understanding of the processes and problems that occur on the ground, identifying troublesome situations. When the model is operating, the system will be ready to be tested with and without a model of rotation in the tasks assigned to the drones, allowing to propose changes that improve the responsiveness of the plant and meet customer requirements.

II. PLANT SITUATION

The plant produces two families of products, coolers and plastic boxes for home. The supplies required to assemble the products are taken from warehouses distributed along the plant. From one of them semi-finished products (boxes and lids) are picked from one them, and accessories (wheels, clips, handles, labels, barcode, etc.) are picked from another. These materials are requested to warehouses, which are later taken to the assembly area, in order to start production.

On the operational planning of the plant multiple variables are presented, which can be used as optimization criterion, such as lead time, cycle time, waiting time, utilization, level of service, inventory level, inventory rotation, plant capacity and in-process inventory. Considering that drones cannot wait for restriction of energy delivered by batteries [16], it will be used the concept “pull” with the use of kanban (kanban signal) to generate the transport order, so that a drone performs transport of materials and semi-finished products.

The model will focus on controlling in-process inventory in both semi-finished products and accessories. The control of in-process inventory is performed by controlling the overproduction, controlling queues and reducing waiting times produced by battery replacement in drones. With this control and reduced manufacturing lead time will be achieved, improving the level of service and customer satisfaction. In this process the use of kanban signal and task rotation in the fleet of drones plays a fundamental role.

III. DATA REQUIREMENNT

A. *Determining size of fleet of drones*

Next, it is presented a method to determine the amount of drones (VTOL) that should be part of the fleet necessary to meet the demand of the plant according to the annual, monthly and daily planning, and per shift.

The formula to estimate the size of the fleet of drones is determined by the following formula.

$$N^{o}\,DRONES = \frac{\frac{DT}{K} * (1+\propto) * TC * (1+\beta)}{CD * \gamma * 3600} * \frac{1}{\Omega}$$

where

DT: Demand transported per shift expressed in kilos, including products, materials, parts and components, and packaging materials to be carried by drones.

α : Safety factor that covers variations in demand, i.e. errors in estimating the load in kilograms. This factor normally takes a value within a range of $5\% \leq \alpha \leq 20\%$.

K : Number of hours worked per shift; this factor normally takes a value between 6 hrs $\leq$ K $\leq$ 7 hrs.

TC : Drone cycle time in seconds. It is the expected time for a round trip.

β : Safety factor that covers variations in cycle time. Typically this value may vary within the range of $5\% \leq \beta \leq 10\%$.

CD : Net maximum load capacity of drone in kilograms. Weight of the container and fixings is not included.

γ : Factor of the drone capacity, this factor normally takes a value within a range of $60\% \leq \gamma \leq 90\%$. The container is not always at full capacity.

Ω : Availability factor of the fleet of drones for failures, maintenance and others. This value may typically vary within a range $80\% \leq \Omega \leq 90\%$.

The drone uses a short time to replace the flat battery for a fully charged. In the formula, this activity is included in the fleet availability factor "Ω". An important part of the unavailability of the fleet of drones is explained by the activity of battery replacement.

IV. DRONE FLEET MANAGEMENT SYSTEM

Given the size of the fleet of drones to cover the activities of transport and production needed to meet demand, the management system now generates routes and assigns them to drones [9-10-11]. The model selected to generate routes to the drones corresponds to the algorithm "First Group Then Route", which generates clusters that avoid crossing paths. Alternative algorithms such as "Route First Then Group" in first instance generate crossroads, with methods such as nearest neighbor and cluster with minimum angle, generate route crosses which must be removed in subsequent processes called refinement solution, so they were discarded as a method.

Transporting semi-finished materials into a plant using a fleet of drones, means taking charge of tasks associated to decisions of routing, payload, and selection of a drone to a determinate ask. If a drone is quite often assigned to tasks which require a lot of weight carried over a long distance route, the battery will tend to run out soon. It is considered desirable that all drones have roughly equal power capabilities on its batteries at any point of time. Therefore, the hard tasks should be shared among all drones. Such rotation in heavy-duty tasks must be a need to assign tasks to the drones. The idea is not to use a simple random selection of a drone, to avoid overload and early depletion of the battery supply.

It is essential to develop a simple and rapid protocol in choosing a drone to perform a task and to ensure rotation. It will be defined with a polynomial and use of weightings for rotation. None of these parameters can fully express all aspects of the suitability of a drone to be selected for a task of delivery or pickup. The following factors are taken into account to select the quadcopter.

$$QW_i = W_1 Pi\, Qi - (W_2 T + W_3 D + W_4 E + W_5 N + W_6 M + W_7 L + W_8 K)$$

where

QW_i: Total weight of the quadcopter weighed up "i" to be selected, that lightest is preferred.
W_1: Weighting of the remaining battery charge of quadcopter *"i"*
W_2 : Weighting of transport time of semi-finished material
W_3 : Weighting of travel time not loading semi-finished material
W_4 : Weighting of time that is active but not performing transport nor empty neither loaded
W_5 : Weighting of the number of times taking off with load
W_6 : Weighting of the number of times taking off without load
W_7 : Weighting of the number of times landing with load
W_8 : Weighting of the number of times landing without load
P_i : Percentage of remaining charge in the batteries of the quadcopter "i"
Q_i : Total charge capacity of the battery(ies) of the quadcopter *"i"* in mAh

T : Accumulated of all time the quadcopter *"i"* has used in transporting semi-finished material, since the last battery charge,

$$T=\sum ts_{ij}$$

where
ts : time for transporting quadcopter semi-nished material *"i"* on task *"j"*
j: work done by Quadcopter

D : Accumulated of all time the quadcopter "i" has used in moving without load from the last battery charge.

$$D=\sum td_j$$

where
td: Quadcopter time *"i"* in moving empty on task *"j"*
j : work done by Quadcopter

E : Accumulated of all time the quadcopter *"i"* has been active but not traveling since the last battery charge.

$$E=\sum te_j$$

where
te: uptime quadcopter *"i"* on task *"j"* (loading, unloading, waiting and others)

N : Accumulated of all time the quadcopter *"i"* has used ito take off with load since the last battery charge.

$$N=\sum tn_j$$

where
tn: time to take off with load in each WS visited by quadcopter the *"i"* in route of task *"j"*

M : Accumulated of all time the quadcopter "i" has used to take off without load since last battery charge.

$$M=\sum tm_j$$

where
tm: time to take off without load in each WS visited by the quadcopter *"i"* task path *"j"*

L : Accumulated of all time the quadcopter *"i"* has used to land with load since the last battery replacement.

$$L=\sum tl_j$$

where
tl: landing time with load on each WS visited by the quadcopter *"i"* in route of task *"j"*

K : Accumulated of all time the quadcopter *"i"* has used to land without load, since last battery replacement.

$$M=\sum tlj$$

where
tl: take off time without load in each WS visited by the quadcopter *"i"* in route of task *"j"*

Among all quadcopters available to perform a task, candidates are those who meet the following restriction

$$Pi^* \ Qi \geq \text{energy consumption of task}$$

Figure 1 shows a drone fleet management system used to perform the pickup of semi-finished and finished products. Semi-finished and finished products are transported from the injection molding machines to the palletizing area.

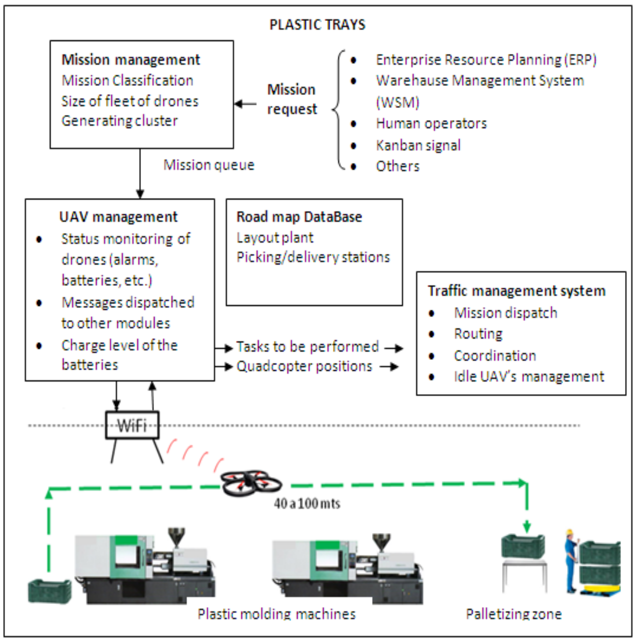

Fig. 1 Pickup

Figure 2 shows a drone fleet management system used to perform the delivery of materials and semi-finished. The materials are transported from warehouses to the injection molding machines and semi-finished products are transported from warehouses to the assembly lines.

In both cases, either for delivery pickup, the Management System performs the following functions.

A. *Generating a mission request (plant level)*

It allows generating a request for transportation service. The source of this order may be a Kanban signal, Enterprise Resource Planning (ERP), Warehouse Management System (WSM), an operator or other entities. Mission Management receives this service request.

B. *Mission management(plant level)*

This function receives service requests from different entities and prioritizes and sequences them according to the situation on the plant, in terms of the state of productive resources and transport, and material flows. This function also determines the size of the drone fleet required to meet transportation requirements, determines the clusters and generates paths for delivery or pickup of materials, semi-finished and finished products. Another important function is to close service orders or to eliminate already made service orders that cannot be performed because of a problem with the resources involved.

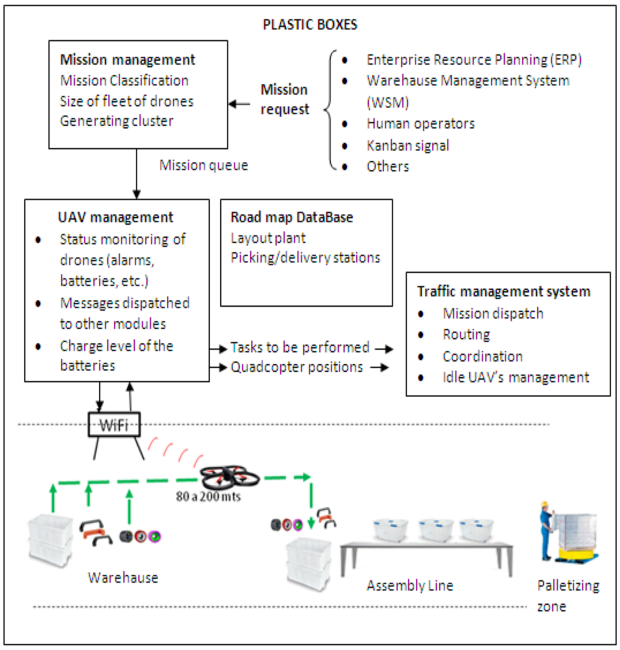

Fig. 2 Delivery

C. *UAVmanagement (fleet level)*

It allows assigning drones to each transport task and ensuring the rotation of drones, so that each drone fleet has similar levels of battery power at any point in time during the operation. It determines the power capacity of the batteries of each drone depending on the battery type and the percentage of remaining power. It also estimates the energy consumption depending on the distance of the path to continue, the payload, and the number of landings and takeoffs, in order to select the most suitable drone.

D. Roadmap database (fleet level)

This function allows managing all the information of the plant layout, the positions of the resources, constraints and changes in paths and direction of transport flow of drones.

E. Traffic Management System(fleet level)

It mainly manages flat battery replacements in drones; dispatches or aborts missions or execution of service orders; modifies the paths to be followed by drones in emergencies or special events.

F. Drone status (nivel UAV)

Drone identification
Position and direction of drone
Battery (ies) health status
Level or percentage of power remaining

V. COMPUTER SIMULATION

For computer simulation, of stochastic and discrete type, the current flow of production in the plant is simulated, in order to quantify inventories generated, fulfillment of work orders (demand) and mainly the use of drones, introducing the increase or reduction of the duty cycle as a result of the number of times that battery replacement should occur during a shift. This simulation considered an assembly line for 2 families of products and each product family with its own service times. The objective is to evaluate the performance of the plant with the following indicators: average in-process inventory, instantaneous in-process inventory, fulfilled orders, lost orders, use of each server and capacity of the plant.

The ideal scenario is the quantification of the indicators mentioned above for a limited queue size and checked previous to each server. For this, Kanban signals are used, so limiting the number of entities in queue previous to each server, achieving control in the in-process inventory. The number of entities in queue previous to each server is what would trigger or stop the entry of entities into the system, permitting to process the ones in queue; therefore the production progresses only when there is a manufacturing order, which would be a gap in a queue previous to each server.

In this case, the kanban signal corresponds to a drone called to perform a transport activity either to pick up or delivery. The Kanban signal is a "Mission Request" as shown in Figure 1 for picking and Figure 2 for delivery.

Matlab was used for computer simulation by its “Simulink” module. In this case the “SimEvents” module is used; this module allows simulating any kind of systems in queue. From this module, the following blocks were used.

A. Materials supply subsystem

It allows maintaining a correct supply of raw material for further manufacture of parts, i.e. semi-finished products and accessories.

B. Production of semi-finished products and accessoriessubsystem

It allows manufacturing semi-finished products (box and lid) and accessories (handles, wheels and others) according to the exact needs for the next stage which is the assembly.

C. Transport by drones subsystem

It allows transporting the semi-finished products and accessories to the assembly line of the final product by drones

D. Final assembly subsystem

It represents the assembly line of finished products.

In Figure 3, it is shown the percentage of availability of equipment, which depends on the time length of the flight of the loaded drone, which in turn depends on the battery capacity in mAh. The range of loaded drone autonomy was established between 5 minutes and 120 minutes. It is estimated 3 minutes to replace the flat battery for a fully charged. The chart in figure 3 shows that for autonomous flight of 30 minutes, operational availability of the drone is over 90%. For minor autonomy, the chart shows that it is undesirable to lower less than 10 minutes, because it significantly reduces the percentage of availability. According to the capacity of the batteries available on the market, a range of autonomy between 10 and 20 minutes could be reached. Batteries that enable over 30 minutes of drone autonomy will be available in mid-term.

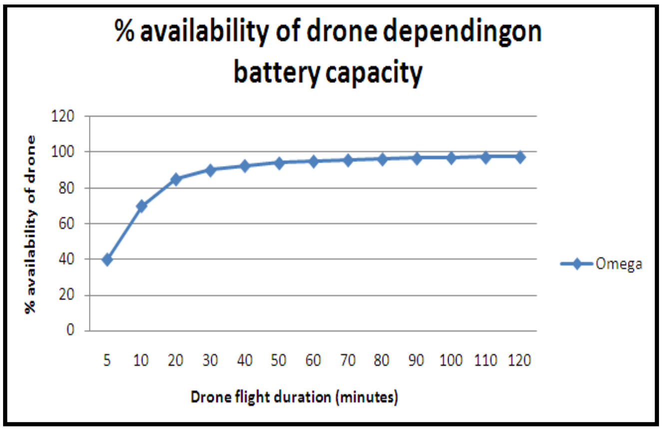

Fig. 3

Figure 4 shows the number of drones needed for different levels of demand of units per shift. It is set here the required size of the fleet of drones for availability over 70% which is typical according to autonomy and battery capacity.

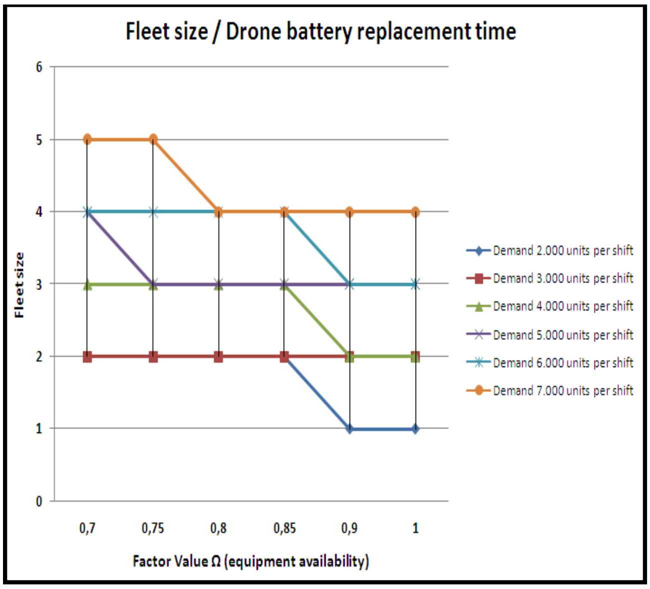

Fig. 4

Table 1 shows a summary of what is shown in figure 4. Here it can be inferred that the size of fleets of drones may vary between 3 and 4 drones. This assumes that availability of drones does not exceed 90% and product demands not exceeding 6,000 units per shift.

Table 1 Drone fleet size

	% Drone availability					
Demand Shift	75	75	80	85	90	100
2.000	2	2	2	2	1	1
3.000	2	2	2	2	2	2
4.000	3	3	3	3	2	2
5.000	4	3	3	3	3	3
6.000	4	4	4	4	3	3
7.000	5	5	4	4	4	4

Figure 5 shoes the number of drones that remain in operation as long as battery remains charged; using rotation functions with the model of selecting a drone for a new task. This keeps the entire fleet of drones longer in operation and reducing the time between the first drones retires for battery replacement and the last fleet drone stalling operation needs a battery replacement.

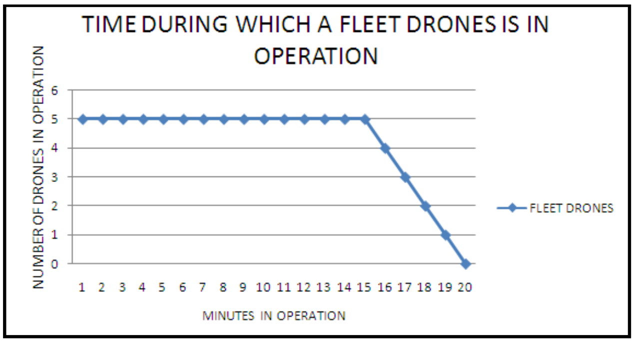

Fig.5 Number of drones in operation

Figure 6 shows the fleet of drones getting reduced by depletion of the battery power and the entry into operation of the fleet of drones with fully charged batteries. It can be seen that the first drone of the fleet retiring due to battery depletion occurs 15 minutes after the fleet of drones begins operations. From that moment up to 20 minutes, all drones of the fleet have been retired for battery replacement. It is also noticeable that the first drone retired for battery replacement in minute 15, goes into operation with fully charged batteries after minute 18, i.e. 3 minutes later. From that moment drones start coming into operation until the last drone to perform battery replacement, comes into operation in minute 23.

Figure 7 shows in orange color, the total number of drones available for picking or delivery operations. From minute 16 the number of drones available for the transport of materials starts to lower, until reaching a minimum of only 2 drones in operation. Then, in minute 23, every drone in the fleet, in this case 5 drones, is available for operation.

In Figure 8 and according to the graphs delivered by Simulink, it can be seen that significant variations occur in the inventories of the semi-finished A and B. Even for the semi-finished A, unsatisfied orders (Number of Dropped Orders) occur in certain periods. These variations and unfulfilled orders are explained to an important extent by the level of demand and changes in transport capacity not covered by the availability Factor of the fleet of drones (Ω)

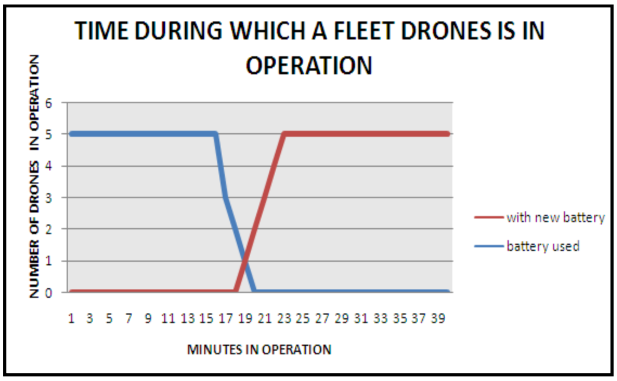

Fig. 6 Time during which a fleet drones is in operation

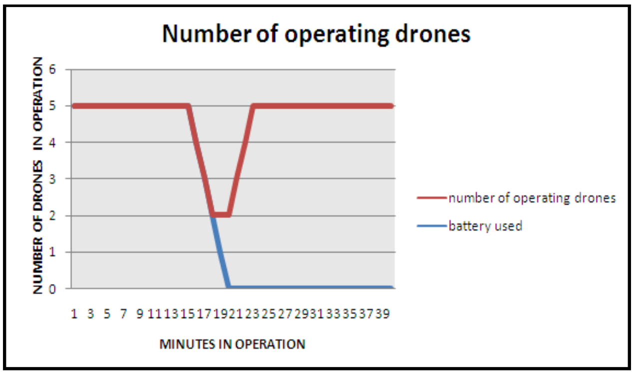

Fig. 7 Number of drones operating

In Figure 9, it can be seen that inventories of the semi-finished A and B remain stable, even for variations in the level of demand. Here variations in transport capacities are covered by the availability Factor of the fleet of drones (Ω) which can increase the size of the fleet of drones to meet demand, but without increasing inventories, thanks to the implementation of kanban.

The above graphs show the number of semi-finished products and accessories that are inventoried and transported by the drones. This information is relevant because it allows determining the amount of drones that are required in a very precise way, in order to meet a certain demand for products.

This simulation model allows that different scenarios of demand and resource capabilities and drones raise, being a reliable source to determine the requirements of drones in terms of units, amount of flight, distances, and power consumed and drained to batteries.

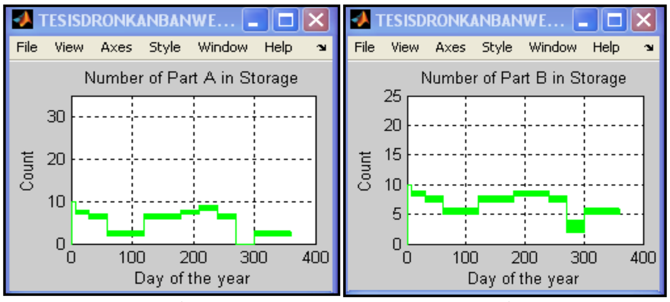

Fig.8 Amount of parts A and B storedwithout model of rotation

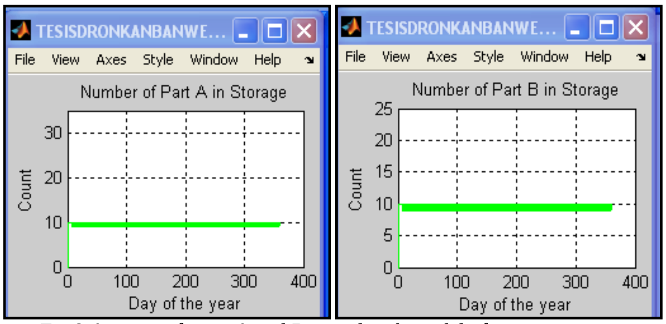

Fig.9 Amount of parts A and B stored with model of rotation

VI. CONCLUSIONS

This work is applied to a plant manufacturer of plastic boxes, in which is simulated a standby system consisting of 2 families of products; boxes and coolers. 2 scenarios for a fleet of drones (UAV Quadcopter) are evaluated. One in which the fleet availability Factor is not considered, where simulation shows important variations in the sizes of inventory and lead times. The other scenario, with fleet availability Factor and rotation of roles, allows having stable and predictable size of inventories.

In the scenario with fleet availability Factor and rotation of roles, in-process inventory is managed due to the size of the queues previous to each server is what would trigger or stop the transport and manufacturing order on each server. This way, a production flow type “pull” is achieved, generating a "Just in time" system, meaning that production proceeds only when there is a manufacturing order, which would be a kanban signal, in a queue before a server. Comparing the current situation and what was displayed by the simulation model, the effect on in-process inventory is a significant reduction. I.e. for both scenarios, the result obtained is a reduction in lead time i.e. the time at which the raw materials are converted to final product is reduced, increasing the company's liquidity and solvency for punctuality. By reducing in-process inventory, working capital needed to operationalize the plant is reduced and a "leaner" organization is obtained, in which the waste of overproduction, waiting time and inventories are reduced and controlled.

The use of drones quadcopter into a plant, at the stage of assembly and / or customization of products, as proposed in this paper, will involve a higher level of efficiency, effectiveness and productivity, based on the main characteristic that quadcopter shave, which is transporting materials in a 3D space, overcoming the limitation of the AGVs conveyors, hand trucks and others, which can only do on a flat surface or on the floor.

A model was designed to determine the size of a fleet of drones (UAV quadrotor) for the indoor transport in a plant, as well incorporating task rotation to select the most suitable drone for the task. In particular, it was shown that they can be implemented in a real plant, with real materials, to design a production planning.

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