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A MATHEMATICAL MODEL TO ASSESS THE PERFORMANCE OF A ROBOTIC KITTING SYSTEM IN AN ASSEMBLY PLANT

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ABSTRACT: *Order picking is the operation that consists in retrieving, from the storage locations, the parts needed for the assembly of final products. Making a ready-to-delivery collection or kit of parts is called Kitting. To improve this operation's performance, flexible robotic systems can greatly help industrials. Indeed, the technological advances that have been achieved in the recent years, in robotics and artificial intelligence make it possible to deal with a large range of items to be picked despite some remaining constraints related to components diversity and parts characteristics. In this paper, we study a robotic kitting system running with a robot arm mounted on a rail system and traveling along a narrow-aisle to pick parts. Through a modeling of elementary kitting operations that the robot performs (pick and place, travel, tool changing, etc.), we aim at evaluating the performance of the robotic kitting system in terms of cycle times. This study conducted with a manufacturer in the context of an ongoing project on automation of kitting operations, can help him to assess the robotic area performance in a given configuration (layout, picking policy, etc.).*

KEYWORDS: *Cycle time, Parts feeding, Robotic Kitting, Assembly.*

1. INTRODUCTION

Over the past decades, many sectors, and especially manufacturing, have undergone a mutation passing from mass production to mass customization to satisfy customers' changing demand. This led to a higher diversity of components and thus, a greater number of parts stored along the border of the assembly line (BoL) with a significant impact on assemblers' productivity (more traveling, more time to fetch parts, etc.).

To clear the BoL from cumbersome racks and unit loads, kitting is increasingly being deployed as an alternative to line stocking or sequencing as a new approach to feed the assembly line[1]. The first one (line stocking) consists in storing parts near their point-of-use at the BoL while sequencing consists in putting in a single container all variants of a component, according to the production sequence, and bringing it to the BoL. According to Bozer and McGinnis (1992), kitting is "the practice of delivering components and subassemblies to the shop floor in predetermined quantities that are placed together in specific containers". The delivery of kits to the point-of-use is carried out in keeping with the production sequence.

The current trend in materials feeding is to enlarge the range of kitted parts to draw closer to what some car manufacturers call "full kitting" i.e even up more than 90%[2] of delivered components to the BoL. Indeed, not all parts should be delivered into kits. It is recommended, according to Sali *et al.*, 2014, to keep, stored on line side, voluminous components with low diversity while the sequencing and the kitting modes would be more convenient respectively for voluminous components with high diversity and small components with a large number of variants.

From the definition of Bozer and McGinnis (1992), we can see the main benefit associated with kitting which is to maximize the value-added share of the assembler's work by eliminating waste (time to fetch parts, travel distances, etc.). However, this leads to transfer these non-value-added operations upstream the assembly line i.e. in the picking areas. To improve picking areas performance, automation of order picking operations is a solution considered in different industries[3]. Actually, automated kitting as an alternative to manual kitting may be considered as a disruptive innovation that will have a huge impact on the final users (manufacturers, e-commerce

[1] Christopher Ludwig, "Automotive Logistics - Redrawing the line side", http://www.automotivelogisticsmagazine.com/opinion/redrawing-the-line-side, 24 February 2014.

[2] Christopher Ludwig, "Nissan North America part 3: The search for southern comfort", http://automotivelogistics.media/intelligence/nissan-north-america-part-3-the-search-for-southern-comfort, 18 December 2015.

[3] Supply Chain Magazine, "Picking 100% automatisé: les prémices d'une mutation", http://supplychainmagazine.fr/TOUTE-INFO/Archives/SCM091/DOSSIER-91.pdf, January-February 2015.

actors, etc.) while contributing to develop leading-edge robotics technologies.

Within the context of an ongoing project on kitting operations automation launched by a manufacturer of customized products, this study aims at evaluating the performance of a robotic kitting cell with a robot arm running on a rail system along the picking aisle to pick parts. The design of such a system is a challenge for automation solution providers and requires a deep knowledge and expertise in robotics and artificial intelligence to deal with parts' diversity. It is equally important, to rise to the challenge, to ensure that the robot meets the cycle time requirements. From the assembly point of view, it is the average time between two successive final products (FP). Since kitting operations are pulled by the assembly line, the robotic kitting system cycle time (i.e. average time between two successive kits) must be at most equal to the assembly line one to prevent time losses at the line.

In this paper, we extend the existing literature on kitting operations by developing a mathematical model of robotic kitting operations which aims at evaluating the performance in terms of cycle time.

To do so, the kitting process is first split into elementary operations based on observations made on the actual manual kitting process and on expert views on how these operations would evolve when the kitting robot will be introduced. The duration related to each elementary operation is then formulated on the basis of relevant assumptions. Finally, the cycle time is obtained.

This paper is organized as follows: Section 2 gives some contextual elements on the industrial environment where this study is developed. Section 3 gives an overview of the related literature. The robotic kitting system layout is presented and operations carried out by the robot are detailed in Section 4. Section 5 provides the mathematical model of the cycle time with a description of each term. Finally, we conclude the paper in Section 6 by suggesting some future research perspectives.

2. CONTEXT OF THE STUDY

As raised in the introduction, actors from different industries show a growing interest for order picking automation. This is especially true for the car industry (Dirk *et al.*, 2015) which is already familiar with automation since it has already taken the largest part of the tasks in stamping and in body in white assembling.

Although today's state-of-art industrial robots can be very accurate, operations of picking parts and placing them into kits are still widely performed employing operators due to parts diversity (shape, weight, material, packaging,…). Indeed, dealing with such a variability, robotic kitting systems have to be as flexible as human counterparts (i.e adaptive to the different parts' characteristics) to meet the required performance in terms of cycle time.

The expressed industrial need on kitting operations automation is part of a large-scale project undertaken by the manufacturer we work with to improve the overall industrial performance of some plants that have high operating costs. This resulted in identifying a set of potential operations to improve (through automated and non-automated solutions) among which we have kitting. Thus, to stay competitive, plants have recourse to automation of non-value added tasks especially those in kits preparation as previously mentioned.

At the end, the solution for picking parts has to break-even within the set threshold and should give potential performance gains in terms of manual non-value added tasks reduction of at least 20 to 30%.

Existing automated order picking systems are generally parts-to-picker systems which allow to increase performance without completely replacing pickers. One of these solutions is called Automated Storage and Retrieval System (AS/RS) that allows to automatically store and retrieve full cases or unit loads for order picking needs. This type of solution is only suitable for products that have high consumption rates. Moreover, AS/RS systems require a substantial investment with a long-term return on investment. A second alternative is the use of a mobile robot (Automated Guided Vehicle (AGV)) to bring shelves with the needed items directly to the picker. This mobile robot positions itself underneath a shelf, raises it off the ground and then navigates among other mobile robots to reach the picking area.

In order to perform full automated order picking in variable environments such as e-commerce or manufacturing, the previously mentioned systems have to be coupled with a performant piece picking robot. Those solutions are not considered acceptable by the manufacturer we work with as they are highly expensive with a very long-term return on investment.

To conclude the description of the existing environment, we can say that as far as we know, nothing with a high degree of flexibility exists on the market yet. There are mainly robotic picking applications for homogeneous items which brings both sectors (e-commerce and manufacturing) along with other actors to conduct research on automated kitting to take it to a higher level. This work joins this dynamic of robotic kitting development.

3. LITERATURE REVIEW

The existing literature has widely addressed issues related to order picking systems. Despite the fact that over 80% of order picking systems in Western Europe are low-level picker-to-parts systems, high-level systems and AS/RS (generally parts-to-picker systems) are the most studied ones in the literature (de Koster *et al*, 2005). This excludes performance evaluation of robotic kitting using a robot arm to perform kitting tasks which very few papers focus on.

Basically, in a picker-to-parts system, the picker moves along the aisles to pick parts while in a parts-to-picker configuration, an automated system is used to retrieve parts from their storage locations and bring them to a stationary picker.

To be aligned with the objective of this paper, we consciously restricted our literature review to the design, organization and performance evaluation of picker-to-parts kitting systems using operators or robots. We first start by manual kitting for which an extensive literature exists.

Dallari *et al.*, (2009) extends a previous work of Yoon and Sharp (1996) and proposes a top-down design methodology of kitting with sequential steps. In particular, a statistical analysis - based on a significant survey panel of 48 distribution centers in Italy - showed that the choice of the most suitable order picking system is mainly related to the number and size of items as well as the number of order lines per day.

Selecting an option among existing order picking systems can be made according to the classification into human-operated and machines-operated (including robot picking) picker-to-parts or parts-to-picker systems given in (de Koster *et al.*, 2005; Dallari *et al.*, 2009).

According to the existing order picking systems classification, the kitting system we study is a low-level picker-to-parts system with 2-levels gravity flow racks.

At the operating level, the main decisions when designing a kitting system are: layout design, storage assignment strategies, routing methods, batching policies and work organization. The demand pattern has also to be considered as an important factor (see Petersen, 1999 and Le-Duc and de Koster, 2005).

To improve order picking efficiency through optimization of these parameters, several algorithms and heuristics dealing with either parameter separately or highlighting the effect of two or more parameters (see Petersen and Aase, 2004) have been developed.

Routing policy which is the sequence in which parts are to be picked, is the first issue that has been widely treated in the literature. The main objective for routing problems is to minimize the average travel distance which is linearly related to the travel time in low-level picker-to-parts with narrow-aisle systems (Caron *et al.*, 1998; Le-Duc and de Koster, 2005) as is the case in our system. Theory on batching policy (or picking-by-item) where parts for multiple orders (final products in our case) are picked simultaneously to reduce the traveling times, can be found in, for example, Parikh and Meller (2008).

Kitting operations modeling with the objective of minimizing the total labor cost can be found in studies on choosing the best line feeding modes. For example, Limère *et al.* (2012) develop a Mixed Integer Programming (MIP) that aims at minimizing the total labor cost by assigning components to either line stocking or kitting (stationary kit). Sali *et al.* (2014) introduce sequencing in addition to line stocking and kitting (traveling kit) and assess operations' costs associated with the three line feeding modes to characterize the conditions that make a line feeding mode the least costly in a given assembly configuration. Caputo *et al.*, (2015a), consider annual costs for two line stocking modes (bulk and batch supply) and give an extension to previously cited works by including error costs. The same is done for kitting in Caputo *et al.*, (2015b). Work dedicated to modeling errors in kitting can only be found in Caputo *et al.*, (2015c). It actually highlights errors related to kitting and gives a tool to estimate them.

Concerning robotic kitting, a limited research exists on the design and performance evaluation of robotic kitting systems. It has to be noted that papers that address robotic kitting from its technical aspects (manipulators, motion, vision, end-effectors…) are not taken into account in this section.

A design method of robotic kitting with sequenced steps is given in Tamaki and Nof, (1991). Design factors and criteria to implement an effective system are also developed in accordance with the design process' steps. A special focus is made on robot hardware design by taking into account kitted parts information, robot workstation environment and kitting task process. This particularly allows to feed a selection methodology of kitting robot manipulator also described in this paper.

Performance evaluation of robotic kitting systems can be found in Sellers and Nof, (1989). This work shows quantitative results for the performance of six different robotic kitting configurations in terms of throughput, average time a kit passes in the system, and robot utilization. According to results based on 88 simulation runs made with a robotic work cell simulator, the most favorable robotic kitting system is found to be the miniload on-board robot/ASR kitting system. As claimed by Sellers and Nof, (1989), the results are case-specific and cannot be generalized.

This allows us to enrich the previous studies with new aspects related to robotic kitting, i.e. the evaluation of the cycle time associated with robotic kitting operations. For this purpose, unlike previously developed models for manual kitting operations, we consider robotic kitting operations that we split into elementary tasks. Following this methodology, we aim at evaluating the performance of the robotic cell in terms of cycle time.

4. ROBOTIC KITTING SYSTEM

In this section, we start by describing the layout of the picking area where the robot operates. Then, we briefly present the hardware associated with the robotic cell. We then summarize the specificities and constraints related to parts to be picked by the robot. Finally, we describe the detailed operating mode and the main assumptions made regarding the cycle time calculation.

4.1. KITTING AREA LAYOUT

The robotic kitting area has a single narrow-aisle with two gravity flow racks on each side. All racks (and thus the two facades) are of the same length and have the same number of equal-sized lanes while classes may be of different sizes (see Figure 1). Either lane of the second level is independent and can be turned into an evacuation ramp (see Figure 2) used to return back empty storage bins.
For the remainder of this paper, we assume that there is only one evacuation ramp per rack.

Concerning the parts storage policy used in the kitting area, we assume that parts initially contained in bins are grouped into classes using a class-based storage policy (classes are represented in Figure 1 with a different color for each class). These classes are defined according to parts point-of-use on the assembly line. For example, in electronic assembly plants we would group in the same storage zone, parts used for the printed circuit board assembly. Moreover, classes may have different sizes depending on the number of parts associated with each class.

A continuously 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 boxes circulated in a closed loop. Thus, to preserve parts integrity, the robot has to put heaviest parts first on the conveyor. Components are then stored in each zone (class), following a dedicated storage strategy and a particular order from the heaviest parts to the lightest and more fragile ones.

4.2. ROBOT CHARACTERISTICS

As seen in the literature, the first and crucial problem to consider when designing a robotic kitting system is the choice of a suitable hardware which includes:

- Robot arm or manipulator: for optimal accessibility, the robot type and size must be adapted to bins' and racks' dimensions to easily reach all parts. It should also have a load capacity adapted to parts weight. Mounted on a linear axis, the robot travels along the two facades to pick items.

- Vision/Cameras: are what allows the system to visualize its environment i.e bins dimensions, shape, size and color of parts. There are four cameras to capture the images of the content of the bins, one camera being dedicated to each rack level. On either picking facades the two cameras are mounted, above bins, on a linear axis. As they are mobile, cameras may be used to anticipate the next part image acquisition.
  From field observations, some components made of translucent material or packed individually in a translucent plastic bag are impossible to visualize by cameras. Thus, these components are not eligible to be picked by the robot.
  Moreover, a control of surrounding light is recommended for parts made of shining materials as they may also be difficult to visualize.

- End-effector: is the part mounted on a robot arm that directly interacts with the environment (parts, bins, bins separators…). As it is case-specific, an end-effector may be any type of tool. In our particular application, the robot needs a set of different gripping tools owing to the important number of different components and variants of components.
  The system is designed so that an adapted gripping tool is associated with each part.
  Types of grippers that can be used are: vacuum (using suction cups) grippers, magnetic grippers, pneumatic or servo-electric (2-jaw parallel or angular) grippers.
  Thus, a great attention is needed when designing an end-effector since it has to be as compact as possible and make as quickly as possible the potential tool changes. There is a trade-off between having a massive end-effector with many tools (which means reduced accessibility to parts) and then selecting one tool by rotation or having a compact end-effector and selecting between independent tools placed on a support.
  In our case, a dedicated support that holds the set of tools needed to pick parts, is placed on the robot's platform which means no travel time is needed to grasp the required tools.

There are also other sensors that allow the robot to collect information about its environment for detecting and avoiding collision with bins. All devices are controlled by the robot controller which is the "brain" of the system. It gives real time instructions to control the robot motion, to choose the appropriate gripping tool, etc.

4.3. CHARACTERISTICS OF PARTS TO BE PICKED

Based on field observations, parts' characteristics concern both the way parts are arranged in the bins and the specificities of components.

Regarding bins' content, parts can be either arranged or put inside the bin in bulk:

- Arranged parts: can be placed on thermoformed plastic, stacked or individually (or not) inserted into partitions formed by crisscross separators.
- Bulk parts: separated or entangled parts, parts in layer bulk (with horizontal separators).

In both configurations, parts' separators or dividers (that are made of different matters, e.g. cardboard, foam, plastic and have different shapes, e.g. sheet, crisscross) are used to preserve fragile components from part-on-part contact.

The diversity of parts to be picked stem from various characteristics such as:

- Material: parts can be metallic, plastic, multi-material (flexible and rigid), foam, cardboard or textile (for example, seatbelts in aircraft or cars)
- Shapes, dimensions and weights : from small to large size and from few grams to more than a kilogram
- Colors
- Aspect: matt, shiny, translucent, smooth or with reliefs…

Finally, parts can be either in direct contact with the bins or packed individually (or in groups) in plastic bags.

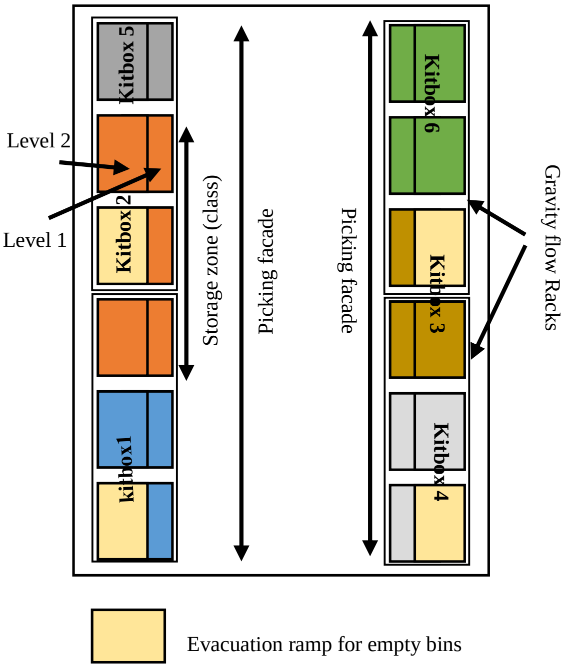

Figure 1: Top view of a detailed robotic kitting area layout

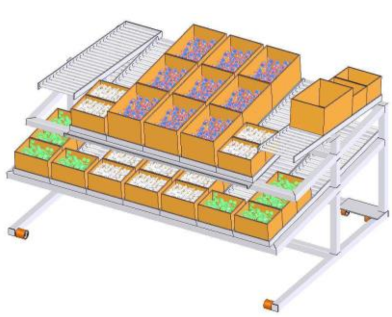

Figure 2: 3D representation of a gravity flow rack with two evacuation ramps

4.4. ELEMENTARY OPERATIONS ASSOCIATED WITH THE PICKING PROCESS

In this Section, we first define concepts related to kitting (i.e. kit, kitbox, and box). Then, we give some descriptive elements related to the robotic kitting operations.

4.4.1. CONCEPT DEFINITION

A kit is a unit-load holding all the parts required for the assembly of one final product FP (i.e. one kit = one FP). Parts that constitute a kit are physically put into several identical (same dimensions) containers that are called boxes. Boxes considered in this study are not compartmented, i.e. parts are placed in bulk and are not oriented while being put into the box.

The number of boxes per FP (or kit) can be different depending on the model of the FP being assembled. We thus distinguish common boxes (that are composed of some common components) used in the assembly of all FPs and specific boxes that are used optionally, depending on the FP model. For example, we can find on the assembly line, a richer FP in terms of components' number (that needs 6 boxes of components, i.e. 4 boxes of common components and 2 boxes of specific components) every 3 FPs (that need only the 4 boxes of common components) (see Figure 3).

A kitbox is the set of boxes that contain the components stored in the same storage zone, i.e the components of the same class. For example, on Figure 3, parts put into the 4 boxes of kitbox 1 are located in the same storage zone, i.e. the zone of kitbox 1.

4.4.2. KITTING PROCESS DESCRIPTION

As described in Section 4.1, parts are stored according to a class-based policy (i.e. a specific zone is dedicated to parts used to constitute a specific type of kitbox) and a specific order in each storage zone.

The robot prepares firstly and one box at a time, all the boxes associated with kitbox type 1. Once the boxes of kitbox 1 are finished, the robot prepares the boxes associated with kitbox type 2 and so on. To prepare a new box, the robot goes back to the beginning of the current storage zone (class) to pick the heavier parts first. In all cases, the robot picks only a single piece of a component at a time as picking several pieces of the same component is technologically not feasible for the moment.

To sum up, the robot remains in the same zone until all needed parts for a given kitbox type are picked.

The reason why the robot prepares one box at a time is to avoid mixing parts of different boxes, since parts are directly dropped, from the conveyor, into a box. This avoids then the need for setting up a sorting system at the end of the conveyor.

If we assume a preparation of V successive FPs (or kits) and a maximum number of boxes per FP equal to K_s, K being the number of common kitboxes, then the set s

(composed of a maximum of K_s*V boxes) the robot will prepare during a cycle is given by the following matrix:

$$\text{Set } s = \begin{array}{c} \begin{array}{cccc} FP\,1 & FP\,2 & \cdots & FP\,V \end{array} \\ \begin{pmatrix} \text{Box } 1.1 & \text{Box } 1.2 & \cdots & \text{Box } 1.V \\ \text{Box } 2.1 & \text{Box } 2.2 & \cdots & \text{Box } 2.V \\ \vdots & \vdots & \ddots & \vdots \\ \text{Box } K.1 & \text{Box } K.2 & \cdots & \text{Box } K.V \\ \vdots & \vdots & \vdots & \vdots \\ \text{Box } K_s.1 & \text{Box } K_s.2 & \cdots & \text{Box } K_s.V \end{pmatrix} \end{array} \begin{array}{l} \\ \text{Kitbox } 1 \\ \text{Kitbox } 2 \\ \\ \text{Kitbox } K \\ \\ \text{Kitbox } K_s \end{array}$$

In this case, the considered cycle time is that of the whole set *s* preparation. The assessed cycle time should be then equal to the time needed to prepare one kit or one FP multiplied by *V* the number of FPs in each set *s*.

In this matrix, columns represent FPs and rows represent the boxes of the same type of kitbox, i.e the boxes of each line contain components located in the same storage zone.

Since kitting operations are realized for *V* successive FPs and since richer products are spaced on the assembly line to balance workload, then we may have at least one richer product in each set *s*. If we consider an example where *FP 2* is a richer product, then some terms of the matrix related to specific components will be equal to zero. In this example, only *FP 2* would have K_s boxes to fill while *FP 1* and products from *FP 3* to *FP V* would have only *K* common kitboxes.

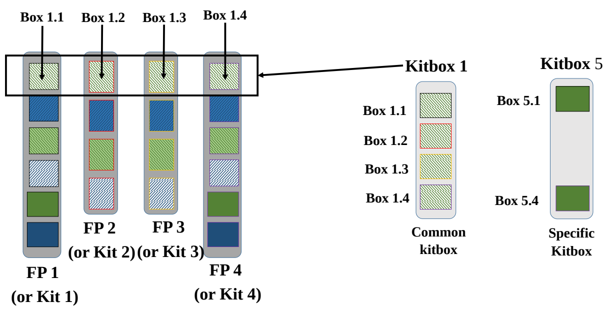

Figure 3: Representation of a kit, a kitbox and a box

As an example, for V = 4 and a number of boxes per FP i.e. K_s = 4 or 6 (which means four common boxes) depending on the models of FPs assembled on the line, the robot traverses each storage zone as shown in Figure 4. In order to focus on robot traveling distances, neither the racks nor the structure of the kitting area are represented in the figure. Since kitbox type 5 and kitbox type 6 are not systematically prepared, the picking area is organized in such a way to have the two zones (kitbox 5 and 6) far from the I/O point which is the starting/ending point for a complete cycle or tour of picking. Boxes to prepare are represented in Figure 4 by *k.v* for each kitbox *k* and each FP *v*. For kitbox 1, we have then 1.1, 1.2, 1.3 and 1.4.

The elementary operations performed by the robot while preparing a box are described hereafter. After receiving the picking list associated with Box 1.1, the camera positions itself above the first bin where parts will be picked and captures an image. This image is then analyzed so that the piece located on top of the related bin is identified to be picked.

The system then defines the robot motion and the most suitable gripper to pick the identified piece and put it on the conveyor.

While the robot rotates to drop the picked piece on the conveyor, the camera either captures another image of the same bin if more than one piece of the component is needed for the preparation or slides to the next bin that holds another component included in the picking list of Box 1.1. This actually allows to perform image acquisition in "hidden time". Once Box 1.1 is filled, the robot proceeds to the preparation of Box 1.2 and so on.

As previously said, some separators may be found inside the bins to preserve items' integrity. Those separators have to be removed by the robot before picking parts inside the concerned bins. Since separators may be different in terms of matter and shape, the right gripper has to be chosen by the robotic system.

The robot lifts the separators off the bins and drops them directly on the conveyor. They are then transported to a waste ejection area where they are pushed-off the conveyor.

As for separators, empty bins are also removed by the robot. Indeed, when a camera detects an empty bin, the robot positions itself in front of it and extracts it from its storage location using the appropriate gripping tool. Then, the robot moves the empty bin to the evacuation ramp. Empty bins are then retrieved by an operator.

In order to have an estimation of the number of separators and empty bins removed by the robot over a given period of time, we consider that the robot consumes only full bins over this period (which gives an integer number of empty bins).

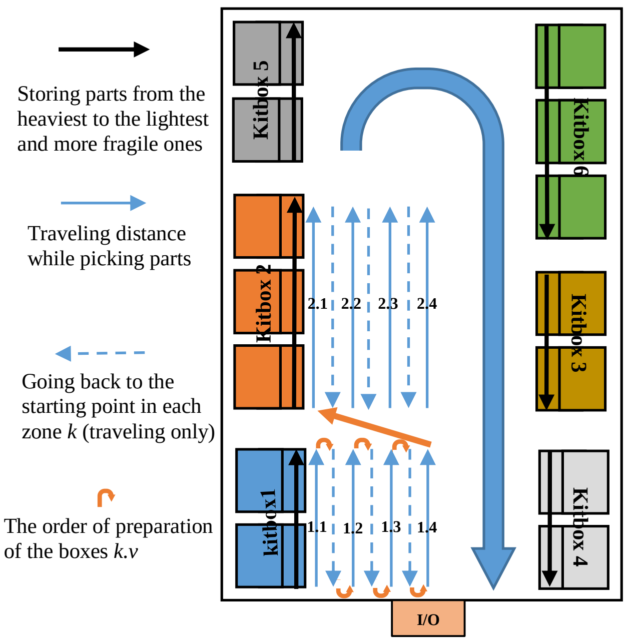

Figure 4: Representation the robot's traveling to prepare boxes *k.v*

5. MODELING KITTING OPERATIONS

In this section, the mathematical model for robotic kitting cycle time calculation is developed. In order to formulate the model, we consider the following general assumptions:

1. The model only considers operations inside the robotic kitting system that is assumed working at full speed without any failure. We also implicitly assume that everything works as expected outside the robotic kitting system which means for instance that both the replenishment of parts and the evacuation of empty bins (accumulated on the ramp) and waste (parts' separators) are regularly carried out by some external resources. Furthermore, we assume that downstream the robotic kitting, the boxes loop does not constitute a bottleneck as parts are systematically collected to make boxes available again.
2. The conveyor where picked parts are put moves continuously at a relatively high speed to allow placing parts one after other with respect to the picking list and to the defined order (according to parts' weight).
3. We assume that the robot can deal with any type of component. Parts having some specificities such as individual packaging inside the bins are not considered in this model.
4. The model aims at formulating the cycle time stemming from the elementary operations over a reference period. This period is assumed to be representative of the expected average robot activity in terms of demand for kitting, i.e. the quantity and model of FPs to be assembled on the line.

The cycle time is calculated for the set s (that contains at maximum K_s*V boxes) of boxes. It results from the sum of the durations associated with the elementary kitting operations that the robot performs (i.e. operations described in Section 4.4.). As a reminder, boxes are prepared one by one and only a single piece is picked by the robot at a time. All parts and separators are directly placed on the conveyor while empty bins are put on the dedicated ramps.

Indexes and notations we adopted for the formulation of elementary operations' duration are given below:

Indexes:

- s : the *set* of boxes prepared in the cycle time
- $k = \{1..K_s\}$: corresponds to a type of kitbox (i.e. a storage zone)
- $v = \{1..V\}$: corresponds to a FP of the set of boxes being prepared
- i : corresponds to components in the kitting area.

Notations:

- K_s : the maximum number of boxes per FP within the set s,
- V : the number of FPs prepared in the cycle time
- R_k : the number of components stored in the storage zone (class) k
- R_{kit} : the total number components in the kitting area

The durations considered are as follows:

- T_{pp_s} : Pick and place time (includes stopping time in front of the needed parts)
- T_{v_s}: Image acquisition time
- T_{tr_s} : Traveling time
- T_{t_s}:Tool changing time (end-effector)
- T_{br_s}: Time to return back empty bins (pick bins, move them and place them on the ramp)
- T_{dr_s}: Time to remove separators (noted "d" for dividers)

The total cycle time can be then expressed as:

$$T_{c\_s}=T_{pp\_s}+T_{v\_s}+T_{t\_s}+T_{tr\_s}+T_{br\_s}+T_{dr\_s} \qquad (1)$$

5.1. PICK AND PLACE TIME

This term considers the duration associated with picking and placing parts on the conveyor. The robot travels along a picking zone (class) and stops in front of each component included in the picking list to retrieve, for each FP v and for each kitbox type k, the needed components i, with the quantities that are specified in the picking list.

The following detailed assumptions are made while formulating the duration T_{pp_s}:

1. The robot picks a single piece at a time
2. For each picked piece, the time needed to rotate in order to place the piece on the conveyor is included in the duration of a single pick and place movement.
3. A failure rate representing "failed picks" is considered in the formulation.

The total pick and place time for a set s of boxes is given by:

$$T_{pp\_s}=\sum_{k=1}^{K_s}\sum_{v=1}^{V}\sum_{i=1}^{R_k}\alpha_{skvi} * T_a+(1+\tau_i) * T_i * C_{skvi}\,,\ \forall s \qquad (2)$$

C_{skvi} is the number of parts of component i to pick for FP v and kitbox k (see Figure 5) and α_{skvi} indicates if the component i of the set s, kitbox k and FP v is part of the picking list or not. In Figure 5, the rows of the matrix represent kitboxes while the columns represent FPs. For the submatrices, rows represent the components in each storage zone (different components for each zone).

$$\alpha_{skvi} = \begin{cases} 1 \text{ if component } i \text{ is part of the picking list} \\ 0 \qquad\qquad\qquad \text{otherwise} \end{cases} \qquad (3)$$

Moreover, T_a is the time estimated for one stop and is taken into account when $\alpha_{skvi} = 1$. The number of stops is then equals to the number of components to pick.

T_i and τ_i are respectively the time needed to pick and place a single piece of component *i* and the failure rate associated with each component *i*. The failure rate is given by:

$$\tau_i = \frac{\text{Number of failed picks}}{\text{Total number of picks}} * 100 \qquad (4)$$

The failure rate is obtained from field tests on the ability of the robot to properly pick parts.

As an example, we consider a set of boxes with only *FP* 2 having specific kitboxes. For the specific kitbox $k = K_s$, α_{sK_svi} and C_{sK_svi} are then equal to zero for all *v* belonging to {{1}, {3... *V*}} and all *i* belonging to $\{1 \ldots R_{K_s}\}$.

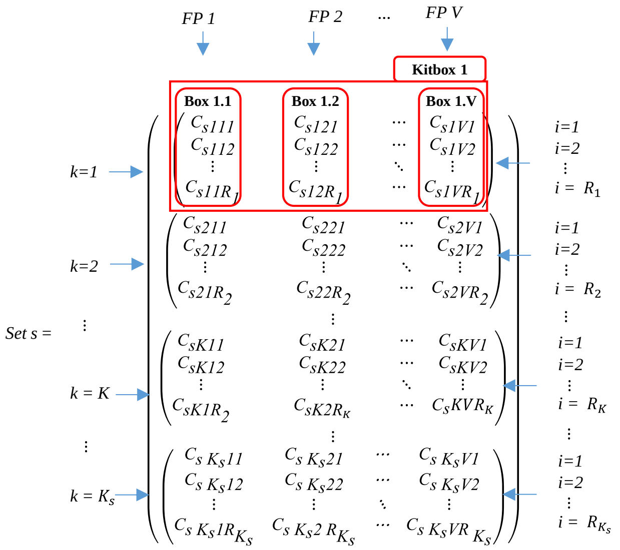

Figure 5: Matrix of boxes' and kitboxes' content for each FP of a set *s*

5.2. IMAGE ACQUISITION TIME

Before giving the detailed formulation of T_{v_s}, we split it into three formulations to simplify the comprehension. First, we only assume that there is an image acquisition (or capture) before each picked piece. So the time dedicated to image capturing would be expressed by:

$$T_{v\_s} = \sum_{k=1}^{K_s} \sum_{v=1}^{V} \sum_{i=1}^{R_k} C_{skvi} * T_{cap} \quad \forall s \qquad (5)$$

Where T_{cap} is the technological time needed for a single acquisition.

If we suppose that a part of this operation may be done as a background task i.e. in "hidden time" while the robot is traveling or dropping a piece on the conveyor, the formulation would be as follows:

$$T_{v\_s} = \sum_{k=1}^{K_s} \sum_{v=1}^{V} \sum_{i=1}^{R_k} (1-p) * C_{skvi} * T_{cap} \quad \forall s \qquad (6)$$

Where *p* is the part of the technological time executed in hidden time. Here T_{v_s} may be zero if $p = 100\%$ i.e if the acquisition is completely executed in hidden time.

In a more detailed formulation, we integrate the failure rate which gives the formulation below:

$$T_{v\_s} = \sum_{k=1}^{K_s} \sum_{v=1}^{V} \sum_{i=1}^{R_k} [\tau_i + (1-\tau_i) * (1-p)] * C_{skvi} * T_{cap} \quad \forall s \qquad (7)$$

When the robot fails to pick an item of component *i* ($\tau_i > 0$), it keeps waiting until the camera captures another image of the bin content which adds extra-time. This is given by the term:

$$\tau_i * C_{skvi} * T_{cap} \qquad (8)$$

On the other hand, the part of time acquisition for successful picks $(1-\tau_i)$ may be executed in hidden time:

$$(1-\tau_i) * (1-p) * C_{skvi} * T_{cap} \qquad (9)$$

5.3. TRAVEL TIME

The main assumptions made for the travel time formulation T_{tr_s} are the following:

1. The two picking facades are of the same length while picking zones (classes) may have different sizes.
2. All the storage lanes have a unique dimension which may be the width of a large bin (or the length of a small bin).
3. To prepare each box *k.v* the robot traverses the entire zone *k*.

The traveling time to prepare the set *s* of boxes is:

$$T_{tr\_s} = \frac{D_s}{v_R} \quad \forall s \qquad (10)$$

Where v_R is the robot's velocity and D_s is the traveled distance to pick all needed parts. It is expressed by:

$$D_s = (2*V-1) * \sum_{k=1}^{K} LZ_k + (2*Sv-1) * \sum_{k=K+1}^{K_s} LZ_k \qquad (11)$$

Where *V* is the total number of FPs to prepare and *Sv* the number of specific FPs. If we generalize the example seen in Figure 4, we have for each picking zone *k* of common components, *V* travels to pick parts in addition to *(V-1)* travels to go back to the starting point (of each zone *k*) which gives *(2*V – 1)*. While the number of travels per zone, for specific components, is given by *(2*Sv – 1)*.

LZ_k is the length of the picking zone (class) *k*. It is given by:

$$LZ_k = \frac{R_k}{2} * Width_{bin} \qquad (12)$$

Where $\frac{R_k}{2}$ is the number of columns (of two superimposed lanes) in a zone *k* and $Width_{bin}$ the width of a large bin.

5.4. TOOL CHANGING TIME

The assumptions considered for this term are as follows:

1. The robot changes the tool for each component in the picking list.
2. Time to perform a single tool change T_t is identical whatever the tool.
3. No travel time is needed to perform a tool change

The average tool changing time is given by:

$$T_{t\_s} = T_t * N_{t\_s} \text{ , } \forall s \tag{13}$$

Where N_{t_s} is the total number of tool changes to prepare the set s of boxes. It is given by summing the total number of components to pick and is expressed as follows:

$$N_{t\_s} = \sum_{k=1}^{K_s} \sum_{v=1}^{V} \sum_{i=1}^{R_k} \alpha_{skvi} \tag{14}$$

5.5. TIME TO RETURN BACK EMPTY BINS

Assumptions made to assess this term are as follows:

1. We assume that the robot consumes only full bins during the reference period.
2. Contrary to picking parts, we consider that there is no picking failures to retrieve empty bins.
3. Time considered for a single tool change is unique regardless the type of bin.
4. Time considered for a single empty bin pick has also a unique value for all the bins.

The average time to remove bins is given by:

$$T_{br\_s} = (T_t + T_b + T_{bm} + 2 * T_a) * N_{br} \tag{15}$$

Where T_t is the time needed for a single tool change. We assume that there is a systematical tool change before removing a bin.

T_b is the time to pick a single bin and place it on the evacuation ramp.

T_a is doubled to take into account the first stop when the robot grabs the bin and the stop in front of the evacuation ramp. Note that the stopping time when going back to pick a part is already integrated in the pick and place time.

Moreover, we consider the time dedicated to moving a box from its location to the evacuation ramp. This is given by:

$$T_{bm} = \frac{Length_{rack}}{v_R} \tag{16}$$

Since we assume that bins located in a rack are evacuated on the same rack, we consider an average distance (between bins and the evacuation ramp) which is half the rack's length traveled back and forth.

N_{br} is the average number of bins removed during the preparation of a set of boxes.

$$N_{br} = \frac{N_{bc}}{N_s} \quad \forall s \tag{17}$$

Where N_{bc} is the number of bins of component i consumed during the reference period. It is expressed as follows:

$$N_{bc} = \sum_{i=1}^{R_{kit}} \frac{N_{p_i}}{N_{UC\_i}} \tag{18}$$

Where R_{kit} is the total number of components in the robotic kitting system, N_{p_i} is the number of parts of component i consumed during the reference period and N_{UC_i} is the number of parts contained in a full bin of component i.

N_s is the number of prepared sets during the reference period. It is given by: $N_s = \frac{N_{FP}}{V}$. Where N_{FP} is the number of FPs produced during the reference period.

5.6. TIME TO REMOVE PARTS SEPARATORS

The assumptions associated with separators removal are as follows:

1. We assume that the robot is able to pick all kinds of separators with no failure.
2. There is a systematical tool change before any separator removal.
3. As parts' separators are dropped directly on the conveyor, this means that there is no traveling time.
4. The total number of separators removed during the reference period is calculated assuming that parts consumed during the same period are contained in full bins.

The average time to remove separators is given by:

$$T_{dr\_s} = (T_t + T_{dp}) * \frac{\sum_{i=1}^{R_{kit}} (N_{d\_i} * \frac{N_{p_i}}{N_{UC\_i}})}{N_s} \quad \forall s \tag{19}$$

Where T_{dp} is the time to pick a separator and place it on the conveyor. This time has unique value for all separators.

N_{d_i} is the number of separators contained in a bin of component i and $\frac{N_{p_i}}{N_{UC\_i}}$ is the number of bins of the same component consumed during the reference period.

6. CONCLUSION AND FUTURE RESEARCH

In this paper, we present a robotic kitting system that consists of a robot arm mounted on a rail which travels along a picking aisle. To assess the system's performance, we first divided the kitting process into elementary operations according to the previously fixed operating mode. Then, we expressed the time needed to perform each operation in order to calculate the total cycle time.

The assumptions made about the system's ability to pick all kind of parts allowed to establish an initial formulation. In reality, however, due to constraints related to parts characteristics (especially individually packed parts), the robotic system cannot deal with all parts. Until such a technical barrier is overcome, a more global system has to integrate those aspects. Thus, the robotic kitting as described along this paper, has to be implemented within a hybrid kitting system working with both a robot and an operator. Here, we can imagine a pick-and-pass system where the robot starts preparing a kit and passes the preparation to be completed by an operator.

In this hybrid kitting system, the notion of cycle time is even more important since the system's cycle time is the one of the resource (robot or operator) having the longest processing time. Thus, the study can be focused on how to maximize both resources' workload while ensuring smooth flows of boxes between the two subsystems (automated and manual). In particular, this problem can be formulated using an integer programming model that aims at minimizing the gap between both subsystems cycle time by assigning components to either the operator or the robot.

Such a system can be addressed in further research including manual operations such as removing parts from plastic bags and varying assumptions on kit preparation modes. We can, for instance, consider single or batch picking and different storage and picking policies. Also, formulations presented in this work such as tool changing time need to be refined as some variables like the number of tool changing are overvalued.

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