Author Accepted Manuscript version of the paper
CAPUTO, A.C., PELAGAGGE, P.M., SALINI, P., “A model for planning and economic comparison of manual and automated kitting systems”, International Journal of Production Research, 59(3), 885–908, 2020, DOI: 10.1080/00207543.2020.1711985

A model for planning and economic comparison of manual and automated kitting systems

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Abstract: Parts kitting is a frequently adopted method to feed parts from a warehouse to an assembly line. While kitting allows minimization of space occupation and Work In Process holding cost at the workstations, also simplifying materials flow and supporting manual assembly, it is penalized by high workforce cost for manual kits preparation. For this reason automated kitting systems have been also proposed although their practical application is somewhat limited owing to the relevant capital investment and scarce performances of robotized kitting systems. Moreover, economic models allowing a quantitative comparison of manual and automated kitting systems are not yet available in the literature. As a contribution to fill this gap, in this paper a cost model useful to compare manual and automation-assisted parts retrieval and kitting systems is presented. The model can be used as a decision making tool when planning and justifying kitting systems. The model includes capital investment, workforce, space occupation and quality costs. A case study as an application example is also included to demonstrate the model capabilities. Results show that automation-assisted kitting systems can be competitive in comparison to manual kitting and that break-even conditions can be also identified by the proposed method.

Keywords: Automated kitting, manual kitting, assembly line, parts feeding.

1. INTRODUCTION

In assembly lines parts kitting is a frequently adopted method to feed parts to workstations. In kitting systems the different parts required to assemble one unit of an end item, or the specific set of parts to be assembled at a workstation, are included in a kit container which is then moved to the assembly line (Brynzèr and Johansson 1995; Bozer and McGinnis 1992; Caputo and Pelagagge, 2011; Caputo et al., 2015a; Hanson, 2012; Sellers and Nof, 1986). This method is radically different from continuous parts supply systems, such as line storage or just in time feeding, where individual containers holding a stock of each part type are permanently stored at the workstations and periodically replenished when parts have been consumed. As compared to continuous parts supply, kitting has some notable advantages (Brynzèr and Johansson 1995; Bozer and McGinnis 1992; Hanson, 2012; Sellers and Nof, 1986). In fact, space occupation and Work In Process holding cost at the workstations is reduced, materials flow is simplified, and assembly operations are more efficient thanks to improved ergonomics and the fact that all parts are already checked, prepositioned, and easily grasped. Moreover, the operator does not spend time walking around to reach the individual parts containers. Kitting is especially suited to mixed model production where end items including parts variants are assembled on the same workstations. Kitting operations can be done at the supplier, at a third party logistics provider or at the original equipment manufacturer (Limère and Van Landeghem, 2009). However, whoever be the actor in charge of kit preparation, the problem arises of deciding how the kitting process should be accomplished.

In this respect two categories of approaches could be identified, namely traditional kitting and direct kitting. Traditional kitting implies that a proper set of parts made available in a warehouse are picked by human operators and/or automated equipment to be placed in kit containers. This is the most frequently used approach for kit preparation. Direct kitting, instead, is an innovative approach where direct digital manufacturing, i.e. resorting to additive manufacturing equipment and digitally controlled machines, are used for the preparation of customized assembly kits (Holmström and Partanen, 2014) by simultaneous fabrication of the set of parts to be kitted. In this manner different parts of an assembly may be produced in one build envelope as easily as manufacturing a batch of identical parts (Khajavi et al., 2013) and the number of handling activities required for kits preparation is strongly reduced. However, pursuit of direct kitting still suffers from the limitation of current additive manufacturing technologies and their limited diffusion on the workplace. It also implies that the logistic provider or the assembler of the end product becomes a manufacturing actor as well. Therefore direct kitting currently represents a niche application and few examples are reported in the literature (Lyly-Yrjänäinen et al., 2016). For the above reason this work will only focus on traditional kitting, where batch-produced and conventionally manufactured parts are kitted and kitting is a separate activity from manufacturing. Nevertheless, manual kit preparation is work-intensive and human error-prone, thus penalizing this feeding option owing to high workforce and quality cost. In order to reduce reliance on workforce, fully automated kitting systems have been also proposed in the literature (Sellers and Nof, 1989; Tamaki and Nof, 1991) but are scarcely adopted in practice (Sellers and Nof, 1986) either for the high capital investment and because parts kitting remains a complex task for robots systems (Balakirsky et a., 2013; Polydoros et al., 2016). Hybrid systems have been also adopted (Boudella et al., 2016, 2017, 2018), where picking of parts is shared between robots and human operators. While models for system planning and cost estimation have been developed for manual kitting (Caputo and Pelagagge, 2011; Caputo et al., 2015a,b; Limère et al., 2012; Sali et al., 2015) works or robotic systems design and performance estimation is much scarcer (Boudella et al., 2017; Tamaki and Nof, 1991). To the best of our knowledge, the only available economic model dealing with kitting automation is that of Caputo et al. (2018a) who compare automated retrieval systems with fully manual solutions. Moreover, no cost estimating model is available for robotized kitting. This prevents from properly comparing different alternative kitting systems in order to select the right option for any given application. As a contribution to fill this gap, this paper a) develops resources planning and costing models for fully or partially automated and manual kitting systems; b) performs an economic comparison and capacity analysis of manual and automated kitting systems; c) investigates the economic convenience of error-avoidance systems. The model can be used as a decision making tool when planning and justifying traditional kitting systems. This paper substantially extends the work of Caputo et al. (2018a) by including a thorough state of the art and classification on the topic, also developing a novel resources planning and costing model for robotic kitting solutions, as well extending the comparison with other automation-assisted or manual systems by carrying out a sensitivity analysis. The paper is organized as follows. After a literature review, and a classification of traditional kitting systems, the considered alternative kitting systems are described at first. Then an economic model is developed to estimate daily equivalent operational cost including capital investment, workforce, space occupation and quality costs, based on production rate. Finally, a sensitivity and risk analysis is carried out in the framework of a case study representing a numerical application example, used to show the model capabilities and point out the existence of break-even conditions. Comments on the obtained results and directions for future research conclude the paper.

2. LITERATURE REVIEW AND CLASSIFICATION OF KITTING SYSTEMS

Parts feeding to assembly lines stations is an important design and management problem in production systems (Boysen et al., 2015; Kilic and Durmusoglu, 2015). The main alternatives include using mixed parts containers, holding the specific assortment of parts required to assemble assigned variants of the finished product (this include stationary and travelling kits, as well as sequencing), or dedicated containers holding the same part type, to be permanently held at assembly workstations and periodically replenished (continuous parts supply systems including line storage and just in time delivery). The various parts feeding methods have both advantages and disadvantages, so that choosing the right method for a specific application, or even planning a hybrid parts feeding system simultaneously using several methods for specific subsets of parts, can be challenging. In the literature the influence of parts features and scenario condition on the choice of feeding method have been analysed (Caputo et al., 2018b) and empirical methods have been suggested to develop hybrid parts feeding policies (Caputo and Pelagagge, 2011; Usta et al., 2017). Mathematical programming techniques to optimally assign parts to multiple feeding policies have been also developed (Caputo et al., 2015b; Limère et al., 2012; Schmid et al., 2018), while several authors developed costing and performance models to compare two or more polices as reviewed by Caputo et al. (2018b). Kitting is recognized to be superior to continuous supply policies as far as material flow simplification and work efficiency of the assembler are concerned. Kitting also offers lower space occupation and WIP at the assembly station, thus resulting particularly suited to mixed model production. Nevertheless, kitting is penalized owing to the cost and manual effort required for kits preparation in the warehouse. Therefore, when circumstances suggest the adoption of kitting, a decision has to be made about how to carry out the kitting process, as this may be performed by human operator or automated resources.

However, it should be pointed out that this work is only focused on comparing alternatives for traditional kitting systems, while it does not consider the problems of selecting kitting as a parts feeding method in comparison to alternative methods. Therefore, we assume that a plant manager has already decided to implement parts kitting and has to select the most cost effective implementation solution in a specific assembly context.

A kitting process, conceptually includes three different steps, namely retrieval of parts from the storage area, picking the right number of parts to be inserted into the kit, and actual parts kitting. The latter kitting operation does not merely implies only placing the picked parts into the kit container but it generally includes a number of possible sub-tasks, namely counting/weighting of parts to ensure that the right number is included in the kit; preparation of components before insertion in the kit (i.e. cutting to measure, package removal, cleaning and quality control); kit preparation (insertion of parts in the right sequence and in the proper housing slot, including correct positioning control); compilation of missing component list for subsequent kit completion. It should be noted that the three above cited phases can either be carried out by the same type of resources (i.e. manual or automated) or assigned to different types, and can be even be combined. For instance, in a picker to parts system the operator walks along warehouse aisle and picks the individual parts, so that the retrieval and picking phases part are merged into a single one. As an extreme case the three steps can be merged into a single one when an operator or a robot picks and simultaneously kits the parts. This gives rise to a combinatorial explosion of different possible systems configurations, including fully automated, fully manual and hybrid ones. Overall, the distinction between parts retrieval and picking is only meaningful when the two steps are carried out by different kinds of resources. Therefore, in a simplified manner one can say that the kitting process generally includes a picking operation and a kitting operation. This allows to refer to the ample literature on order picking systems (OPS) to attempt a classification of kitting systems (excluding direct kitting).

Standard order picking classification (Dallari et al., 2009, De Koster et al., 2007) usually distinguishes between machine-based and human-based OPS. The former perform fully automated order picking resorting to robots or automatic dispensers (i.e. A-frames). This is an unfrequent solution only adopted for small sized parts with regular shapes (i.e order fulfilment in pharmaceutical distribution centres) or high value items. Human-based OPS are subdivided in picker-to-parts (i.e. fully manual OPS or automated man-on-board systems), parts-to-pickers systems, and put systems. The latter employ an automated system to retrieve parts containers and present them to manual pickers. Among the automation technologies used in parts to picker systems the following can, for instance, be cited, namely Vertical lift Modules (VLM), horizontal or vertical carousels, Automated Storage and retrieval cranes (AS/RS), miniload systems, multi-shuttle systems (SBS/R, Shuttle Based Storage/Retrieval, or Automated Vehicle Based Storage/Retrieval, AVS/RS), compact storage systems such as Swisslog's Autostore, robot based systems, including Robotic Mobile Fulfillment Systems (RMFS) such as the Kiva system. A general procedure for design order pick systems was provided by Yoon and Sharp (1996), while Dallari et al. (2009) map the most suitable technologies according to OPS characteristics and Van Gils et al. (2018) review planning problems in OPS. As far as automation technologies in OPS are concerned, an earlier review of the literature on automated storage and retrieval systems has been carried out by Roodbergen and Vis (2009), while Sellers and Nof (1986) focus on reviewing automated kitting systems. A recent classification and overview of robotized warehousing system is instead carried out by Azadeh et al. (2017) and Boysen et al. (2018). However, for the sake of this paper, a classification shown in Figure 1 based on the type of resource and the phases of the kitting process has been preferred. Figure 1 also shows the particular architectures chosen for the four systems compared in this paper, namely Type I, II, III and IV as described in the following Section.

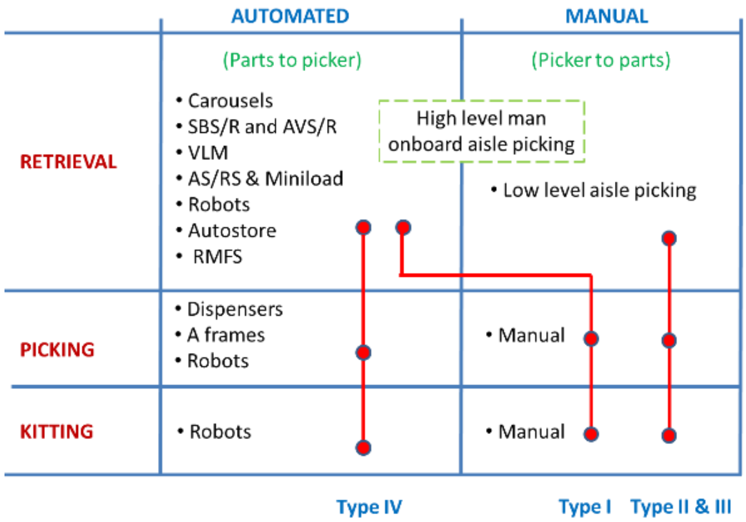


Figure 1. Classification scheme for generating kitting systems architectures.

Several design and performance estimation model are available for automated warehousing systems, also allowing comparison between alternative systems. For instance Bozer and White (1990) model automated end-of–aisle OPS, Bozer and Aldarondo (2018) compare miniload and RMFS. Vasili et al. (2012) review AS/RS design and control criteria, while Lehrer and Srami (2012) provide a design procedure for AS/RS, Khojasteh and Son model single cranes AS/RS serving multiple aisles, Sari et al. (2005) analyse flow-rack based AS/RS, Liu et al. (2018) model split-platform, AS/RS. Lerher et al. (2016) model shuttle-based storage and retrieval systems. Foley and Frazelle (1991) and Foley et al. (2004) model miniload systems. Fukunari and Malborg (2009), Kuo et al. (2007), Heragu at al. (2011), Roy et al. (2012), Kai et al. (2014), Ekren et al. (2014) and Marchet et al. (2012, 2013) use queueing network to model performances of AVS/R systems even providing design guidelines and trade-off analyses. Hanson et al., 2018 give a practical overview RMFS, while Lamballais et al. (2017) and Yuan and Gong (2017) analyse performances of RMFS and provide design guidelines, whilst Xiang et al. (2018) and Zou et al. (2017) discuss management issues of RMFS. Boysen et al. (2018) survey research on automated sortation conveyors. Hwang et al. (2002) consider automated end-of-aisle OPS combined with Automated Guided Vehicles, Zijm et al. use queueing theory to analyse performances of an automated kit transportation system. Carousel and VLM systems have been instead modeled by Hwang and Ha (1991), Meller and Klote (2004), Park et al. (2003), while Litvak and Vlasious (2009) perform a general in depth review of such systems. Tappia et al. (2019) discuss design and performance assessment of Integrated storage-order picking systems. Nevertheless, all of the above references do not address specifically the use of the above cited technologies in the context of automation-assisted kitting systems, nor provide guidelines for architecting a kit preparation system.

As already mentioned fully robotic kitting systems are seldom utilized, owing to technical difficulties robots encounter in performing complex tasks such as picking single parts in bulk containers, orienting parts to place in kit containers, removing packaging and interleaving cardboard sheets and dividers in parts containers, although experimental applications have been described (Liang et al., 2015; Polydoros et al., 2016). Tamaki and Nof (1991) discuss issues in robotic kitting systems also exploring configuration of robots integrated with Automated Guided Vehicles, carousels or AS/RS performing retrieval tasks. Selers and Nof (1989) perform a preliminary quantitative performance analysis of robotic kitting systems including a simplified model for estimating cycle time. Finally, Boudella et al. (2016, 2017) develop performance model allowing to estimate in detail the cycle time in hybrid kitting systems where parts picking and kitting is shared between robots and operators. Their model is subsequently used to optimize parts allocation between resources in order to meet a cycle time constraint imposed by an assembly line to be fed in just in time manner (Boudella et al., 2018). Costing issues of robot systems, instead, has been discussed by Landscheidt and Kans, 2016).

Overall, the above review shows that although detailed modelling and analysis approaches have been developed for each specific warehouse automation piece of equipment, general resources requirements computation criteria, as well as cost evaluation methods for design of kitting systems, either manual or automated, are still lacking in the literature.

3. DESCRIPTION OF EXAMINED KITTING SYSTEMS

Owing to high capital investment and technical limitations of fully automated kitting approaches, in this work we focus our attention on fully manual and automation-assisted "hybrid" kitting systems. The latter include either automation in the parts retrieval, and or picking phases, or the use of automated error proofing systems. A robotized kitting system, where the robots performs parts picking and kitting, is included in the hybrid systems category because owing to technical difficulties in picking or kitting of some parts, more often, the robot will kit a subset of parts while the remainder parts will be kitted manually. Then the ratio of robotic to manually kitted parts will be the parameter chacterizing this system alternative. In particular we examine the following alternatives.

<u>Type I. Automated Retrieval - Manual picking and kitting.</u>

In this case picking is performed by an Automated Storage/Retrieval System (AS/RS) such as a mini-load system. Retrieved parts container are moved to the AS/RS output bay and placed on a buffer conveyor. After manual picking the container are stored in the warehouse while the operator places the required parts in the kit containers. The buffer conveyor allows to avoid interferences between manual operators and the automated storage/retrieval cycles. Ready kits are temporarily stored in the kitting area before transportation towards the line. In the order picking literature this architecture may be considered a put system (De Koster et al., 2007). Figure 2a depicts the system layout.

<u>Type II. Manual Picking - Manual kitting.</u>

In this case a traditional warehouse is used where the operator manually picks the required amount of parts from their storage containers and delivers them to the kitting area where manual kitting takes place, as shown in Figure2b. Please note that this figure only shows the arrangement of the storage and picking area and not the separate kitting station. In this system the arrangement of kitting stations is assumed to be similar to Type I systems with the difference that picked parts instead of parts containers are delivered to the kitting station. However, the alternative very common approach where the kitting station is fed with manually retrieved containers from the warehouse, and the human kitting operator moves and picks parts from the container and places them in kits can be accounted as well by this model as described in Section 4. Moreover, in this system the picker uses a paper pick list to get information about parts to be picked.

Type III. Automation-assisted Picking - Manual kitting.

This is the same of Type II exception made for the adoption of pick-to-light warehouse racks and RFID systems used to help parts identification and reduce errors in manual operations.

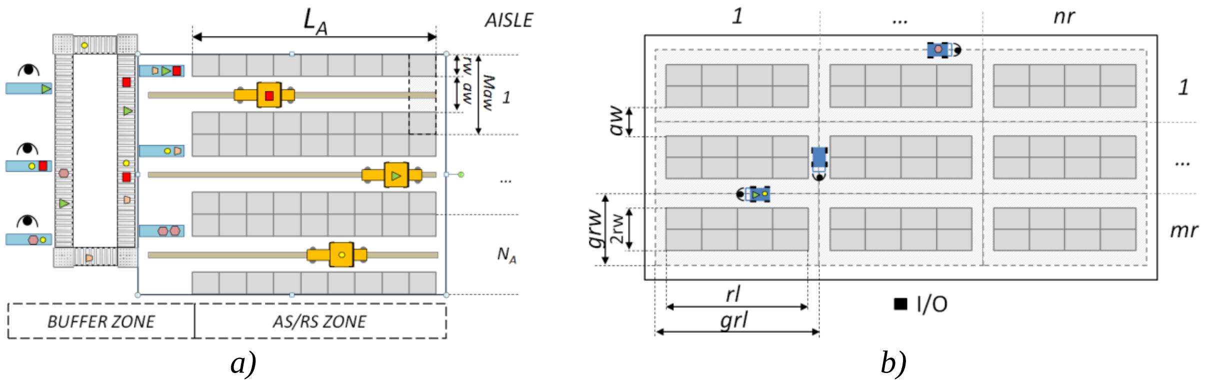


Figure 2. Warehouse conceptual layout, a) for Systems Model I and b) for Systems Model II & III

Type IV Hybrid Robotized/manual picking and kitting.

This is a totally automated kitting systems where robots moving through storage aisles, like the cranes in an AS/RS, pick parts and kit them. In case some parts cannot be picked or kitted by the robot, then a traditional manual kitting system (Type II) is used to supplement the robotic kitting system to complete kit preparation with the missing parts (see Figure 3).

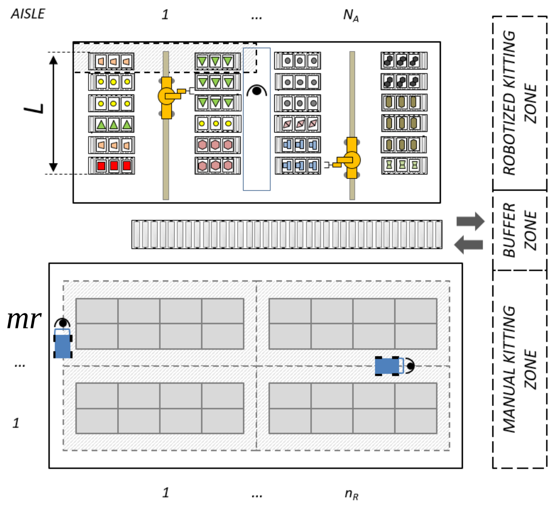


Figure 3. Conceptual scheme for Systems Model IV

4. RESOURCE PLANNINGAND COSTING MODEL

For each system type at first the resources requirements are computed based on the demand of end products. Then investment and operational costs are computed. A yearly equivalent total cost is thus evaluated for economic comparison purposes including capital investment (AS/RS cranes, storage racks, other automated equipment), workforce cost, energy consumption, space occupation cost based on the surface area of the warehouse and kitting zone, and quality cost deriving from errors correction. In Type I systems resources to be planned are number of AS/RS cranes, volume of storage racks, number of operators. In Type II only storage racks volume and number of operators for retrieval, picking, kitting and warehouse replenishment have to be computed. In Type III systems, as compared to Type II, the RFID and pick-to-light systems costs are included. In Type IV systems resources requirements to be computed are number of picking/kitting robots, volume of storage racks, number of operators for auxiliary parts kitting and storage racks replenishment. Transportation cost of kits to workstations, WIP holding cost at the line and kits containers cost are neglected being common to all alternatives.

Resources planning models

Let us assume that M types of End Products (EP) are assembled, with j=1,..,M subscript denoting the type of end product. N distinct part types are used, with i=1,..,N denoting the i-th part type. D_j is the daily average demand of j-th end product, and n_{ij} is the multiplicity of i-th part type in one unit of the j-th product (n_{ij} = 0 in case the product does not use the part). Furthermore, let us assume that $\alpha_{ij} = 1$ when $n_{ij} = 1$ and $\alpha_{ij} = 0$ in case $n_{ij} \neq 1$, while $\beta_{ij} = 1$ when $n_{ij} > 1$ and $\beta_{ij} = 0$ if $n_{ij} \leq 1$. VC_i is the volume of the storage container holding the i-th part type, while $A_i = \sum_{j=1}^{M} D_j \, n_{ij}$ is the total daily consumption of the i-th part type. As far as robotic kitting is concerned, we also define $\gamma_{ij} = 1$ in case the i-th part type, required for the j-th kit type allows robotic picking/kitting, while $\gamma_{ij} = 0$ when technical reasons prevent robotic picking/kitting of that part type. The ratio ω = number robotically kitted part types/overall number of part types is a system parameter. In case $\omega = 1$ a fully robotic kitting system is obtained, while when $\omega = 0$ a system Type II is obtained.

The required number of workers in the kitting department NopK, may be computed as

$$\mathrm{NopK} = \left\lceil \frac{\mathrm{TKT}}{OpT} \right\rceil \quad (1)$$

where ⌈ ⌉ is the ceiling function representing rounding to next integer, with OpT (h/day) the daily available work hours of a worker (i.e. the daily contract work hours time the worker's efficiency η_{op}) and TKT (h/day) the total work man-hours required for manual operations, expressed as

$$TKT = \sum_{j=1}^{M} D_j \, TK_j \quad (2)$$

being TK_j (hr) the time to prepare one kit of a type *j* product.

$$TK_j = \sum_{i=1}^{N} \left(Tps_i + Tin_i + Trepl_i + Tck \right) + Trl \quad (3)$$

where Tps_i (h) is the time required to pick the *i-th* part from storage containers. In case of Type I systems, being Tp the unit picking time $Tps_i = n_{ij}\ T_p$ because the container is brought to the picker by the AS/RS system. In case of Type II and III systems $Tps_i = Nt_i\ (2L_i/vtp) + n_{ij}\ T_p$ because the picker has to reach the storage location before picking the part and come back. In the above equation Nt_i is the number of trips to pick items of type *i* needed for one kit from the storage area, L_i (m) is the picking distance (it depends from the warehouse layout and parts storage policy) and vtp (m/h) is the picker's walking speed. The number of trips necessary to retrieve the required number of parts of type *i* to prepare one kit is

$$Nt_i = \left\lceil \max\left(\frac{n_{ij}}{n_{\max}}; \frac{n_{ij}\ P_i}{P_{\max}}; \frac{n_{ij}\ V_{ei}}{V_{\max}}; \right) \right\rceil \qquad (4)$$

where P_i is the weight of one item of type *i*, $V_{ei} = V_i/(1-\xi_i)$ is the equivalent part volume based on the part physical volume V_i and the filling coefficient ξ_i of the container, n_{max}, P_{max}, V_{max} are respectively the maximum number, weight and volume of parts that a picker can transport at once in a single trip. In case $Nt_i < 1$ it means that in a single trip the operator can retrieve a number of parts of type *i* enough to prepare more than one kit or will pick multiple part types during the same trip.

Please note that in case the picker moves an entire parts container, having capacity CC_i, to the kitting station, then $Nt_i = n_{ij}\ /CC_i$.

$Tin_i = n_{ij}\ t_{kit}$ (h) is the time required to insert the items of type *i* into the kit. Average time t_{kit} required to kit one unit of a part type can be measured or computed resorting to traditional time studies methods. It includes all required operations (i.e. parts counting and preparation, positioning and cheking). Tck (h) = $n_{ij}\ t_{ck}$ (h) is the time required to check each part type in a kit before delivery, Trl (h) is the time required to stow away the ready kit before delivery. $Trepl_i$ (h) = $T_{CR}\ (n_{ij}\ V_{ei}\ /\ V_{Ci})$ is the equivalent warehouse replenishment time deriving from the amount of of *i-th* part type consumed for each EP_j kit, being T_{CR} the time required to substitute an empty part container with a full one.

In Type IV systems the number of required operators is computed in the same manner as in Type II and III systems with the exception that TK_j is computed according to Equation (3) only for parts requiring manual picking/kitting (i.e. $\gamma_{ij} = 0$), while for parts allowing robotic picking/kitting (i.e. $\gamma_{ij} = 1$) TK_j only includes the empty box replenishment term for the robotized kitting area.

In order to assess storage area requirements the warehouse must be sized as described below. For Type I systems (automated retrieval and manual picking and kitting) an automated warehouse has to be used, whereas for Type II and III systems (manual retrieval, picking and kitting) a traditional warehouse is adopted as shown in Figure 2b. In both cases, to determine the warehouse dimensions the volume *VC* (m^3) of SKUs and the maximum rack height *Hmax* (m) are imposed. *VC* and *Hmax* may differ for Type I, II and III systems. For Type IV systems the kitting area floor space, KAS, includes both the (possible) manual warehouse area, sized as in case of Type II and III but limited to part types not allowing robotic picking/kitting, and the area occupied by robotized aisles.

However, the arrangement of the racks in the robotic area is somewhat different as compared to the manual picking area. In fact, to allow the robotic arm and the vision system to properly interface with the containers, only racks with three vertical storage levels are used, a fixed storage location is assigned to each part type, gravity flow racks are used so that when an empty container is removed by the robot it is immediately substituted by a new full container. A conceptual scheme for one aisle of robotized warehouse is shown in figure 4, where WR is the single gravity flow rack width**,** RA is the robot aisle width**,** OL the replenishment operator walkway width and WAR the full width for each aisle.

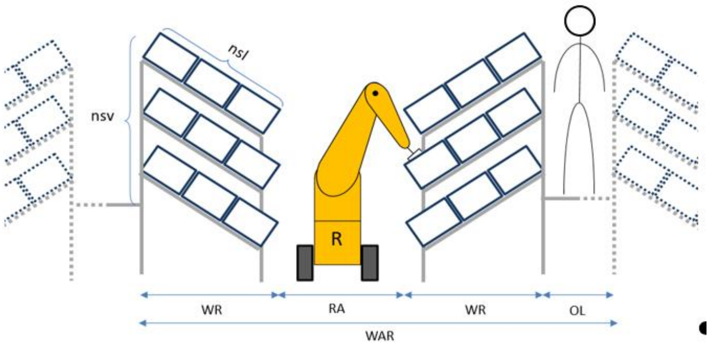


Figure 4. Conceptual cross-section of a single warehouse robotized aisle for Type IV system.

The required warehouse capacity *WV* (SKU) and the required throughput rate *TR* (SKU/h) are dictated by demand *D* and are computed as follows. The gross volume *VDD* (m^3/day) of all parts needed to satisfy the daily demand of end products is

$$VDD = \sum_{j=1}^{M} \sum_{i=1}^{N} n_{ij} \cdot D_j \cdot V_{ei} \qquad (5)$$

The total number of parts of type *i* required to satisfy the daily production volume is

$$A_i = \cdot \sum_{j=1}^{M} n_{ij} \cdot D_j \qquad (6)$$

In Type I system assuming that each time the container holding the *i-th* part is retrieved, the operator, picks an amount Q_i of parts, then the daily number of retrievals of the *i-th* container is $R_i = N_i/Q_i$, so that the warehouse required throughput is

$$TR = \frac{1}{h} \cdot \sum_{i=1}^{N} \left\lceil \frac{A_i}{Q_i} \right\rceil \qquad (7)$$

The whole warehouse capacity is computed as

$$WV = \left\lceil VDD \cdot (1 + f_{SS}) \cdot \frac{RI}{VC} \right\rceil \qquad (8)$$

where *RI* (day) is the time between replenishments, assumed the same for all items type, f_{SS} (%) accounts for safety stock and VC is the container volume. To determine the AS/RS configuration, the method by Bozer and White (1984) is adopted which computes the mean duration of both single command tm_{SC} (s) and dual command tm_{DC} (s) storage/retrieval cycle duration once the horizontal v_x and vertical v_y velocities of miniload cranes have been chosen. The length of aisles L_A (m) is then chosen to minimize cycles duration

(Caron et al., 1997). Assuming that f_{EC} (%) is the percentage of single command cycles, the average cycle time *Tm* (h) for each miniload crane is

$$Tm = tm_{SC} \cdot f_{EC} + tm_{CC} \cdot (1 - f_{EC}) \tag{9}$$

The warehouse aisles number (N_A) is then computed as

$$N_A = \lceil TR \cdot T_m \rceil \tag{10}$$

Finally, the automated warehouse floor surface AWS (m^2) and the rack volume ARV (m^3) are computed as

$$AWS = L_A \cdot Maw \cdot N_A + BS \tag{11}$$

$$ARV = (L_A \cdot H_{max} \cdot rw) \cdot 2 \cdot N_A \tag{12}$$

where *BS* (m^2) is the buffer area occupied by the closed loop conveyor whose order of magnitude is

$$BS = (N_A \cdot Maw) \cdot Maw \tag{13}$$

being *Maw* = (2 *rw* + *aw*) the aisle module width, with *rw* the rack width (m) and *aw* the aisle width (m).

For manually operated warehouse (systems Type II, III and a possible portion of the storage area for Type IV) racks length *rl* (m) and rack width *rw* (m) are chosen based on the container size. The warehouse floor surface area is then defined imposing the required capacity *WV*

$$WV = \left\lceil nr \cdot mr \cdot \frac{rl \cdot 2 \cdot rw \cdot H_{max}}{VC} \right\rceil \tag{14}$$

and the minimization of average path length

$$(nr \cdot grl) = 2 \cdot (mr \cdot grw) \tag{15}$$

The number of parallel racks along the warehouse *mr* and across the warehouse *nr* are computed from the system of Eq (14) and (15). Then manual warehouse space occupation *MWS* (m^2) and *MRV*(m^3) result

$$MWS = (glr \cdot nr + aw) \cdot (grw \cdot mr + aw) \tag{16}$$

$$MRV = mr \cdot nr \cdot (rl \cdot 2 \cdot rw \cdot H_{max}) \quad (17)$$

where *glr* and *grw* are the gross rack dimensions augmented to consider one half aisle width per side.

In Type IV system, the number of robots (and storage aisles) N_A and length of each aisle L are evaluated by an iterative procedure, since the time consumed by a robot to produce a generic single kit depends on aisle length.

Let us define RAM=H_S N_S A_R the daily robot work hours, being H_S the hours per shift, N_S the number of daily shifts and A_R the robot availability, whereas RWH is the time required to perform the robotic picking and kitting operations for the daily kits demand

$$RWH = \sum_{j=1}^{M} D_j \; T_{RKj} \quad (18)$$

being T_{RKj} the time a robot consumes to produce one unit of the *j-th* kit type, in the following referred to as cycle time. RWH depends on T_{RKj} which, in turn, depends on aisle length L, as detailed in the following.

The warehouse aisle number N_A is the minimum number allowing

$$N_A \cdot RAM \geq RWH \left(\frac{L'}{N_A}\right) \quad (19)$$

where L' is a first trial length determined as follows.

The required robotized warehouse capacity, for Type IV, in terms of flow gravity rack ramps number (RN) is

$$RN = \sum_{i=1}^{N} \frac{N_{SKUi}}{nsl} \quad (20)$$

being N_{SKUi} the number of required stock keeping unit (SKU) for component *i*, and *nsl* the number of stock keeping unit in a single rack ramp. N_{SKUi} is computed as

$$N_{SKUi} = \left\lceil A_i \cdot (1 + f_{SS}) \cdot \frac{RI}{VC} \right\rceil \quad (21)$$

Once *RN* is known, it is possible to estimate the robotized warehouse first trial length *L'* as

$$L' = \left\lceil \frac{RN}{2 \cdot nsv} \right\rceil \cdot W_s \quad (22)$$

where *nsv* is the number of vertical level in a gravity flow racks on each opposite sides of picking robot aisle, assuming that for each flow rack ramp only one component type is allowed, and W_S is the stock keeping unit dimension parallel to aisle ($xSKU_R$) increased by a factor *eps* to consider the flow rack structure dimension ($W_S = xSKU_R \cdot (1 + eps)$).

The robotized warehouse is designed using the iterative procedure depicted in Figure 5.

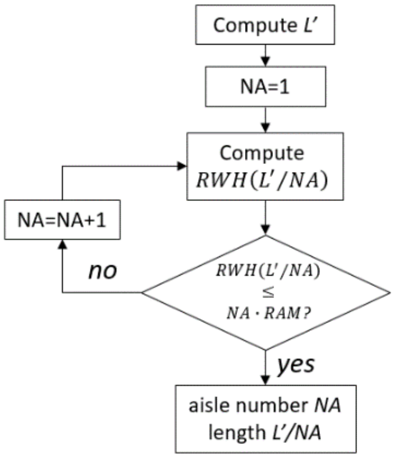


Figure 5: Robotized warehouse design procedure.

To obtain the warehouse design the amount of time spent in robotic picking and kitting operations for the daily production volume (RWH) is required.

In order to compute RWH, the evaluation of T_{RKj} is mandatory. We must at first describe the components of the cycle time, and this will be made in a simplified manner partially inspired to the more detailed modeling approach of Boudella et al. (2016, 2017, 2018).

$$T_{RK\ j} = T_{PP\ Tot\ j} + T_{V\ Tot\ j} + T_{T\ Tot\ j} + T_{TC\ Tot\ j} + T_{BR\ Tot\ j} + T_{PR\ Tot\ j} \quad (23)$$

where $T_{PP\ Tot\ j}$ is the total picking and placing time of all parts types allowing robotic kitting to be included in the *j-th* kit type,

$$T_{PPTot\ j} = \sum_{i=1}^{N} \gamma_{ij}\ n_{ij} T_{PPi}\ (1 + f_i) \quad (24)$$

being T_{PPi} the pick and place time for each unit of *i-th* part type and f_i the the pick failure rate.

$T_{V\ Tot\ j}$ is the total image acquisition and processing time by the robot vision system for the j-th kit type

$$T_{VTot\ j} = \sum_{i=1}^{N} \gamma_{ij}\ n_{ij} T_V\ (1 - htp) \quad (25)$$

being T_V the unit image capture and processing time pick and place time for each unit and htp the percentage of T_V which can be carried out as a background task (i.e. in hidden time) while the robot is performing another task.

$T_{T\ Tot\ j}$ is the total travel times along the picking aisle to reach the locations of the part types to be picked to prepare one kit of j-th type

$$T_{T\ Tot\ j} = \sum_{i=1}^{N} \frac{\gamma_{ij}}{N_l\, N_f} \left(\frac{L}{4\, v_R} + T_S \right) \quad (26)$$

being L the aisle length, v_R the robot advancement speed, T_S the stopping time in front of a storage location, N_l the number of vertical levels in the storage racks reachable by the robot, and N_f the number of different facades from which the robot can pick at once. In equation (26) the summation over γ_{ij}/N_lN_f represents the net number of robot repositioning moves to reach all required part types, while L/4 is the average trip length. Please note that the aisle length depends on N_l, N_f, the number of different part types to be stored in the aisle (depending on the mix of kits types assigned to the robot moving within the aisle) and the width along the aisle axis of the parts containers. Here we assume that $N_l = 3$ and that $N_f = 2$.

$T_{TC\ Tot\ j}$ is the total tool change time to prepare one kit of *j-th* type provided that T_{TC} is the unit tool change time and each different part type requires a tool change in the robot end effector.

$$T_{TC\ Tot\ j} = \sum_{i=1}^{N} \gamma_{ij}\ T_{TC} \quad (27)$$

$T_{BR\ Tot\ j}$ is the time to remove empty bins and place them on the evacuation ramp of the aisle, referred to the equivalent number of bins removal implied by the parts consumed to prepare one unit of the *j-th* kit type. Given that the gravity shelf makes available a new full bin to the robotic arm as soon as an empty bin is removed, we assume that the robot does not leave the position to reach the evacuation ramp during the picking cycle but disposes the empty bin only before reaching a new picking position.

$$T_{BRTot\ j} = \sum_{i=1}^{N} \gamma_{ij}\ n_{ij}\ \frac{V_{ei}}{VC_i} \left(T_{TC} + 2T_{BR} + 2\frac{L_R}{v_R} + T_S \right) \quad (28)$$

being V_{ei} the equivalent part volume, VC_i the parts container volume, T_{TC} the tool changing time, T_{BR} the time required to remove the empty bin from the shelf or the time to place the bin on the evacuation ramp, L_R the average distance to be covered to reach the aisle evacuation ramp. In Eq. (28) $n_{ij}\ V_{ei}/VC_i$ is the equivalent number of containers of *i-th* part type consumed when preparing one unit of the *j-th* kit type.

$T_{PR\ Tot\ j}$ is the total time required to remove cardboard interlayers sheet and dividers from the parts containers while parts are being picked, being DD_i the number of interlayer sheets and dividers included in each container of *i-th* part type and T_{PR} the time to remove the divider.

$$T_{PRTot\ j} = \sum_{i=1}^{N} \gamma_{ij}\ n_{ij}\ \frac{V_{ei}}{VC_i}\ DD_i\ (2T_{TC} + T_{PR}) \quad (29)$$

Cost models

The total equivalent kitting cost C_K (€/year) can be expressed as

$$C_K = C_{wK} + C_{mK} + C_{sK} + TECC_K \quad (30)$$

where C_{wK} (€/yr) is the annual cost of personnel, C_{mK} (€/yr) is the equivalent annual cost of kitting department equipment (i.e. materials storage racks, automated picking equipment, RFID system), C_{sK} (€/yr) is the annual cost of surface occupation of the kitting department, $TECC_K$ (€/yr) is the annual error correction cost.

$$C_{wK} = NopK\ Ow \quad (31)$$

where NopK is computed resorting to Eq. (1), and Ow is the annual operator wage.

The equivalent cost of kitting department equipment is C_{mK} (€/year) = $C_{AS/RS} + C_R + C_{SR} + C_{RFID}$ where

$$C_{AS/RS} = (C_C\ N_A + C_B + C_{CC})\ (\tau c + m) + P_C\ N_A\ h\ W\ C_e \quad (32)$$

is the equivalent annual AS/RS cranes cost being C_C (€) the unit AS/RS crane cost, N_A the number of aisles, C_B (€) the conveyor buffer capital investment, C_{CC} (€) the AS/RS control system capital investment, τ_c the capital recovery factor, m the annual maintenance cost expressed as percentage of capital investment, P_C (kW) the crane power, C_e the unit energy cost (€/kWh), h the daily work hours and W the annual work days.

For Type IV systems the term C_R is the equivalent annual cost of picking/kitting robots, expressed as in Equation (32) with the exception that C_C is to be intended as the robot unit cost, C_{CC} the robots control system capital investment, and P_C the robot installed power.

The equivalent annual cost of storage racks is

$$C_{SR} = \left(\sum_{j=1}^{M} \sum_{i=1}^{N} n_{ij}\ D_j\ V_{ei}\ RI \right) RCK\ \tau_{rack} \quad (33)$$

where RCK is the storage rack capital investment per unit volume (€/m^3), which can change passing from traditional to pick-to-light racks and to robotic picking racks, τ_{rack} is the capital recovery factor computed referring to the storage equipment life, and RI is the replenishment interval, deriving from the chosen replenishment frequency of the racks. This under the assumption that storage racks volume must allow enough space to store the amount of parts consumed during the replenishment interval RI. Please note that in case of Type IV system C_{SR} terms has to be computed separately for the manual kitting area, using Eq. (33), and for the robotic kitting area.

Whereas, for RFID system, cost may be computed by Eq.34

$$C_{RFID} = C_{I\ RFID}\ \tau_R + C_{TAG}\ WV \tag{34}$$

where $C_{I\ RFID}$ (€) is the RFID system capital investment (gantry reader, computer systems etc.), C_{TAG} (€/piece) the unit tag cost (each one of the WV reusable containers has attached one tag), and τ_R is the capital recovery factor.

Please note that in case of Type I system $C_{RFID} = C_R = 0$; in case of Type II system $C_{AS/RS} = C_{RFID} = C_R = 0$; in case of Type III system $C_{AS/RS} = C_R = 0$. In case of Type IV system $C_{AS/RS} = C_{RFID} = 0$.

The annual cost of the floor area occupied for kit preparation is

$$C_{sK} = (KAS)\ C_s \tag{35}$$

where KAS (m^2) is the overall kitting system floor space, while C_S (€/m^2 yr) is the specific annual unit cost of floor space.

Computation of KAS depends from system Type. In case of Type I KAS = AWS + BS + KSS, where AWS and BS are computed according to Eqs. 11 and 13, while KSS is the surface area occupied by the kitting workstations. In case of Type II and III systems, KAS = MWS + KSS, being MWS computed according to Eq. 16. In case of Type IV system KAS = MWS + AWS + KSS where evaluation of N_A and L for the robotized warehouse, as depicted in Figure 5, allows computation of AWS in a similar manner as for Type I warehouse, while MWS is computed as shown for Type II system referring to the residual part types not amenable to robotic kitting. However, given that the surface KSS is roughly similar for the various systems it can be neglected for the sake of cost comparison.

The annual error correction cost $TECC_K$ can be instead computed referring to the work of Caputo et al. (2017a,b), using event trees to compute error probability. The procedure, detailed in the Appendix, at first allows to identify the relevant quality problem (QP) types, namely QP1 = end of line correction of errors from utilization of kits having undetected parts errors and QP2 = before assembly correction, at the workstation, of detected parts errors within a kit. Then it allows to determine the QPs occurrence probabilities (p_{QP1Kj} and p_{QP2Kj}) and, finally, enables to compute the corresponding quality costs $QC1_{Kj}$ and $QC2_{Kj}$ for each kit type. Thus, in a kitting system, the total expected annual error correction cost $TECC_K$ (€/yr), referring to all components of all kits handled to produce the required number of assemblies per year (each one requiring a kit), is

$$TECC_K = W \sum_{j=1}^{M} D_j \left(p_{QP1_{Kj}}\ QC1_{Kj} + p_{QP2_{Kj}}\ QC2_{Kj} \right) \tag{36}$$

5. NUMERICAL APPLICATION

In this section the above described model is applied to a realistic industrial example referring to a manufacturer of electrical home appliances performing in-house kits preparation. Nevertheless, this case study can be assumed as representative of any factory assembling small sized consumer products of moderate complexity. In fact, we assume that individual parts volume ranges from 4.16 to 721 cm^3, whereas weight ranges between 10 g and 3.8 kg. We also assume that the products range includes 15 different types of end items each one assembled in up to 5 variants, for a total of 45 different end products. Overall, the considered number of handled part types is 250 and the average number of parts types in each kit, determining the end product variant, is 15. However, in order to show average results of a typical mixed or multi-model production strategy, we consider a reference production mix, obtained as an average of randomly generated production mixes.

In this numerical application we compare Type I, II, III and IV systems on the basis of total equivalent yearly kitting cost when changing the end items production volume of the reference average production mix from 5000 to 40,000 units/year. Table 1 shows adopted numerical values of system parameters, whereas, Table 2 shows adopted error probability values (as defined in the Appendix) necessary to evaluate the Total Error Correction Cost. Numerical values indicated in Tables 1 and 2, although realistic and representative, have a demonstrative purpose, and were assumed based on engineering judgment and experience in actual assembly plants. Apart from changing the production volume, we also consider two values of the percentage ω of the number of part types amenable to robotic picking, in order to carry out a parametric analysis in scenarios favourable or unfavourable to robotic picking applications. Obtained results of this base case are shown in Figure 6. Furthermore, in order to assess the impact of quality costs, we also compare the base case of Figure 6 to alternative cases where the Total Error Correction Cost (Eq. 36) is multiplied by a factor 10 (Figure 7) and a factor 100 (Figure 8) respectively. This allows considering cases where the error correction cost is much higher than the base-case value owing to internal organizational issues. Please note that in this model (see Appendix) we assume that all errors are corrected, so that only conforming products are sold to the customer. Therefore, the error correction cost is basically the internal workforce cost required for product disassembly and/or resupplying and substituting the proper components (Figure 6). However, when a risk of selling non-conforming products exists, external quality costs should be factored in, such as product recall and liability costs, costs to handle customers complaints and returns, lost sales and customer ill-will due to defective outputs, and costs to restore reputation. Such costs can be order of magnitude that the internal component substitution and reassembly cost.

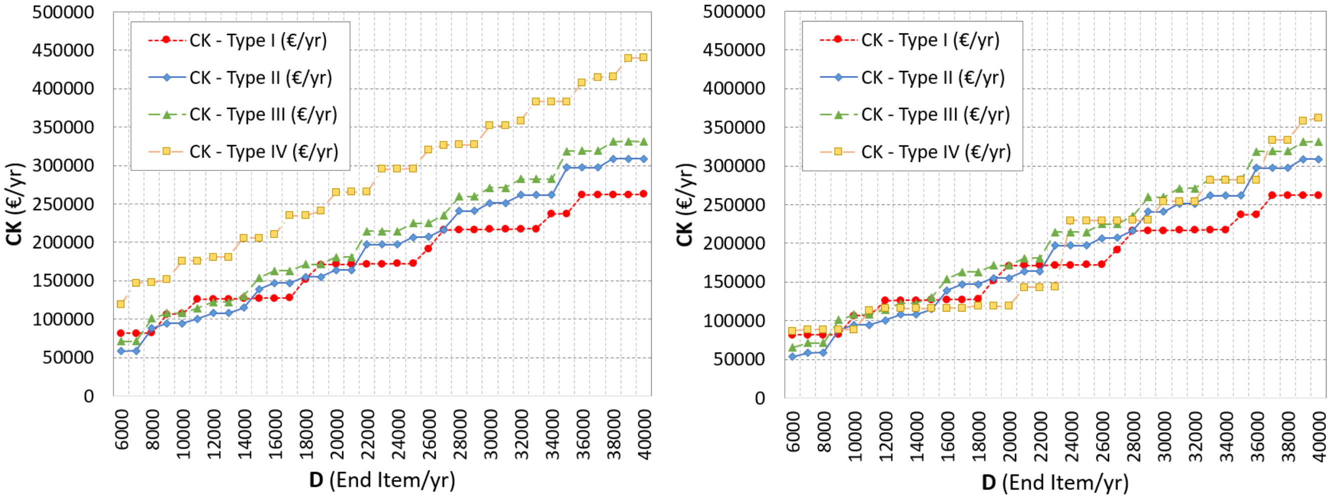
Table 1. Parameters data for numerical application

Ar	(-)	0.95	*Nf*	(-)	2	T_{CR}	(min)	10
aw	(m)	1 (I) 1.7 (II&III)	*Nl*	(-)	3	T_d	(min)	10
C_B	(€)	30000	n_{max}	(-)	50	T_i	(min)	5
C_C	(€)	80000	*Ow*	(€/day)	110	*tkit*	(s/item)	3
C_{CC}	(€)	50000	*p*	(%)	20	*Tp*	(s/item)	5
C_e	(€/kWh)	0.12	P_C	(kW)	5 (AS/RS) 8 (robot)	T_{PPi}	(s)	2.5
$C_{I\,RFID}$	(€)	50000	p_{DE}	(-)	0.2	T_{PR}	(s)	5
C_S	(€/m^2 yr)	40	p_{EA}	(-)	0.02	T_{rl}	(s/KIT)	25
C_{TAG}	(€/TAG)	0.25	P_{max}	(kg)	25	T_S	(s)	3
d_{avg}	(m)	50	*RCK*	(€/m^3)	75 (I); 50 (II) 100 (III);60 (IV)	T_{TC}	(s)	10
DS_i	(-)	3	*RI*	(day)	10	*Tv*	(s)	0.5
f_{EC}	(%)	70	*rl*	(m)	5 (only for II&III)	*VC*	(m^3/SKU)	0.025 (I); 0.020 (IV) 0.007 (II&III)
fi	(%)	2	*rw*	(m)	0.7	V_{max}	(m^3)	0.6
fss	(%)	10	T_a	(min)	10	*vr*	(m/s)	1.8
h	(h/day)	8	T_{BR}	(s)	15	*vtp*	(m/s)	0.7
Hmax	(m)	3.5 (I) 1.8 (II&III)	t_{ck}	(s/part type)	3	τ_C, τ_R, τ_{rack}	(-)	0.2
m	(%/yr)	2						

Legend: Roman numbers in parentheses denote System Type.

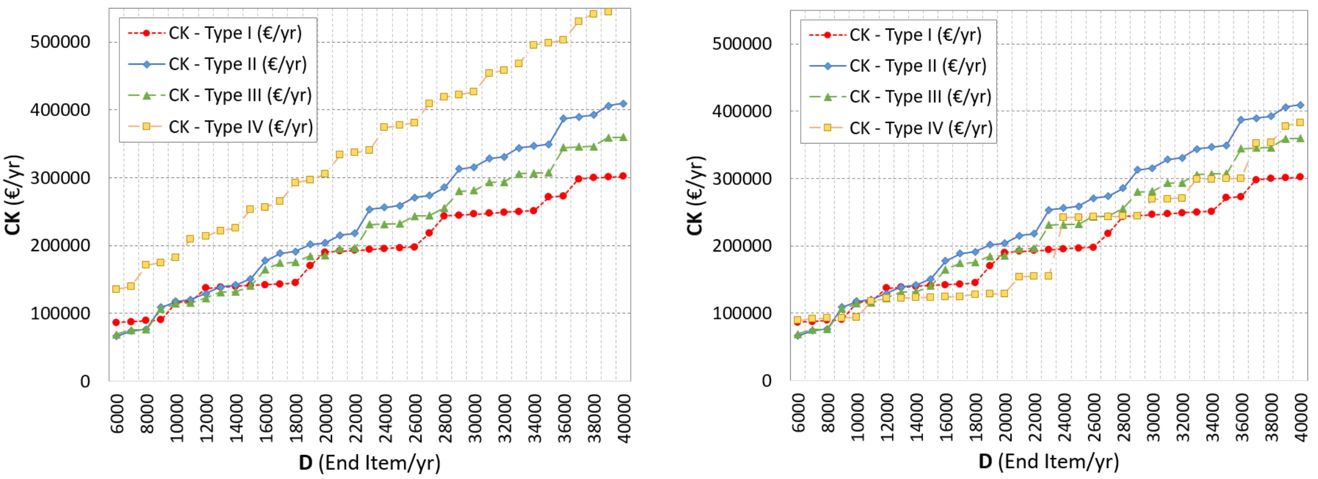
Table 2. Error probability values

Probability	Type I)	Type II)	Type III)	Type IV
η	0.95	0.97	0.98	0.97
θ	0.99	0.85	0.99	0.85
γ	0.5			
ι	0.05			
κ	0.02			
λ	0.04			
μ	0.95			



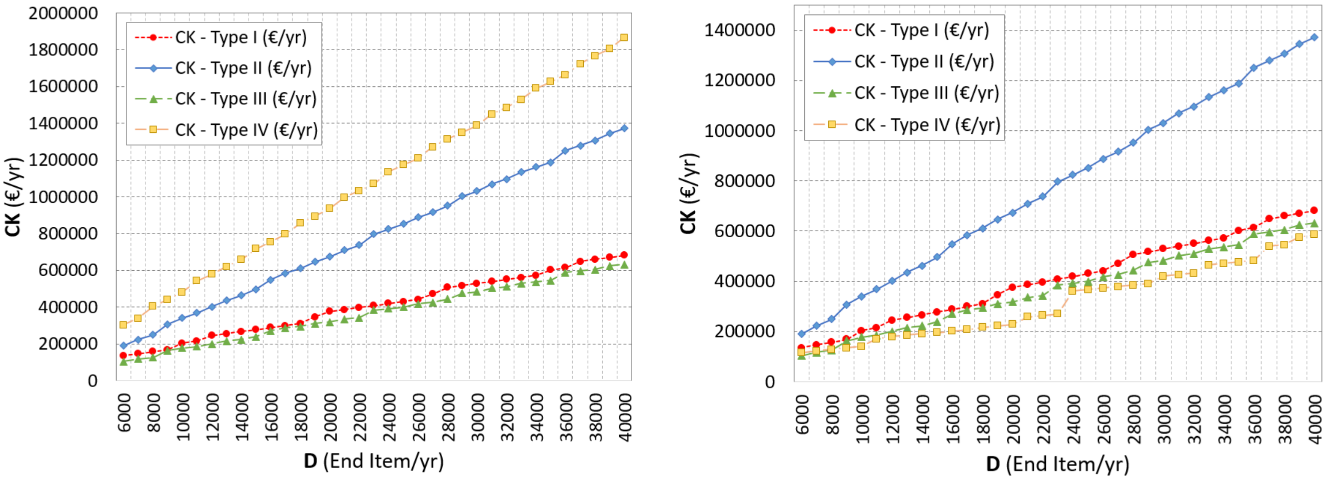
a) *b*

Figure 6. Yearly kitting cost comparison: a) ω=30% , b) ω=75%.



a) *b*

Figure 7. Yearly kitting cost comparison: a) ω=30% , b) ω=75% [TECC cost increased 10 times].



a) *b*

Figure 8 Yearly kitting cost comparison: a) ω=30% , b) ω=75% [TECC cost increased 100 times].

Figure 6a shows the economic comparison of kitting systems when Table 1 and 2 parameters values are used. The figure is obtained for 30% (ω value) of component picked by robotic system. In this kind of systems economies of scale effects are substantially absent. Therefore, cost increases fairly linearly with capacity. In case of manual systems, capacity increase is more gradual as additional single operators are added, while in automated system capacity increase is somewhat discontinuous each time a new aisle is added. Given the roughly linear cost function a break-even point exists depending on the relevance of fixed costs (higher in automated warehouses) and the rate of growth of variable costs (slower in case of automated system owing to lower workforce requirement).

System Type IV is not competitive for small values of parameter ω, showing the highest cost through the entire demand variation range. However, increasing the percentage of components handled by robotic picking systems (see Figure 6b Type IV, where ω grows up to 75% of total part types) cost become comparable or lower as compared to other systems cost.

It should also be pointed out that manual retrieval is much less time consuming as compared to kitting activities. For this reason workforce requirement of type II and III systems is only slightly lower than Type I system.

Therefore, the location of the break-even point between Type I and Types II & III systems strongly depends on the capital investment of AS/RS aisles and labor productivity. Small changes in such factors can significantly affect the convenience of a system as compared to the others. The same consideration is valid for system Type IV, where the robot system determines high investment cost, but in this case even the ω parameter plays a relevant role.

In this case study, as expected, manual retrieval systems (Type II and III) are convenient in case of very small production rates, while automated retrieval system (i.e. Type I) is superior when throughput is increased, with a cost saving getting higher the greater is the production rate. System Type IV, having relevant investment cost, is suitable if the number of component handled by robot is high. It can be concluded that despite the widespread adoption of manual kitting, an automated solution is strongly competitive and often superior, except in case of very low demand.

Passing from low to high error correction costs (i.e. from Figure 6 to 8) automation-assisted manual systems (Type III) become progressively more cost-effective, especially when the majority of parts requires manual picking, thus becoming error-prone, up to the point of becoming the cheaper option in the case of Figure 8a.

Therefore, although impact of error correction cost is relevant when comparing kitting systems to alternative parts feeding methods (Caputo et al., 2017a), it plays a minor role, respect other cost items, when comparing alternative options for kitting systems, unless the unit error correction cost is high. Overall, even if picking and kitting errors are a negative factor affecting kitting operations in general, an investment in error avoidance automation-assisted kitting can be justified only when the unit error cost is high. However, the use of automation-assisted manual picking in the form of pick-to-light or similar approaches, instead of being aimed at reducing error rates, may be also useful to reduce picking time, thus increasing workers productivity. This would increase the range of production volume where manual solutions are lower cost as compared to automated ones. Finally, floor space occupation is significantly lower in Type I systems, but given that shop floor cost is a minor contribution to total cost it does not affect significantly the break-even conditions.

The above results point to the following conclusions.

Robotized systems (Type IV), owing to the relevant investment, are not convenient in case only a small fraction of part types are amenable to robotic picking, irrespective of the production volume and the unit manual error correction cost. On the contrary, robotized picking may be convenient when the majority of parts is amenable to robotic picking, and when manual error correction cost is high. In this case the robotic system has similar or even lower costs as compared to both AS/RS systems (Type I) and automation-assisted manual systems (Type III), exception made for low demand scenarios, where the burden of high capital investment is more evident.

Automation- assisted system (Type III) is cost-effective when the majority of parts are only amenable to manual handling, unit error correction cost is high, and demand is low, thanks to the lower investment compared to automated solutions.

Manual systems (Type II) are convenient when unit error correction cost is low and demand is low.

Automated retrieval with manual picking/kitting systems (Type I) are convenient at high production volumes and for medium to high unit error correction cost, and in cases where most parts can not be picked by robots.

Overall, besides providing evidence that automated kitting systems can be competitive with manual systems, it was also shown that the alternatives have similar economic performances, requiring fairly detailed cost modeling, as carried out in this work, in order to decide the most cost-effective solution.

In order to provide a broader picture of the application scenarios where each system is more convenient, a further mapping has been carried out to explore the combined effect of variation in investment cost, labor rate, and percentage of parts suitable for robotic picking. Let us define *IC factor* a multiplier to the nominal investment cost, in the range $0.2 \leq$ *IC factor* ≤ 1.4; *Ow factor* a multiplier of the nominal labor cost, in the range $0.2 \leq$ *Ow factor* ≤ 1.4, and *Omega* (ω) the fraction of parts types suitable for robotic picking. Here nominal investment cost and labor cost are intended as the investment and labor cost of the base case obtained by this model assuming the data of Tables 1 and 2. In Figures 9 to 13 a color-coded dot shows the lowest cost system when changing values of *IC, Ow* and *ω factor*, and for various values of the end product production volume.

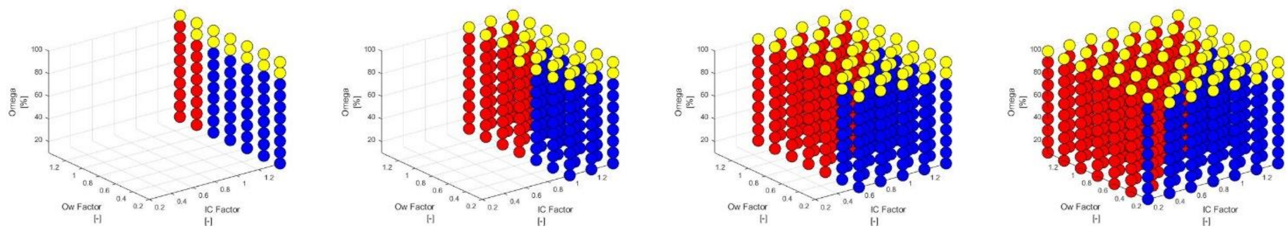


Figure 9: Minimum cost kitting system for D = 8.000 items/yr (Red = Type I, Blue = Type II, Green = Type III, Yellow = Type IV).

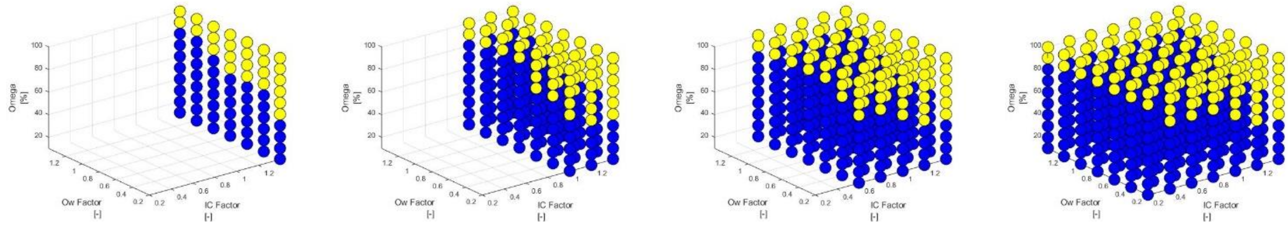


Figure 10: Minimum cost kitting system for D = 12.000 items/yr (Red = Type I, Blue = Type II, Green = Type III, Yellow = Type IV).

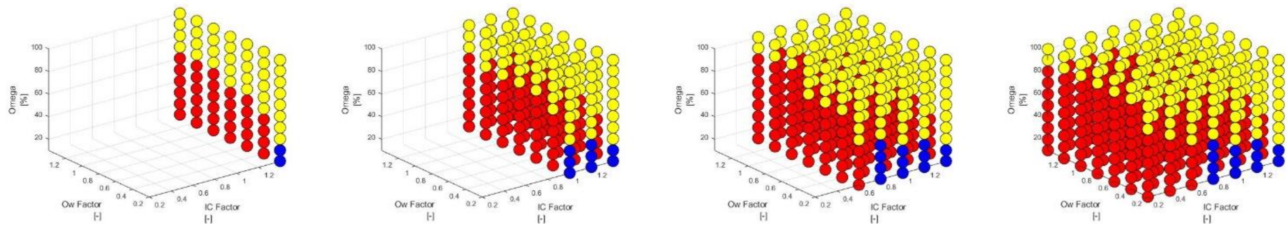


Figure 11: Minimum cost kitting system for D = 16.000 items/yr (Red = Type I, Blue = Type II, Green = Type III, Yellow = Type IV).

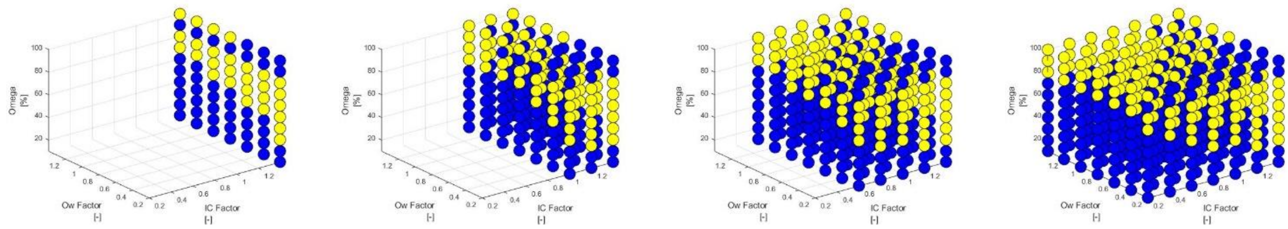


Figure 12: Minimum cost kitting system for D = 20.000 items/yr (Red = Type I, Blue = Type II, Green = Type III, Yellow = Type IV).

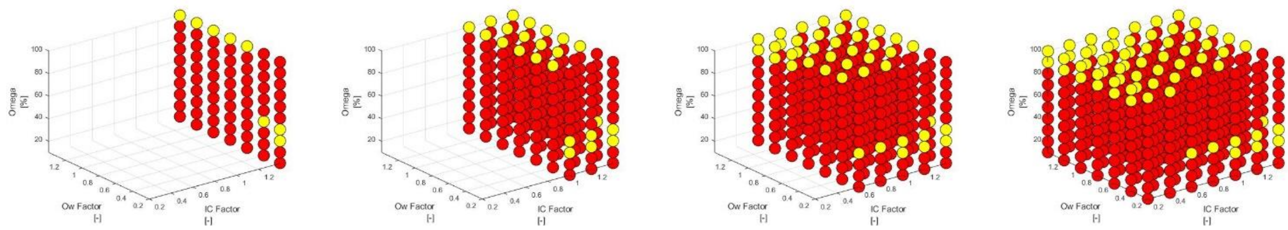


Figure 13: Minimum cost kitting system for D = 40.000 items/yr (Red = Type I, Blue = Type II, Green = Type III, Yellow = Type IV).

The above mapping shows that in case of low-to medium demand (Figure 9) manual systems are preferred in case of low labor rate, but as labor rate increases and investment cost decreases Type I systems are more convenient. Robotic picking systems are only viable for high ω values. In case of lower demand values (not shown here) the optimum system is always the fully manual one (Type II).

When demand grows (Figures 10 to 13) the convenience area of Type IV robotized systems grows significantly even when investment costs grow, labor cost reduces and the percentage of parts picked by robot falls. For intermediate demand values (Figures 10 to 12) a break-even may be reached between manual (Type II) and automated retrieval systems (Type I), as shown by the alternated switching between Type I and Type II systems in Figures 10, 11 and 12. Nevertheless, when demand grows to higher values the system of choice becomes an automated one irrespective of labor rate and variations of investment costs, as shown in Figure 13. However, this mapping also demonstrates that it is not easy to generalize the convenience area of each system, as it is highly influenced by demand value. Therefore, a detailed cost modeling is necessary for each specific application case.

CONCLUSIONS

In this paper the problem of choosing the most cost-effective kitting system was investigated. In the paper at first a classification framework was introduced to categorize alternative kitting systems, then a detailed planning and costing model was developed able to compare fully manual with automated retrieval and or automation assisted kitting systems as well as robotic kitting. The two above cited topics represent the main contribution of this paper to the existing kitting literature.

However, the analysis is carried out under the assumption that kitting has been already selected as the preferred parts feeding method to supply assembly workstation, as compared to other supply alternatives such as line stocking and just in time delivery. The choice of the parts feeding method, in fact, has been dealt with elsewhere in the literature, including prior papers by the same authors. Moreover this paper only considers traditional kitting operations, where batch-produced and conventionally manufactured parts are kitted, with kitting being a separate activity from manufacturing. In this respect this paper neglects the promising, but today scarcely adopted, practice of direct kitting, where digital manufacturing technologies are used to simultaneously manufacture the set of different parts to be kitted, thus avoiding individual parts storage and picking. Moreover, this paper only considers four different kitting systems implementation out of the combinatorial explosion of possible technological alternatives. Namely one fully manual and three automation-assisted “hybrid” systems are considered, including mini-load based automated retrieval with manual picking and kitting, automation-assisted picking and manual kitting, hybrid robotized/manual picking and kitting.

Utilization of the model in a sample case study demonstrated the model capabilities and its usefulness as a decision support tool. Results showed that automated retrieval solutions are cost effective and competitive as compared to traditional manual retrieval kitting, except in case of low demand, and that breakeven production volumes can be quickly identified by this model. Fully manual kitting is instead convenient the lower the labor cost, and mostly in cases of intermediate to low production volume. The model also showed that error-avoidance automated systems are only justified in case of high unit error cost. Error issues, therefore, appear to be more relevant when comparing kitting with alternative parts feeding policies than when comparing alternative solutions for kitting systems, unless external quality costs are much higher than internal labor cost for error correction. In such cases error cost may be the ruling factor when choosing the kitting system. The above findings, even if obtained through a specific application example, can be considered of general validity. In future work the model will be extended to account for further configurations of automation assisted kitting, including fully automatic kitting, especially focusing on alternative configurations of robotized kitting as well as further configurations of automated warehousing equipment, such as those using robotic mobile fulfillment systems in conjunction with robotic or manual picking. Moreover, the validity of findings will be tested considering in a parametric manner a wider range of assembly sectors (from kitting of small electronic or mechanical components typical of consumer products to kitting of heavy and cumbersome parts as can be encountered in assembly of vehicles). The role of parts features, i.e. weight and size, will be also explored. Finally, research will be also aimed at developing suitable models for direct kitting applications.

ACKNOWLEDGMENT

Authors wish to acknowledge that this paper is a revised and expanded version of a paper titled "Economic comparison of manual and automation-assisted kitting systems", presented at the IFAC INCOM Conference, 11-13 June 2018, Bergamo, Italy.

NOMENCLATURE

A	(-)	total daily consumption of each component type
A_R	(-)	robot availability
ARV	(m^3)	automated warehouse rack volume
aw	(m)	warehouse aisle free pass width
AWS	(m^2)	automated warehouse floor surface
BS	(m^2)	buffer area surface for automated warehouse
C	(€/yr)	total annual cost
C_B	(€)	conveyor buffer capital investment
C_C	(€)	AS/RS crane cost
C_{CC}	(€)	AS/RS control system capital investment
CC	(parts/container)	Storage capacity of parts container
CDE_K	(€/error)	cost of kit correction in case of line operator detection
C_e	(€/kWh)	unit energy cost
$C_{I\ RFID}$	(€)	RFID capital investment
C_{oh}	(€/h)	operator hourly cost
CRQ_K	(€/error)	cost of off-line correction of undetected kit error
C_S	(€/m^2 yr)	specific annual floor space cost
C_{TAG}	(€/piece)	unit tag cost
D	(item/day)	daily average demand
d_{avg}	(m)	average distance between kitting area and workstation
DD	(-)	number of interlayers sheet in one container
EP	(-)	end product
eps	(-)	numerical constant
f_{EC}	(%)	percentage of AS/RS single command cycle
f_i	(-)	robotized picking failure rate
f_{SS}	(%)	safety sock as a percentage of daily volume of components
grl	(m)	gross rack length, per unit
grw	(m)	gross rack width, per unit
h	(h/day)	daily working hours
$Hmax$	(m)	maximum allowable warehouse height
H_S	(h/shift)	hours per shift
htp	(%)	percentage of hidden time for vision system
KAS	(m^2)	kitting area floor space
L	(m)	picking distance or aisle length
L'	(m)	AS/RS first trial length
L_A	(m)	aisle length
L_R	(m)	average distance storage location - evacuation bin ramp
M	(-)	total type of end product
m	(%/yr)	maintenance percentage cost
Maw	(m)	automated warehouse aisle full width
mr	(-)	rack number in cross section warehouse direction
MRV	(m^3)	manual warehouse rack total volume
MWS	(m^2)	manual warehouse floor area
n	(-)	multiplicity of a part type in one end item
N	(-)	total type of component
N_A	(-)	aisle number of AS/RS system
N_{Aj}	(-)	number of single unit part into a kit

N_{Bj}	(-)	number of part into a kit with multiplicity greater than one
N_{EK}	(-)	total number of errors for each kit
N_{EKA}	(-)	number of parts (multiplicity one) with one or more kitting error
N_{EKB}	(-)	number of parts (multiplicity greater than one) with one or more kitting error
N_f	(-)	number different facades from which robot picks at once
N_l	(-)	number of vertical levels in storage racks for system IV
$NopK$	(-)	kitting department required workers
nr	(-)	rack number in longitudinal warehouse direction
N_S	(-)	number of daily shift
N_{SKU}	(-)	number of stock keeping unit
nsl	(-)	number of stock keeping unit in a single rack ramp
nsv	(-)	number of vertical levels in a single rack ramp
Nt	(-)	number of trips
OL	(m)	operator line width for case IV
OpT	(h/day)	daily work hours
Ow	(€/yr)	annual operator wages
P	(kg)	weight
P_C	(kW)	crane/robot power
p_{DE}	(%)	probability that the line operator detects a kitting error for one component
p_E	(%)	probability of kitting error presence
p_{EA}	(%)	probability of kitting error presence for parts with multiplicity one
p_{EB}	(%)	probability of kitting error presence for parts with multiplicity greater than one
p_G	(%)	probability of kitting error absence
p_{GA}	(%)	probability of kitting error absence, for parts with multiplicity one
p_{GB}	(%)	probability of kitting error absence, for parts with multiplicity greater than one
p_{QP1k}	(%)	probability of having an end of line error correction cost in case of undetected parts error
p_{QP2k}	(%)	probability of having an end of line error correction cost in case of detected parts error at workstation
Q	(-)	number of parts picked at a time
$QC1_{Kj}$	(€/piece)	cost of end of line error correction for kits having undetected parts error
$QC2_{Kj}$	(€/piece)	cost for correcting detected parts error at workstation
QC_K	(€/piece)	quality cost due to kitting errors
R	(trip/day)	daily number of retrievals
RA	(m)	robot aisle width for case IV
RAM	(h/day)	daily robot available hours
RCK	(€/m^3)	storage rack cost per unit volume
RI	(day)	replenishment interval
rl	(m)	rack length
RN	(-)	gravity rack ramps number
rw	(m)	rack width
RWH	(h)	time to perform robotic picking and kitting
t	(h)	time
T_a	(h/piece)	time to reassemble a defective end item
T_{BR}	(s)	unit time to remove and evacuate one empty bin
$T_{BR\ Tot}$	(s)	total time to remove and evacuate empty bins
Tck	(h)	time to check all part in a kit
t_{ck}	(s)	time to check one unit of a part type
T_{CR}	(-)	substitution time of an empty part container
T_d	(h/piece)	time to disassemble one end product
$TECC_K$	(€/yr)	total expected annual error correction cost
T_i	(h/piece)	inspection time
Tin	(h)	time to insert items into a kit
TK	(h)	time to prepare one kit
t_{kit}	(s)	time to kit one unit of a part type
TKT	(h/day)	total work man-hours for manual operations
Tm	(h)	average miniload cycle time
tm_{DC}	(s)	time duration of dual command AS/RS cycle
tm_{SC}	(s)	time duration of single command AS/RS cycle

Tp	(h)	unit picking time
T_{PP}	(s)	robotized picking and placing time for each component
$T_{PP\ Tot}$	(s)	total robotized picking and placing time
T_{PR}	(s)	time to remove each interlayers /divider of a container
$T_{PR\ Tot}$	(s)	total time to remove interlayers sheet in part container
Tps	(h)	time to pick parts
TR	(SKU/h)	required warehouse throughput
$Trepl$	(h)	warehouse replenishment time
T_{RK}	(h)	robot time to produce one kit
Trl	(h)	time to stow away ready kit before delivery
T_S	(s)	robot stopping time in front of a storage location
$T_{T\ Tot}$	(s)	total travel time along picking aisle for system IV
T_{TC}	(s)	unit tool change time for robot
$T_{TC\ Tot}$	(s)	total tool change time to prepare one kit
T_V	(s)	image capture and processing time for each component
$T_{V\ Tot}$	(s)	total image acquisition and processing time for vision system
V	(m^3)	volume
VC	(m^3)	volume of stock keeping unit
VDD	(m^3/day)	gross volume of daily needed components
v_R	(m/s)	robot advancement speed
v_{tp}	(m/s)	operator walking velocity
v_x	(m/s)	velocity in x direction for miniload and AS/RS cranes
v_y	(m/s)	velocity in y direction for miniload and AS/RS cranes
W	(day/yr)	annual work days
WAR	(m)	full aisle width for case IV
WR	(m)	flow rack width for case IV
Ws	(m)	stock keeping unit dimension parallel to the aisle
WV	(SKU)	required warehouse capacity
$xSKU_R$	(-)	stock keeping unit axis parallel to the aisle

SUBSCRIPT

AS/RS	automated storage and retrieval system
C	container
ck	check
e	equivalent
i	component type
j	end product type
K	kitting
max	maximum
mK	kitting department
R	picking/kitting robot
$RFID$	radio frequency identification system
sK	sufrace of kitting department
SR	storage racks
wK	personnel

GREEK SYMBOLS

α	(-)	binary variable
β	(-)	binary variable
γ	(-)	binary variable
δ	(-)	probability of having an error free kit
ε	(-)	overall probability of kitting error detection by line operator
η	(-)	probability of part presence into a kit

η_{op}	(-)	operator efficiency
θ	(-)	probability of error in a kitted part selection
ι	(-)	probability of a kitted part quantity error
κ	(-)	probability of a kitted part damage
λ	(-)	probability of a kitted part positional mistake
μ	(-)	probability of a kitted error detection
ξ	(-)	filling coefficient of a container
τc	(-)	capital recovery factor
τr	(-)	capital recovery factor for RFID system
$\tau rack$	(-)	capital recovery factor for rack system
ω	(-)	numerical parameter

Appendix

In order to compute the Total Error Correction Cost a mapping of possible error conditions is required. This may be accomplished by using binary event trees. A binary event tree depicts a sequence of possible events (nodes) having only two outcomes (event occurring or not), represented by branches departing from nodes. Each branch has an assigned probability of occurrence. Each sequence of events (paths through the tree) determines a possible final outcome, having as a probability the product of probabilities associated to the branches describing the path from the tree root to the considered final outcome. Figure A.1 depicts the occurrences of logic errors in a kitting process.

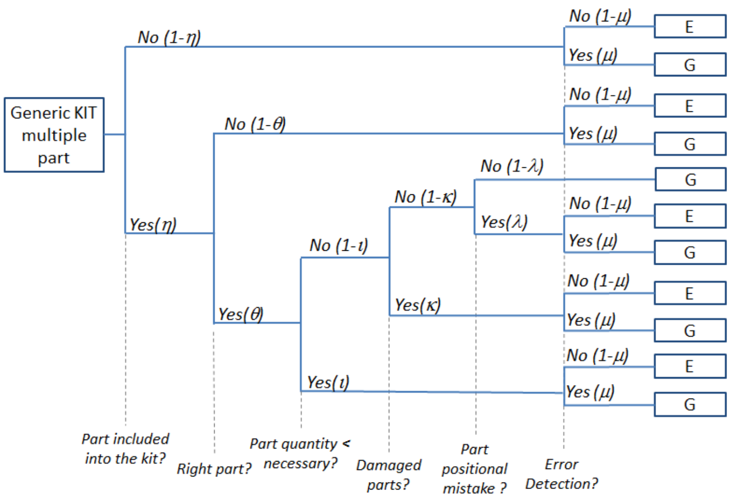


Figure A.1. Kitting errors event tree.

According to the tree in Figure A.1, the overall probability p_G of not having a kitting error for the generic part is the sum of probabilities associated with a Good (G) outcome

$$p_G = 1 - p_E = \mu + \eta\theta(1-\iota)(1-\kappa)(1-\lambda)(1-\mu) \tag{A.1}$$

However, it is convenient to distinguish between two parts typologies, namely parts of Type A where a single unit of that part type has to be included into the kit, and parts of Type B, where a given multiplicity of items of the same type has to be included. In the latter case a counting error may occur resulting in the kit containing a multiplicity lower that the required one (in fact, a multiplicity higher than the required one does not result in parts shortage and is not accounted as an error given that extra parts can be returned to the warehouse). Therefore, probability $p_{G,B}$ of not having a kitting error for the generic part of Type B can be directly computed according to Equation (A.1), while probability $p_{G,A}$ of not having a kitting error for the generic part of Type A is computed using the same Equation (A.1) but imposing $\iota = 0$. Considering that a kit for the *j-th* end product contains $N_{Aj} = \sum_{i=1}^{N} \alpha_{ij}$ part types of Type A and $N_{Bj} = \sum_{i=1}^{N} \beta_{ij}$ part types of Type B, and assuming for simplicity that error probabilities do not depend on specific parts attributes (i.e the error probability is independent from the type of part being handled) the overall probability δ_j of having a mistake-free kit is the product of probabilities p_G of not having errors for all parts of Type A and Type B included into the kit.

$$\delta_j = \left(p_{GA}^{N_{Aj}}\right)\left(p_{GB}^{N_{Bj}}\right) \quad \text{(A.2)}$$

Moreover, in average a generic kit will contain $N_{EKAj} = p_{EA} N_{Aj}$ parts types of Type A with one or more errors, and $N_{EKBj} = p_{EB} N_{Bj}$ parts types of Type B with one or more errors, being $p_{EA} = 1 - p_{GA}$ and $p_{EB} = 1 - p_{GB}$ respectively.

The event tree for assessing errors in the kits usage process is instead depicted in Figure A.2. Please note that errors in kit delivery are not considered here because do not depend on the way kitting is performed. In this case the events to be tracked are that the kit is error-free (yes/no), and that the line operator detects all parts errors within the kit (yes/no).

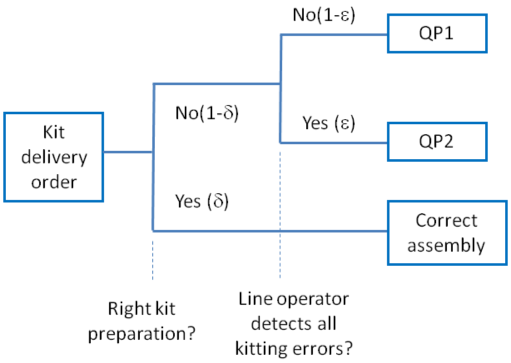


Figure A.2. Kitting process errors event tree.

Referring to Figure A.2 defining p_{DE} as the probability that the line operator detects an error in a generic part included into the kit, then the probability ε_j that the operator detects all potential errors in a *j-th* kit type is the product of error detection probabilities for all expected non conforming part types ($N_{EKAj} + N_{EKBj}$)

$$\varepsilon_j = p_{DE}^{(N_{EKAj}+N_{EKBj})} \quad \text{(A.3)}$$

Therefore, the following Quality Problems (QP) may arise which bear a corresponding correction or quality cost.

QP1 = end of line correction of errors from utilization of kits having undetected parts errors.
QP2 = before-assembly correction, at the workstation, of detected parts errors within a kit.

Based on the event tree of Figure A.2 the probabilities for the possible QPs, for each utilized kit, are.

$$p_{QP1_{kj}} = (1 - \delta_j)(1 - \varepsilon_j) \quad \text{(A.4)}$$

$$p_{QP2_{kj}} = \varepsilon_j(1 - \delta_j) \quad \text{(A.5)}$$

Error correction cost includes correction of kitting errors detected by the line assembler (i.e. replacement of wrong or damaged components inserted in the kit, or picking of missing components, which implies a jolly operator to return to the kitting area and pick a substitute part), bearing a unit cost CDE_K (€/error).

$$CDE_K = \left(T_p + \frac{2d_{avg}}{v_{tp}}\right)C_{oh} \tag{A.6}$$

Otherwise the off-line correction of undetected errors is required. In the latter case a unit cost CRQ_K (€/error) occurs,

$$CRQ_K = CDE_K + (T_d + T_i + T_a)\, C_{oh} \tag{A.7}$$

where T_p (h) is the time to pick the replacement component in the kitting area, d_{avg} the average distance between the kitting area and workstations, v_{tp} the walking velocity of the operator or the speed of the material handling vehicle, C_{oh} (€/h) the operator's hourly cost, T_d (h) the time to disassemble the end product to replace a component, T_i (h) the inspection time needed to identify the component to be replaced, T_a (h) the time to reassemble the end item. We also assume that all errors in a kit will be corrected, either on line or off line, so that only conforming products are sold to customers.
Therefore, the following possible quality costs expressions (QC_K) can be associated to the previously identified QPs outcomes for each kit handled.

$QC1_{Kj}$: Cost for end of line correction of errors from assembly of kits having undetected parts errors. This includes three separate contributions, namely the end of line correction of the expected number of undetected errors in both Type A and Type B parts, the end of line correction of assembly errors related to error-free parts contained in the kit (accounted for by the error probability p_{EA} when assembling a part), and the before-assembly correction of detected parts errors, as shown in Equation (A.8) where $N_{EKj} = N_{EKAj} + N_{EKBj}$ and $N_j = N_{Aj} + N_{Bj}$.

$$QC1_{Kj} = CRQ_K(1 - p_{DE})(N_{EKAj} + N_{EKBj}) + CRQ_K\, p_{EA}\left[(N_{Aj} - N_{EKAj}) + (N_{Bj} - N_{EKBj})\right] + \left[(p_{DE}\, N_{EKAj})(CDE_K + p_{EA}\, CRQ_K)\right] + \left[(p_{DE}\, N_{EKBj})(CDE_K + p_{EA}\, CRQ_K)\right] = CRQ_K\left[N_{EKj}\,(1 - p_{DE})(1 - p_{EA}) + N_j p_{EA}\right] + p_{DE}\, N_{EKj}\, CDE_K \tag{A.8}$$

$QC2_{Kj}$: Cost for correcting at workstation detected parts errors within a kit for EP_j before assembly

$$QC2_{Kj} = CDE_K\, N_{EKj} \tag{A.9}$$

Obviously the type of adopted kitting system (i.e. manual, hybrid, automation-assisted or robotic) will affect number of manual operations to be carried out and their error rate, impacting on the values of p_{EA}, p_{EB}, p_{GA}, and p_{GB} which, in turn, will affect δ_j, ε_j, N_{EKAj}, N_{EKBj}, p_{QP1Kj}, p_{QP2Kj}, $QC1_{Kj}$, $QC2_{Kj}$. Please note that $\iota = 0$ for Type A parts irrespective of the adopted kitting system, while probabilities ι, κ, λ, μ do not depend from the chosen kitting system (see Table 2). For Type IV system, picking errors are related to a subset of components for which robotic kitting is technically not feasible ($\gamma_{ij} = 0$) and kit preparation is performed by human operators. This is why system error probability values in Table 1 for Type II and Type IV are the same.

REFERENCES

Azadeh, K., De Koster, R., Roy, D., (2017), Robotized warehouse systems: Developments and research opportunities, Available at SSRN at http://dx.doi.org/10.2139/ssrn.2977779

Balakirsky, S., Kootbally, Z., Kramer, T., Pietromartire, A., Schlenoff, C., Gupta, S. (2013). Knowledge driven robotics for kitting applications. *Robotics and Autonomous Systems*, Vol. 61, 1205-1214.

Boudella, M.E.A., Sahin, E., Dallery, Y. (2016). A mathematical model to assess the performance of a robotic kitting system in an assembly plant. Proc of the 11th International Conference on Modeling, Optimisation and Simulation, Montreal, August 22-24.

Boudella, M.E.A., Sahin, E., Dallery, Y.,(2017).Modelling kitting operations in a semi-robotic environment, Proc. 7th IESM Conference, October 2017, Saarbrucken, Germany.

Boudella, M.E.A., Sahin, E., Dallery, Y., (2018). Kitting optimisation in Just-in-Time mixed-model assembly lines: assigning parts to pickers in a hybrid robot–operator kitting system, International Journal of Production Research, Vol. 56, 16, pp. 5475-5494.

Boysen, N., Emde, S., Hoeck, M., Kauderer, M. (2015), Parts logistics in the automotive industry: Decision problems, literature review and research agenda, European Journal of Operational Research, Vol. 242, pp. 107-120.

Boysen, N., Briskorn, D., Fedtke, S., Schmickerath, M., (2018), Automated sortation conveyors: A survey from an operational research perspective, https://doi.org/10.1016/j.ejor.2018.08.014

Boysen, N., De Koster, M.B.M., Weidinger, F., 2018, Warehousing in the e-commerce era: A survey, European Journal of Operations Research, https://doi.org/10.1016/j.ejor.2018.08.023.

Bozer, Y.A., Aldarondo, J., (2018), A simulation –based comparison of two good-to-person order picking systems in an online retail setting, International Journal of Production Research,Vol. 56, pp. 3838-3858.

Bozer, Y.A., McGinnis, L. F. (1992). Kitting versus line stocking: A conceptual framework and a descriptive model. *Int. J. of Production Economics*, Vol. 28, 1-19.

Bozer, Y.A., White, J. A. (1984). Travel-Time Models for Automated Storage/Retrieval Systems. *IIE Transactions*, Vol.16 (4), 329 - 338.

Bozer, Y.A., White, J.A., (1990), Design and performance models for End-Of-Aisle order picking systems, Management Science, Vol. 36, 7, pp. 852-866.

Brynzér, H., Johansson, M.I. (1995). Design and performance of kitting and order picking systems. *Int. J. of Production Economics*, Vol. 41, 115-125.

Cai, X., Heragu, S.S., Liu, Y., (2014), Modeling and evaluating the AVS/R with tier-to-tier vehicles using a semi-open queueing network, IIE Transactions, Vol. 46, 9, pp. 905-927.

Caputo, A.C., Pelagagge, P.M. (2011). A Methodology for Selecting Assembly Systems Feeding Policy. *Industrial Management and Data Systems*,Vol. 111 (1), 84-112.

Caputo, A.C., Pelagagge, P.M., Salini, P. (2015a), A model for kitting operations planning, Assembly Automation, Vol. 35, No. 1, pp. 69 - 80.

Caputo, A.C., Pelagagge, P.M., Salini, P. (2015b), A Decision Model for Selecting Parts Feeding Policies in Assembly Lines, Industrial Management and Data Systems,Vol. 115, No. 6, pp. 974-1003.

Caputo, A.C., Pelagagge, P.M., Salini, P. (2017a), Modeling Errors in Parts Supply Processes for Assembly Lines Feeding, Industrial Management & Data Systems, Vol. 117, 6, pp. 1263-1294.

Caputo, A.C., Pelagagge, P.M., Salini, P. (2017b), Modeling Human Errors and Quality issues in Kitting Processes for Assembly Lines Feeding, Computers & Industrial Engineering, Special Issue on Human factors in industrial and logistic system design, Vol. 111, pp. 492-506.

Caputo, A.C., Pelagagge, P.M., Salini, P. (2018a), Economic comparison of manual and automation-assisted kitting systems, IFAC INCOM Conference, 11-13 June 2018, Bergamo, Italy, IFAC-PapersOnLine, Vol. 51, 11, 1482-1487.

Caputo, A.C., Pelagagge, P.M., Salini, P. (2018b), Selection of assembly lines feeding policies based on parts features and scenario conditions, International Journal of Production Research, Vol. 56, 3, pp. 1208-1232.

Caron F., Marchet, G., Wegner, R. (1997). Impianti di movimentazione e stoccaggio dei materiali. Criteri di progettazione. Hoepli, Milan, Italy (in Italian).

Dallari, F., Marchet, G., Melacini, M., (2009), Design of order picking systems, International Journal of Advanced Manufacturing Technology, Vol. 42, pp. 1-12.

De Koster, R., (2004), How to assess a warehouse operation in a single tour, RSM Erasmus University, The Netherlands.

De Koster, R., Le Duc, T., Roodbergen, K.J., (2007), Design and control of warehouse order picking: A literature review, European Journal of Operational Research, Vol. 182, 2, pp. 481-501.

Ekren, B.Y., Heragu, S.S., Krishnamurthy, A., Malmborg, C.J., 2014, Matriz-geometric solution for semi-open queuing network model of autonomous vehicle storage and retrieval system, Computers & Industrial Engineering, Vol. 68, pp. 78-86.

Foley, R.D., Frazelle, E.H., (1991), Analytical results for miniload throughput and the distribution of dual command travel time, IIE Transactions, Vol. 23, 4, pp. 273-281.

Foley, R.D., Hackman, S.T., Park, B.C., 2004, Back-of-the-envelope miniload throughput bounds and approximations, IIE Transactions, Vol. 36, 3, pp. 279-285.

Fukunari, M., Malborg, C.J., (2009), A network queuing approach for evaluation of performance measures in autonomous vehicle storage and retrieval systems, European Journal of Operational Research, Vol. 193, pp. 152-167.

Hanson, R. (2012). *In-plant materials supply: Supporting the choice between kitting and continuous supply*. Ph.D. Thesis, Department of Technology Management and Economics Division of Logistics and Transportation, Chalmers University of Technology, Göteborg, Sweden.

Hanson, R., Medbo, L., Johansson, M.I., (2018), Performance Characteristics of Robotic Mobile Fulfillment Systems in Order picking applications, IFAC_PapersOnLine, Vol. 51, 11, pp. 1493-498.

Heragu, S.S., Cai, H., Krishnamurthy, A., Malmborg, C.J., (2011), Analytcal models for analysing automated warehouse material handling systems, International Journal of Production Research, Vol. 49, 22, pp. 6833-6861.

Holmström, J. and Partanen, J., (2014), "Digital manufacturing-driven transformations of service supply chains for complex products", Supply Chain Management: An International Journal, Vol. 19, No. 4.

Hwang, H., Ha, J.-W., (1991), Cycle time models for single/double carousel system, International Journal of Production Economics, Vol. 25, pp. 129–140.

Hwang, H., Moon, S. and Gen, M. (2002),"An integrated model for the design of end-of-aisle order picking system and the determination of unit load sizes for AGVs", *Computers & Industrial Engineering*, Vol. 42, pp. 249-258.

Khajavi, S., Partanen, J., Holmström, J., (2014), Additive manufacturing in the spare parts supply chain: A case study of the F-18E/F, Computers in Industry, Vol. 65, No. 1, pp. 50-63.

Khojasteh, Y., Son, J.D., (2016), A travel time model for order picking systems in automated warehouses, International Journal of Advanced Manufacturing Technology, Vol. 86, pp. 2219-2229.

Kilic, S.H., Durmusoglu, B.M. (2015), Advances in assembly line parts feeding policies: a literature review, Assembly Automation, Vol. 35, No. 1, pp. 57 - 68.

Kuo, P.H., Krishnamurthy, A., Malmborg, C.J., (2007), Design models for unit load storage and retrieval systems using autonomous vehicle technology and resource conserving storage and dwell point policies, Applied Mathematical Modelling, Vol. 31, pp. 2332-2346.

Lamballais, T., Roy, D., De Koster, M.B.M., (2017), Estimating performance in a Robotic Mobile Fulfillment System, European Journal of Operational Research, Vol. 256, 3, pp. 976-990.

Landscheidt, S., Kans, M., 2016, Method for assessing the total cost of ownership in industrial robots, Procedia CIRP, Vol. 57, pp. 746-751.

Lerher, T., Srami, M., (2012), Designing unit load automated storage and retrieval systems, in Manzini, R. (Ed.) Warehousing in the Global Supply Chain, Springer, pp. 211-232.

Lerher, T., Ekren,B.Y., Dukic, G., Rosi, B., (2016), Travel time model for shuttle-based storage and retrieval systems, International Journal of Advanced Manufacturing Technology, Vol. 78, pp. 1705-1725.

Liang, C., Chee, K.J., Zou, Y., Zhu, H., Causo, A., Vidas, S., Teng, T., Chen, I.M., Low, K.H., Cheah, C.C., (2015), Automated robot picking systems for E-commerce fulfillment warehouse applications, Proc. 14th IFToMM World Congress, October 25-30, Taipei, Taiwan.

Limère, V., Van Landeghem, H. (2009), Cost model for parts supply in automotive industry, Proc. 16th European Concurrent Engineering Conference (ECEC'2009), 15-17 April, Brugge, Belgium.

Limère, V., Van Landeghem, H., Goetschalckx, M., Aghezzaf, E.H., McGinnis, L.F. (2012), Optimising part feeding in the automotive assembly industry: deciding between kitting and line stocking, Int. J. of Production Research, Vol. 50, No. 15, pp. 4046-4060.

Litvak, N., Vlasiou, M., (2009), A survey on performance analysis of warehouse carousel systems, Eurandom Technical Report, TU Eindhoven, The Netherlands.

Liu, T., Gong, Y., De Koster R.B.M., (2018), Travel time models for split-platform automated storage and retrieval systems, International Journal of Production Economics, Vol. 197, pp. 197-214.

Lyly-Yrjänäinen, J., Holmström, J., Johansson, M.I., Suomala, P. (2016), Effects of combining product-centric control and direct digital manufacturing: The case of preparing customized hose assembly kits, Computers in Industry, Vol 82, pp. 82–94.

Marchet, G., Melacini, M., Perotti, S., Tappia, E., (2012), Analytical model to estimate performances of autonomous vehicle storage and retrieval systems for product totes, International Journal of Production Research, Vol. 50, 24, pp. 7134-7148.

Marchet, G., Melacini, M., Perotti, S., Tappia, E., (2013), evelopment of a framework for the design of autonomous vehicle storage and retieval systems, International Journal of Production Research, Vol. 51, 14, pp. 4365-4387.

Meller, R. D., Klote, J. F., (2004). A throughput model for carousel/VLM pods, IIE Transactions, Vol. 36, pp. 725–741.

Park, B. C., Park, J. Y., Foley, R. D., (2003). Carousel system performance, Journal of Applied Probability, Vol. 40,pp. 602–612.

Polydoros, A.S., B. Großmann, F. Rovida, Nalpantidis, L., Krüger, V. (2016). Accurate and Versatile Automation of Industrial Kitting Operations with SkiROS. Proc. 17th Annual Conference TAROS, Sheffield, UK, June 26 - July 1.

Roodbergen, K.J., Vis, A.F.A., (2009), A survey of literature on automated storage and retrieval systems, European Journal of of Operational Research, Vol. 194, pp. 343-362.

Roy, D., Krishnamurthy, A., Heragu, S.S., Malmborg, C.J., (2012), Performance analysis and design trade-offs in warehouses with autonomous vehicle technology, IIE Transactions, Vol. 44, 12, pp. 1045-1060.

Sari, Z., Saygin, C., Ghouali, N., (2005), Travel-time models for flow-rack automated storage and retrieval systems, International Journal of Advanced Manufacturing Technology, Vol. 25, pp. 979-987.

Schmid, N.A., Limère, V., Raa, B., (2018), Modeling variable space in assembly line feeding, IFAC-PapersOnLine, Vol. 51, 11, pp. 164-169.

Sellers, C.J. and Nof, S.Y. (1986), "Part kitting in robotic facilities", *Material Flow*, Vol. 3, pp. 163-174.

Sellers, C.J., Nof, S.Y. (1989). Performance analysis of robotic kitting systems. *Robotics & Computer-Integrated Manufacturing*, Vol. 6 (1), 15-24.

Sali, M., Sahin, E., Patchong, A. (2015), An empirical assessment of the performances of three line feeding modes used in the automotive sector: line stocking vs. kitting vs. sequencing, Int. J. of Production Research, Vol. 53, No. 5, pp. 1439-1459.

Tamaki, K., Nof, S.Y. (1991). Design method of robot kitting system for flexible assembly. *Robotics and Autonomous Systems*, Vol. 8(4), 255 – 273.

Tappia, E., Roy, D., Melacini, M., De Koster, R., (2019), Integrated storage-order picking systems: Technology, performance models, and design insights, European Journal of Operational Research, Vol. 274, 3, pp. 947-965.

Usta, S.K., Oksuz, M.K., Durmusoglu, M.B., (2017), Design methodology for a hybrid part feeding system in lean-based assembly lines, Assembly Automation, Vol. 37, 1, pp.84-102.

Van Gils, T., Ramaerkers, K., Caris, A., De Koster R.B.M., (2018), Designing efficient order picking systems by combining planning problems: State-of-the-art classification and review, European Journal of Operational Research, Vol**.** 267, 1, 16, pp. 1-15.

Vasili, M.R., Tang, S.H., Vasili, M., (2012), Automated storage and retrieval systems: A review on travel time models and control policies, in Manzini, R. (Ed.) Warehousing in the Global Supply Chain, Springer, pp. 159-2010.

Xiang, X., Liu, C., Miao, L., (2018), Storage assignment and order batching problem in Kiva mobile fulfillment system, Engineering Optimization, https://doi.org/10.1080/0305215X.2017.1419346.

Yoon, C.S., Sharp, G.P., (1996), A structured procedure for analysis and design of order pick systems, IIE Transactions, Vol. 28, 5, pp. 379-389.

Yuan, Z., Gong, Y., (2017), Bot-in-time delivery for Robotic Mobile Fulfillment Systems, IEEE Transactions on Engineering Management, Vol, 64, 1, 83-93.

Zijm, W.H.M., Adan, I.J.B.F., Buitenhek, R., van Houtum, G.J., (2000), Capacity analysis of an automated kit transportation system, Annals of Operations Research, Vol. 93, pp. 423-446.

Zou, B., Gong, Y., Xu, X., Yuan, Z., (2017), Assignment rules in robotic mobile fulfillmentsystems for online retailers, Internatinal Journal of production Research, Vol. 55, 20, pp. 6175-6192.