Modeling kitting operations in a semi-robotic environment

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Abstract—With increasing components variety in mixed-model assembly lines, kitting is an innovative line feeding mode to reduce congestion at the border of the line. This paper proposes a preliminary mathematical formulation of kitting activities for a hybrid robot-operator kitting system that delivers parts to a mixed-model assembly line. Indeed, elementary kitting operations are formulated, based on field assumptions, by distinguishing operations performed by the robot and the operator. Based on the formulation provided, the perspective of future research is to refine the model and to use the formulations in order to propose a quantitative model that would optimize the performance of the hybrid system.

Keywords—line feeding; kitting operations modeling; efficiency

I. Introduction

Kitting is one of the line feeding approaches used for supplying parts to mixed-model assembly lines. It consists in preparing a collection or “a kit” of parts needed to assemble a specific end product (EP) which is sequenced on the assembly line (see [1] and [2]). Hence, parts are physically placed together in one or more containers referred to as “kitting boxes”, ready to be used on the assembly line.

Recently, due to technological improvements, hybrid robot – operator (human) kitting systems are introduced in industry. Indeed, both resources (robot and operator) working in series are involved in the preparation of kitting boxes. More specifically, the robot would start the kitting boxes preparation by delivering partially filled boxes. The operator then retrieves the preparation made by the robot and completes it with the remaining parts needed in the kit.

In such a system, one interesting question concerns tasks assigned to each resource and system performance assessment. In order to address this question, the elementary kitting operations have to be identified, by separating operations performed by the robot and by the operator. Then, assumptions stemming from discussions with company experts, technological solution provider and observations made in company current kitting processes enable to give a formulation of kitting operations modeled.

This paper is organized as follows: Section II gives a literature review related to the analyzed issue. Section III gives (i) an overview of the kitting system considered (ii) the formulations of operations carried out by the robot and the operator to deliver kits. Finally, we conclude the paper in Section IV.

II. Literature review

The literature on line feeding operations is expanding. However, most of existing models are developed for low-level picker-to-parts kitting systems where the picker is a human. The difference in our paper, is that we consider a hybrid kitting system working with both a robot and an operator.

In [1], authors develop the first descriptive model to quantify the trade-offs in material handling, space requirements in shop floors and work-in-process between two line feeding modes namely kitting and line stocking. In [3], authors develop a Mixed Integer Programming (MIP) that aims at minimizing the total labor cost by assigning components to line stocking or kitting (kit in its stationary form). Following a same approach for modeling operations related to line feeding, [4] introduces sequencing in addition to line stocking and kitting (traveling kit) and proposes an empirical assessment of operations’ costs associated with the three line feeding modes. The aim of their study is to characterize the conditions (values of each parameter) that make a line feeding mode the least costly. In [5], authors rely on optimization to assign components to each of the three line feeding modes studied in their previous work. References [3], [4] and [5] all model operating costs pertaining to the studied line feeding modes (costs at the point-of-use in the assembly line, internal transport costs, costs for kitting and supermarket replenishment costs). In [6], authors consider annual costs for kitting and give an extension to previously cited works by integrating investment and error costs in addition to administrative costs related to pick lists preparation. Modeling kitting errors in manual kitting can be found in [7]. In [8], authors investigate the impact of parts features, namely size and cost, on the choice between kitting, line stocking and JIT policy.

Other research papers have addressed issues on ergonomics and time efficiency related to order picking activities. Authors in [9], show the impact of packaging type and size, angle of exposure of storage bins, height of storage racks and part size on picking efficiency. In [10], authors focus on packaging and show that picking efficiency can be impacted by picking from different sections in a pallet. Regarding kitting systems, authors in [11], analyze 15 case studies from the automotive industry and identify the most impactful factors on man-hour consumption. The parameters that have the biggest impact on kitting efficiency appear to be the type and size of bins, the type and design of storage racks, the batch size and the size of the picking area.

Limited research exists on the design and performance evaluation of robotic kitting systems. In [12], design factors and criteria to implement an effective robotic kitting system are also developed in accordance with the design process steps. Based on simulations, [13] shows quantitative results for the performance of six different robotic kitting configurations in terms of throughput, average time a kit spends in the system, and robot utilization.

The work presented in this paper is in the continuity of [14] that proposes a first formulation of operations performed by a robotic kitting cell in a given layout and a set of components already assigned to the robot. The current paper considers hybrid kitting system where a robot works in series with an operator to deliver kits. We propose the formulation of elementary kitting operations for both the robot and the operator, under the assumption of components are already assigned to either the robot or the operator. To our knowledge, this is among the first works that introduce the use of a robotic arm in existing manual kitting processes.

III. Modeling kitting operations

This section aims at giving the formulation of elementary activities taking place in the hybrid kitting system.

A. Hybrid kitting system description

As showed in Fig. 1, the hybrid kitting system involves a robot working in series with an operator. They prepare and deliver a kit (or a collection) of parts for each end product (EP) to be assembled. Parts needed by an EP are placed in kitting boxes before they are sent to the assembly line. We use the term “box” when referring to a kitting box. Physically, the size of a box is adapted to receive all parts needed at the same point-of-use (in the assembly line). For example, parts intended to be assembled on the left side of an EP are grouped into one box to ease their positioning close to the point-of-use. In Fig. 1, locations of parts associated with one kitting box are represented by the same color which means that in our case, we have 6 different kitting boxes (both resources deal with all box types). Physically, boxes are compartmented and the number and arrangement of compartments are specific to each box according to the number and shape of received parts.

In the robotic kitting area, components intended to be in the same box are grouped in zones (denoted as Zone 1 to 6 in Fig. 1) following a class-based storage policy as represented in Fig. 1. Hence, each box is of a certain “type” and is denoted as box 1 to 6 following the numbering of storage zones.

In the manual kitting area, parts are assigned following a volume-based strategy where highly-demanded components are located close to the buffer (i.e. close to the input/output point of the area). As we can see in Fig. 1, SKUs intended to be in a certain box are spread over the entire manual kitting.

Actually, components to assemble may have one (the parent component) or several variants based on the same component definition. Each EP uses one variant of a component. Those variants differ on one or more characteristics and have a unique SKU. When we speak about “parts” we refer to pieces of an SKU. As in [4], [7], [8] and [13], we consider elements at the variant (SKU) level since variants of the same component type may have different usage rates. The usage rate of a particular SKU is the percentage of EPs that use this SKU.

Each SKU is stored in a dedicated bin that may be of different sizes, materials and be foldable or not. Due to quality and transportation concerns, parts of an SKU may need specific inner packaging elements (plastic bags, cardboard and/or foam interlayers, dividers) to prevent damage to parts.

The robot starts by picking parts and placing them directly on a moving conveyor that drops them within large trays downstream the robotic kitting area. After that, the operator retrieves those parts, places them into boxes and completes the boxes with the remaining parts in their kitting area.

In our study, we only focus on operations that take place in the hybrid kitting system which is assumed to work at full speed without any failure (especially for the robotic kitting area). We also implicitly assume that everything works without failure outside the hybrid kitting system which means for instance that the replenishment of parts, the evacuation of empty bins (accumulated on evacuation ramps) and inner packaging elements are regularly carried out by external resources. Moreover, as a first approach, we assume that downstream the robotic kitting, the buffer (trays loop) does not constitute a bottleneck since parts are systematically collected by the operator to make trays available for a new preparation.

Fig. 1 presents a particular case of a hybrid kitting area where 6 boxes can be prepared for an EP. In fact, there are basic EP models that need common components while others with higher diversity, due to more design options, need more components (in addition to those of basic EPs). In terms of preparation, basic EPs only need 4 boxes to hold their parts while specific EPs need all the 6 boxes (boxes 5 and 6 being specific).

To prepare kits, different picking strategies can be adopted. In the single picking approach, a preparation cycle consists in picking parts associated with one EP. In the case of batch picking, the system prepares multiple EPs in one picking list.

1) Characteristics of the robotic kitting area

The robotic kiting area has a single narrow-aisle with 2-levels gravity flow racks on each side. Those racks are assumed to be of the same length with only one evacuation ramp for depleted bins per rack. The number of levels is limited to allow a better accessibility to the robot.

The moving conveyor belt, on which the robot places the picked parts one after the other, traverses the picking aisle so that parts are dropped within trays circulated in a closed loop. Each tray receives parts from one and only one class. Thus, to preserve parts integrity, the robot has to place the heaviest parts first. To make this easier, components are stored in each zone (class), following a dedicated storage strategy and a particular order from heaviest parts to more fragile ones.

2) Characteristics of the manual kitting area

The manual kitting area has 4-levels gravity flow racks. Unlike the robotic kitting area, the top level is entirely dedicated to the evacuation of bins.

The operator starts a kit preparation by loading, on their cart, empty boxes consumed at the assembly line and returned to the kitting area.

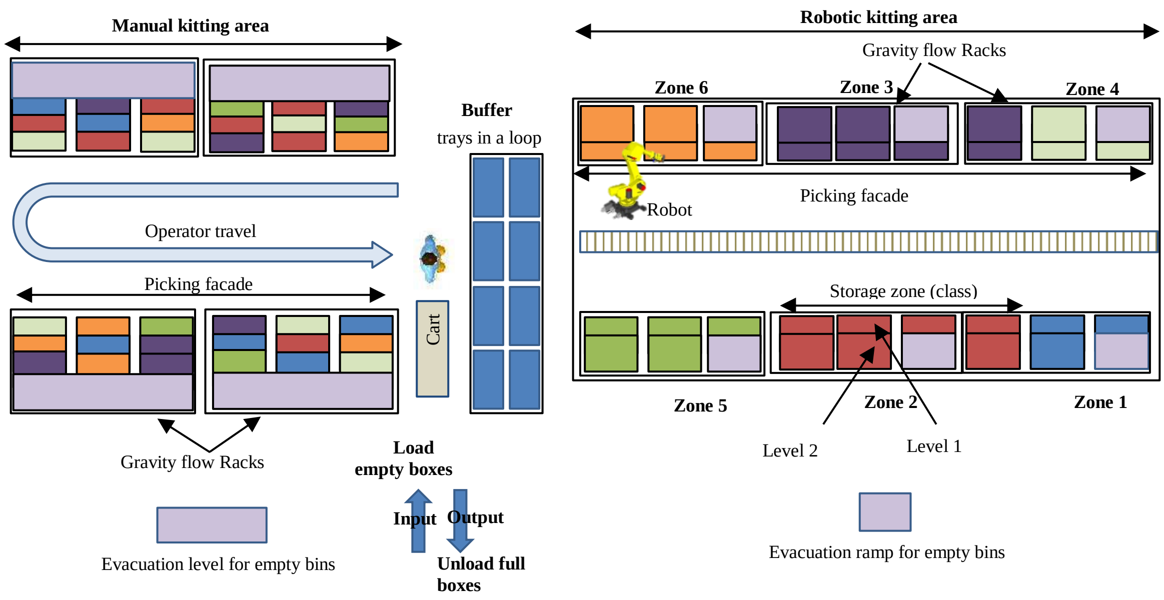

Fig. 1. Hybrid kitting system

After that, the operator retrieves, from each tray at a time, the preparation of the robot and places it in the destination box. For example, parts picked by the robot for box type 1 and held in one tray are retrieved by the operator and positioned in compartments of one box of type 1.

To complete each box, the operator travels to pick parts in their area and places them within the associated box. To help an operator in their tasks, there is a pick-to-light system that indicates the needed SKUs' location using light displays.

B. Formulation of kitting operations

Based on company common practices, discussions with experts and observations made on current kitting areas, the formulation of kitting cycle time components is developed in this section. Due to paper space limitations, details pertaining to the assumptions would not be developed.

Indeed, the robot and operator cycle times are the sum of elementary activities they perform each to prepare a kit of parts for a batch of EPs.

In more details, to give the formulation of kitting operations, we consider a representative preparation cycle over a reference time period. Hence, starting from picking lists in the reference period, we propose a calculation of an average cycle time for each resource (robot or operator) based on SKUs' usage frequency and average number of parts to pick per SKU. Indeed, with each EP to produce is associated a picking instruction (or list) that lists all SKUs needed in the kit and gives, for each SKU, the amount of parts to pick. Let i be the SKUs index. Thus, the usage rate τ_i of SKU i is the percentage of EPs in the reference time period that use this SKU. The average number of parts n_i to pick for SKU i is calculated by summing, for this particular SKU, BOM (Bill Of Material) coefficients of all EPs produced in the reference period and dividing the result by the number of EPs that use this SKU.

Each SKU is handled either by the robot or the operator. We denote the SKU index i, for SKUs assigned to the robot (i = 1.. C_R) and the SKU index j, for SKUs assigned to the operator (j = 1..C_O).

Hence, the formulation of the robot cycle time is done for a set of C_R and C_O SKUs supposed to be already assigned respectively to the robot and the operator.

For the remaining of the paper, indexes and notations we adopt for the formulation of elementary operations' duration are given below:

- i, j: SKUs index;
- C_R : total number of SKUs assigned to the robot
- C_O : total number of SKUs assigned to the operator
- BS: batch size which is the number of EPs to prepare simultaneously i.e. a single picking strategy is adopted when BS = 1;
- K : number of common boxes per EP;
- K_{max} : maximum number of boxes per EP;
- We display "R"; which refers to the robot; and "O"; which refers to the operator; as superscripts in the formulation of activities done by both the robot and the operator.

C. Modeling the robot cycle time

The **robot cycle time** is an aggregation of all elementary activities that the robot performs to prepare a kit of parts for each batch of *BS* EPs. Equation (3) expresses the total cycle time of the robot.

$$CT^R = T^R_{pick/place} + T_{vision} + T_{tool} + T^R_{trav} + T^R_{B\_rem} + T^R_{pack\_rem} \quad (3)$$

$T^R_{pick/place}$ is the total **pick and place time**; T_{vision} is the total **image acquisition time** of storage bins content; T_{tool} is the total **grasping tool changing time**; T^R_{trav}, the total **travel time**; $T^R_{B\_rem}$ is the total **time needed to return back empty bins** (pick bins, move them and place them on the evacuation ramp) and $T^R_{pack\_rem}$ is the **total time to remove inner packaging elements**.

Equation (4) gives the total **pick and place time** for each preparation cycle.

$$T^R_{pick/place} = \sum_{i=1}^{i=C_R} [(1+\pi_i) * T^R_i * BS * \tau_i * n_i]. \quad (4)$$

T^R_i and π_i are respectively the time needed for the robot to pick and place a single part of SKU *i* and the proportion of failed picks associated with each SKU *i*. The failure rate provides information on the ability of the robot to properly pick parts at the first attempt. τ_i and n_i are respectively the usage rate of SKU *i* and the average number of parts needed for SKU *i*. Equation (5) expresses the average number of parts n_i.

$$n_i = \frac{\sum_{EP} BOM\_Coefficient_i}{Total\ number\ of\ EPs\ that\ use\ the\ SKU\ i\ in\ the\ reference\ period} \quad (5)$$

Image acquisition consists in taking a picture of bins' content. Afterwards, the image is analyzed by the robotic kitting system to identify and propose potential parts to pick (generally parts on top). We assume that a part of this operation may be done as a background task i.e. in "hidden time" while the robot is traveling or rotating to drop a part on the conveyor. This is given in (6) as follows:

$$T_{vision} = \sum_{i=1}^{i=C_R} (1 - p) * BS * \tau_i * n_i * T_{cap} \quad (6)$$

T_{cap} is the technological time needed for a single acquisition and *p* is the part of the technological time executed in hidden time. Here, T_{vision} may be zero if $p = 100\%$ i.e. if the acquisition is completely executed in hidden time.

The average **time to travel** to pick all parts required for the preparation of *BS* EPs is given in

$$T^R_{trav} = \sum_{i=1}^{i=C_R} \left[\frac{2*BS - (F^R - Ps^R)}{Ps^R} * \frac{B_i}{v_R * N^R_{levels}} + BS * \tau_i * T^R_s \right]. \quad (7)$$

The robot travel time is given by the covered distance during a preparation cycle divided by the robot's velocity v_R as in (8) and the time needed to stop in front of bins as expressed by (9).

$$\frac{2*BS - (F^R - Ps^R)}{Ps^R} * \frac{\sum_{i=1}^{i=C_R} B_i}{v_R * N^R_{levels}} \quad (8)$$

The covered distance is given by the total number of roundtrips made by the robot $(1/Ps^R)*(2*BS - (F^R - Ps^R))$ multiplied by the total picking façade length $\sum_{i=1}^{i=C_R} B_i / N_{levels}$ as in (8).

F^R and Ps^R are respectively the number of façades in the robotic kitting area and the number of façades from which the robot picks parts at a time to prepare a box. B_i and N^R_{levels} are respectively the size of a storage bin that contains parts of SKU *i* and the number of storage levels (in a rack) in the robotic kitting sub-systems.

In each storage zone, the robot performs *BS* travels to pick parts in addition to $(BS - (F^R - Ps^R))$ travels to go back to the starting point of each storage zone which gives a total of $2*BS - (F^R - Ps^R)$ travels in a storage zone. This is equivalent to $2*BS - (F^R - Ps^R)$ travels along the robotic kitting aisle.

For example, in a batch picking strategy ($BS > 1$), the robot picks all parts needed by an EP in a storage zone before moving to the next EP of the batch. If we consider a batch of four EPs, the robot starts moving inside the blue storage zone (in Fig. 1) to pick parts for EP 1, then he goes back to the beginning of this storage zone (to pick heavy parts first) to travel again and pick parts for EP 2 and so on until EP 4. At the end of this batch picking preparation cycle, the robot has prepared four kits.

$$\sum_{i=1}^{i=C_R} BS * \tau_i * T^R_s \quad (9)$$

The expression $BS * \tau_i * T^R_s$ in (9) refers to the average stopping time in front of the storage location of SKU *i* calculated for each batch of EPs.

Equation (10) gives the average **tool changing time**.

$$T_{tool} = T_{tool\_chg} * \sum_{i=1}^{i=C_R} BS * \tau_i. \quad (10)$$

T_{tool_chg} is the technological time needed to perform a single tool change.

Equation (11) gives the average **time to remove bins** $T^R_{B\_rem}$.

$$T^R_{B\_rem} = (T_{tool\_chg} + T^R_B + T_{Bm} + 2*T^R_s) * \sum_{i=1}^{i=C_R} \frac{BS * \tau_i * n_i}{P_i} \quad (11)$$

T_{tool_chg} is the time needed for a single tool change. The value of T_{tool_chg} considered in (11) is equal to the one in (10). T^R_B and T_{Bm} are respectively the time required to the robot for removing a bin from its storage location and placing it on the evacuation ramp and the time needed for moving the bin from its storage location to the evacuation ramp. T^R_s is doubled to include the first stop when the robot removes the bin and the second stop in front of the evacuation ramp. P_i is the number of parts of SKU *i* contained in a bin.

The average **time to remove packaging elements** (apart from plastic bags) is given by

$$T^R_{pack\_rem} = T_{tool\_chg} * \sum_{i=1}^{i=C_R} (CL_i * T^R_{CL} + D_i * T^R_D) * \frac{BS * \tau_i * n_i}{P_i}. \quad (12)$$

T_{tool_chg} is the time needed for a single tool change. It is also equal to T_{tool_chg} in (11) and (10). We assume that whatever the task (changing the tool to pick a part or a bin a packaging element), a tool change requires the same amount of time. T^R_{CL} and T^R_D are respectively the time to pick and place, on the conveyor, a cardboard interlayer sheet and a divider. CL_i and

D_i are respectively the number of cardboard interlayer sheets and the number of dividers contained in a bin of SKU i.

D. Modeling the operator cycle time

The **operator cycle time** is an aggregation of all elementary activities that the operator performs to prepare a kit of parts for each EP of the BS EPs in the batch. Equation (13) gives the total cycle time of the operator.

$$CT^O = T_{load} + T_{retrieve} + T^O_{pick/place} + T^O_{trav} + T^O_{B\_rem} + T^O_{pack\_rem} + T_{unload} \quad (13)$$

T_{load} is the total **time to load empty boxes** on the kitting cart when starting the preparation; $T_{retrieve}$ is the total **time to retrieve parts** prepared by the robot before completing with the remaining SKUs; $T^O_{pick/place}$ is the total **pick and place time**; T^O_{trav} is the total **travel time**; $T^O_{B\_rem}$ is the total **time to return back empty bins** (pick bins, move them and place them on the evacuation ramp); $T^O_{pack\_rem}$ is the total **time to remove inner packaging elements** and T_{unload} is the total **time to unload filled boxes** with parts from the kitting cart.

The average **total time to load empty** boxes T_{load} is given by

$$T_{load} = (BS * T_{kb} + T^O_s) * [K + \pi_{rich\_EP} * (K_{max} - K)]. \quad (14)$$

T_{kb} is the time required to the operator for handling one box. The proportion of rich EPs over the reference period and the average number of boxes to prepare per EP are given respectively by π_{rich_EP} and $[K+\pi_{rich\_EP} * (K_{max}-K)]$. A time to stop in front of each box type (before loading) is also considered.

Time to retrieve parts prepared by the robot is given in

$$T_{retrieve} = (BS * T_{ret} + T^O_s) * [K + \pi_{rich\_EP} * (K_{max} - K)]. \quad (15)$$

T_{ret} is the estimated time to retrieve all parts contained in a tray and place them inside the appropriate box.

Equation (16) expresses the average **pick and place time**.

$$T^O_{pick/place} = \sum_{j=1}^{j=C_O} \frac{BS * \tau_j * n_j}{\theta_j} * T^O_j. \quad (16)$$

T^O_j is the time required to execute a single movement of picking parts of SKU j and placing them in the boxes that are on the cart. θ_j is the number of parts the operator picks simultaneously. It would correspond to the minimum between the number of parts of SKU j needed, i.e. $BS * \tau_j * n_j$ and a_j the maximum number of parts the operator can pick simultaneously as in (17). The value of a_i depends on the size (small, medium, large) of SKU j and so does T^O_j.

$$\theta_j = min\,(BS * \tau_j * n_j,\ a_j) \quad (17)$$

The average **time to travel** along the aisle to pick all parts required for a set of BS EPs is given when $BS = 1$ by

$$T^O_{trav} = \sum_{j=1}^{j=C_O} \left(\frac{2 - (F^O - Ps^O)}{Ps^O} * \frac{B_j}{v_O * N^O_{levels}} + \tau_j * T^O_s \right). \quad (18)$$

For batch picking i.e. for $BS > 1$, the average **travel time** needed to prepare a batch of BS EPs is

$$T^O_{trav} = \sum_{j=1}^{j=C_O} \left([K + \pi_{rich\_EP} * (K_{max} - K)] * \frac{2 - (F^O - Ps^O)}{Ps^O} * \frac{B_j}{v_O * N^O_{levels}} + \tau_j * T^O_s \right). \quad (19)$$

Indeed, for BS (>1) EPs in the batch, the operator prepares BS boxes of one box type (common or specific) at a time. Hence, the operator performs $[K+\pi_{rich\_EP} * (K_{max}-K)]$ travels to prepare all $[K+\pi_{rich\_EP} * (K_{max}-K)]*BS$ boxes needed for a batch.

The operator travel time can be divided into two terms. Firstly, the covered distance during a preparation cycle divided by the operator's velocity v_O as in (20) for $BS = 1$ and in (21) for $BS > 1$. Secondly, the time needed to stop in front of bins as in (22).

$$\frac{2 - (F^O - Ps^O)}{Ps^O} * \frac{\sum_{j=1}^{j=C_O} B_j}{v_O * N^O_{levels}} \quad (20)$$

$$[K + \pi_{rich\_EP} * (K_{max} - K)] * \frac{2 - (F^O - Ps^O)}{Ps^O} * \frac{\sum_{j=1}^{j=C_O} B_j}{v_O * N^O_{levels}} \quad (21)$$

The covered distance is given by the total number of roundtrips $(2 - (F^O - Ps^O)/Ps^O)$ when $BS = 1$, as in (20), or $(2 - (F^O - Ps^O)/Ps^O) * [K+\pi_{rich\_EP} * (K_{max}-K)]$ roundtrips when $BS > 1$, as in (21), multiplied by the total picking façade length which is given by $\sum_{j=1}^{j=C_O} B_j / N^O_{levels}$ in both (20) and (21).

F^O and Ps^O are respectively the number of façades in the manual kitting area and the number of façades from which the operator picks parts at a time to prepare a box or multiple boxes (in case of batch picking). B_j and N^O_{levels} are respectively the size of a storage bin that contains parts of SKU j and the number of storage levels (in a rack) in the manual kitting sub-system.

As the operator only stops one time to pick all parts needed for a SKU, the average stopping time of the operator in front of the storage location of SKU j is given by $\tau_j * T^O_s$ as in (22).

$$\sum_{j=1}^{j=C_O} \tau_j * T^O_s \quad (22)$$

Equation (23) gives the average **time to remove bins**.

$$T^O_{B\_rem} = \sum_{j=1}^{j=C_O} (T^O_B + T_{fold} * Fold_j) * \frac{BS * \tau_j * n_j}{P_j}. \quad (23)$$

T^O_B is the time needed by the operator for removing an empty bin from its storage location and placing it on the evacuation ramp. In addition, if the bin is foldable, we add the second term $T_{fold} * Fold_j$ in (23) that corresponds to the time needed for folding a single bin. Not all bins are foldable that is why we introduce the parameter $Fold_j$ that equals to 1 when the bin, where SKU j is stored, is foldable and equals to zero otherwise.

Equation (24) expresses the average time to remove inner packaging elements.

$$T^O_{pack\_rem} = \sum_{j=1}^{j=C_O} (CL_j * T^O_{CL} + FL_j * T_{FL} + D_j * T^O_D + Pb_j * T_{pb}) * \frac{BS * \tau_j * n_j}{P_j} \quad (24)$$

The total time needed to remove the packaging elements is given by the time to remove all elements in a bin multiplied by the number of bins consumed during a preparation cycle which is $BS*\tau_j*n_j/P_j$.

T^O_{CL}, T_{FL}, T^O_D and T_{pb} are respectively the time needed to evacuate (in a trash bin) a cardboard interlayer, the time needed to evacuate a foam interlayer, the time needed to evacuate a divider and the time needed to evacuate a plastic bag.

For each bin of SKU j, CL_j, FL_j, D_j and Pb_j are respectively the number of cardboard interlayers, the number of foam interlayers, the number of dividers and the number of plastic bags.

The average total **time to unload the filled boxes** (from the cart), before sending them to the assembly line, is given by

$$T_{unload} = (BS*T_{kb}+T^O_s)*[K+\pi_{rich\_EP}*(K_{max}-K)] \quad (25)$$

T_{kb} is the time required to the operator for handling a box. We assume that this time is the same for loading and unloading a box. The operator unloads all boxes of a box type on a dedicated gravity flow lane. Thus, the operator needs to stop in front of each lane (i.e. for each box type).

IV. Conclusion and perspectives

The contribution of the paper is twofold. Firstly, by considering a hybrid kitting system, we clarify the activities performed by each resource (robot and operator) involved in the system. Second, based on company practices, discussions with experts and field observations, we propose a first mathematical formulation of kitting operations that take place in the system, for each resource.

The modeling approach developed in this paper is generic and can be used for analyzing other possible configurations (e.g. two robots in the robotic area, one for picking parts, the other for placing them into boxes, in order to reduce the recurrent operations of the operator). This is indeed possible by adapting the formulations provided in this paper to the new configuration of interest.

Besides, based on elementary kitting operations formulation, our future objective is to build a refined model that would optimize the performance of the hybrid system. We argue that the current paper provides an interesting relevant basis for the development of such an optimization model.

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