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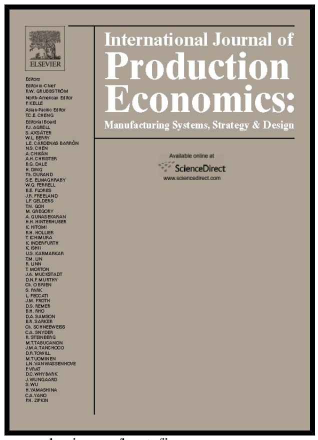

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PII: S0925-5273(16)00010-4
DOI: http://dx.doi.org/10.1016/j.ijpe.2016.01.009
Reference: PROECO6321

To appear in: *Intern. Journal of Production Economics*

Received date: 22 August 2014
Revised date: 25 November 2015
Accepted date: 12 January 2016

Cite this article as: Mustapha Sali and Evren Sahin, Line feeding optimization fo Just in Time assembly lines: an application to the automotive industry, *Intern Journal of Production Economics,* http://dx.doi.org/10.1016/j.ijpe.2016.01.009

Line feeding optimization for Just in Time assembly lines: an application to the automotive industry

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Abstract

The performance of mixed-model assembly lines used in sectors such as the automotive industry depends on the availability of a large number of components that have to be supplied to the line on time and at minimum cost. In such settings, components may have different features such as volume, weight, bill of material coefficient, etc. Additionally, a given component may have several alternative variants among which a single one is used in the assembly of end products. Each variant is thus characterized by a varying degree of usage rate. Hence, the diversity of parts requires the selection of the best assembly line feeding mode that aims at minimizing the average total operating cost which mainly consists of labor costs associated with parts preparation before assembly, transportation to the line, picking operations during assembly, as well as parts storage cost. This paper proposes an optimization model that assigns each individual component to the most efficient line feeding mode among three alternatives which are line stocking, kitting and sequencing modes. The developed mixed integer program is applied to a first tier supplier plant in the automotive sector. Based on this model, insight is gained on the trade-off to be considered when deciding the more appropriate line feeding mode for each individual component and how system parameters impact this trade-off.

Keywords: in-plant logistics, line feeding, material handling, kitting, sequencing, line stocking.

1. Introduction

Just In Time (JIT) automotive part assembly plants are characterized by high end-products diversity and synchronous assembly based on customer order sequence. In such production systems, end product diversity stems from the combination of different components associated with different end product configurations. Hence, each component has several "variants" that enter the assembly of a specific end product. For instance, in a seat assembly plant, a headrest is a generic component which may have several variants which differ in terms of color and texture. The diversity of components, i.e. the increasing number of variants, contributes to the increase of internal logistic processes that aim at supplying the components necessary for assembly to the Border of Line (BoL), which is the area parallel to the assembly line where parts are stored. Indeed, practitioners are continuously in search of innovative practices to improve the line feeding process which aims at preparing and delivering components to the BoL at minimum cost. As a consequence, new line feeding modes such as "kitting" and "sequencing" have been introduced recently (Hanson and Brolin 2013) to challenge the performance of the traditionally used "line stocking" feeding mode. In this paper, we propose a mathematical model that supports the decision of selecting the most efficient line feeding mode for each component in order to minimize the average total operating cost.

According to Johansson (1991), three principal modes, namely continuous supply, batch supply, and kitting, can be used for feeding the line. Johansson and Johansson (2006) introduce a fourth approach that is called "sequential supply" or "sequencing". Continuous supply consists of storing all parts (i.e. all variants associated to a given component) used for assembly near their point of use at the BoL, in individual boxes. A box corresponds to the container that regroups several units of the same variant. The replenishment of the stock hold at the BoL is usually performed by a consumption renewal or a kanban type signal. Batch supply differs from continuous supply in the sense that parts arriving from the supplier are repackaged into smaller boxes before they are delivered at BoL to obtain quantities that correspond to the requirement for the assembly of a batch of end products. Since all parts are stored at BoL in both continuous and batch supply, they are grouped under the generic term "line stocking" in the existing literature. In the remainder of this paper, the term "line stocking" refers to continuous supply since batch supply do not fall within the scope of our study.

Line stocking requires large storage areas since full boxes of all variants used in assembly need to be stored at BoL. This mode also leads to large walking distances for operators to fetch parts that have to be assembled. Hence, two alternative modes, i.e. kitting and sequencing, are introduced to supply parts to the line. Instead of storing all parts at the BoL, under these modes, only the specific variants needed for the forthcoming end products to be assembled are brought at BoL. In the kitting mode, variants are put in containers that either follow the end products to be assembled on the assembly line conveyor (i.e. travelling kits) so that variants that are in each container are used in more than one workstation, or they are supplied close to each assembly workstation (i.e. stationary kits). Sequencing is a particular form of stationary kit where only one part reference, i.e. the variants of a specific component, is carried per kit. Because each end product that is assembled on the line is equipped with specific variants requested by the customer, kit containers and sequenced parts are supplied to the line in a specific order that corresponds to the production schedule provided by the customer.

Although kitting and sequencing require an additional parts preparation process which is usually performed upstream the line, they contribute to reduce parts inventory stored at the BoL (Hua and Johnson 2010). Reduced stock at the BoL means less crowded BoL storage and reduced operator travels to retrieve parts needed. Aside from these (potentially) quantifiable advantages, the performance of line feeding modes also vary according to some qualitative criteria such as operators' ergonomic conditions, production flexibility in case of defects or assembly sequence change, ease of re-balancing the line, etc. that are not considered in this study.

Our study is based on the case of a first tier supplier that assembles seats for automakers in JIT mixed-model assembly lines. The importance of performing parts handling operations efficiently is a top company priority because of the large number of transactions occurring in the physical flow (and the associated financial flow) of the plant every day. Hence, materials feeding principle of travelling kits and sequencing have been recently introduced in several pilot plants as alternatives to line stocking. This was done with the objective of space savings at the BoL, reduction in assembly operator walking distances and greater flexibility for balancing the line. However, there is actually a lack of studies describing the relative benefit of implementing kitting and sequencing, in comparison with line stocking. The company is therefore interested in comparing the performance of these three line feeding modes on quantitative bases.

The aim of this paper is to develop a mathematical model that supports the decision of selecting the most efficient line feeding mode for each individual component in order to minimize an average total operating cost. Costs considered are mainly related to BoL picking operations, in-plant transportation, parts' preparation before assembly, and parts' storage cost. Since each mode has distinct operating characteristics (and therefore different cost), our model aims at getting insights regarding the choice of one mode over others, for each component level. Hence, the first contribution of this paper is to properly identify all cost components pertaining to each line feeding mode and to propose a mathematical formulation of the total operating cost. Our second contribution is the development of a decision making model that determines the optimal assignment of components to the different modes. Finally, we use the model to conduct a complete numerical analysis that shows how system parameters (such as variant and plant layout characteristics, times associated with operators' unit movements, etc.) affect the optimal assignment.

Our paper is organized as follows. Section 2 gives a synthesis of the literature comparing the performance of different line feeding modes. Section 3 describes the line feeding process and presents our modeling assumptions. Based on this description, Section 4 develops the mathematical model. Section 5 provides details on the numerical study conducted based on the case company considered. Section 6 proposes a sensitivity analysis carried out on the optimal solution. To conclude, further research perspectives to extend this study are discussed in Section 7.

2. Literature review

The line feeding problem receives still an attracting interest from practitioners and academic researchers as reported by Kilic and Durmusoglu (2015) and Boysen et al. (2015). Despite this interest, the literature does not provide clear insights that would help decision makers to select the right line feeding mode. Indeed, some authors emphasize that kitting is better performing than line stocking (Ding 1992) while other research reports some opposite conclusions (Field 1997). The objective of the literature review presented in this section is to analyze studies that aim at comparing the performances of several line feeding modes, with a quantitative approach.

Hence, Bozer and McGinnis (1992) propose a preliminary model to quantify the trade-offs in terms of material handling, shop floor space requirements and work-in-process between kitting and line stocking. This represents the first model that targets a quantitative comparison between the two feeding modes. Caputo and Pelagagge (2011) adapt the previous model of Bozer and McGinnis by considering three modes namely line stocking, kitting and continuous supply. They provide analytical expressions for work-in-process, material handling, and space utilization under each mode. An ABC-analysis is used as a basis for developing hybrid policies. Their model considers the case of a single product which eliminates a part of the complexity observed in real multi-product assembly lines where end product diversity implies parts diversity where components are declined in several variants. In a more recent paper (Caputo and Pelagagge 2015), the same authors propose an optimization model allowing the choice of parts feeding policy among kitting, line stocking and continuous supply in order to minimize the total operating cost including work in process inventory. The context studied remains a single-model assembly line where, among policies considered, the sequencing mode is not analyzed.

Battini and al. (2009) consider three feeding modes; pallet to work station (i.e. line stocking), trolley to work station (i.e. stationary kit), and kit to assembly line (i.e. traveling kit). They simultaneously consider the centralization versus decentralization decision of components storage as well as the choice of the right feeding policy. The centralization problem is addressed through a search of a tradeoff between inventory and material handling costs. Then, based on a multi-factorial analysis involving parameters such as lot size, number of components, and distance between warehouse and assembly line, a single optimal feeding mode is chosen for the complete line. Because of the focus on multi-model assembly lines (and not Mixed-model assembly lines), this study does not enable to assess the impact of component diversity on the performance of line feeding modes. The work of Hua and Johnson (2010) is a more qualitative study that enumerates factors that influence the choice between kitting and line stocking. Hence, production volume, component variety and size are identified as important factors for decision making. According to the authors, the relatively large variety of components would push towards kitting while line stocking would likely be the best option in settings where products use similar components.

Based on two qualitative case studies, Hanson and Brolin (2013) identify the effects of kitting and continuous supply on man-hour consumption, product quality, the flexibility, the inventory levels, and the space requirements. According to authors, the kitting man-hour consumption exceeds the one of continuous feeding. The time required to pick each part in preparing the kits exceeds the time saved at the assembly line. Kitting improves the product's quality by avoiding errors in assembly. Moving kits enhance the assembly line flexibility by facilitating the rebalancing as it is possible to move assembly tasks between assembly stations without rearranging the component racks. Inventory levels remain relatively identical when moving from continuous feeding to kitting. Even if the overall space requirements at the assembly plant (including the kit preparation area) increase as a result of the introduction of a specific kitting area, one of the most interesting advantages offered by kitting is that it frees space at the assembly line. Despite the descriptive interest of their study, Hanson and Brolin (2013) do not provide any operational mean to make trade-offs between kitting and line stocking to support the decision making.

In their paper, Sali and al. (2015) propose a total cost formulation of processes related to line stocking, kitting and sequencing modes in the context of mixed-model assembly line. Authors provide some empirical results on the behavior of cost components depending on parts' characteristics, instead of developing an optimization problem. Faccio (2014) compares the cost of three feeding policies (Kanban continuous supply, Kitting and hybrid policy). Through a simulation study, he derives a decision-making tool to identify the best feeding policy definition. The results obtained from the proposed model are observations that remain very general and that ignore the operational constraints related to the line feeding processes.

Limère and al. (2012) propose a mixed integer program that aims at minimizing a total labour cost by assigning components to one of two possible line feeding modes: kitting, in its stationary version, or line stocking. Results obtained show that a configuration where all components are line stocked would be the best option in terms of reduced cost. In the optimization model, this option is restricted by the space constraint which forces some components to be kitted. Authors also show that, in some cases, kitting can be preferred to line stocking even when there is no space constraint. However, conditions that make a component a desirable candidate for kitting are not explicitly explored. Furthermore, while formulating the cost related to operators moving under the line stocking mode, Limère and al. (2012) simplify the problem by considering three categories of component variants defined according to the range of average consumption. Variants belonging to the same category (i.e. variants whose average consumptions are in the same range) are assumed to be located at the same place at the BoL. In contrast, we consider that each variant has its proper location to take into account the impact of diversity on the operator moving cost. Limière and al. (2015) propose an extension of the previous model and consider variable operator walking distances at the BoL. Authors also provide an interesting analysis that demonstrates how the specific part characteristics influence the chances of a part being kitted.

The methodology used in our study is close to the one used by Limère and al. (2012, 2015). Nevertheless, when comparing the modelling approaches and the scope of the analysis, some important differences are worth noting. Hence, Limère and al. (2012, 2015) focus on only two line feeding modes while we analyse three line feeding modes namely, kitting (in its traveling version), line stocking, and sequencing. Additionally, in our model, binary decision variables are defined at component level. By doing so, we reduce the size of the problem and eliminate a useless constraint. The delivery of parts is also modelled differently since we assume that a tugger train is shared by all modes. Furthermore, in (Limère and al. 2012, 2015) space is assumed to be a constraint with no associated cost, and takt time constraints are not formulated. Some additional minor differences exist regarding layout configuration and the way the preparation process is carried in batches: in our model, we assume centralized components storage, preparation areas dedicated to each mode, shared tugger train between all modes.

3. Process description

This section describes the overall line feeding process based on the operations of an automotive parts supplier company. The process description as well as assumptions provided in this section form the basis of the mathematical model proposed in Section 4.

First, Section 3.1 provides the general assumptions (valid for all line feeding modes) of the study. Then, Section 3.2 presents the specific assumptions related to each process and highlights the main differences observed between the three line feeding modes considered.

3.1. General assumptions

Main processes concerned with line feeding are the preparation of parts before assembly, the transportation that is realized by a tugger train delivering parts from the preparation area to the BoL, and picking activities realized at BoL. A part is a component that is supplied to the line for the assembly of end products. To each component is associated a set of alternative variants from which one and only one is used in the assembly of a specific end product. For example, the headrest of a seat is considered as a component, and all its 4 declinations in color and texture are variants (e.g. for a middle range car seat, a headrest have up to 4 variants). Figure 1 provides an overview of the overall line feeding processes. Each preparation area is represented by a specific color. In the preparation areas, shapes represent components and colors represent the different variants of each component. For instance, the square component (component n°1) has four variants, while the triangle component (component n°2) has only two variants. To distinguish between individual parts and boxes, we represent boxes with shapes that have a black outline and that are crossed by two perpendicular lines. Since no repackaging activity is considered, boxes stored at the BoL are the same as the ones used in the preparation areas.

The first two work stations of the assembly line are also represented. Dotted lines correspond to the movements of operators (both in the sequencing and kitting preparation areas as well as in front of the BoL) while a solid line is associated with the tugger train circuit.

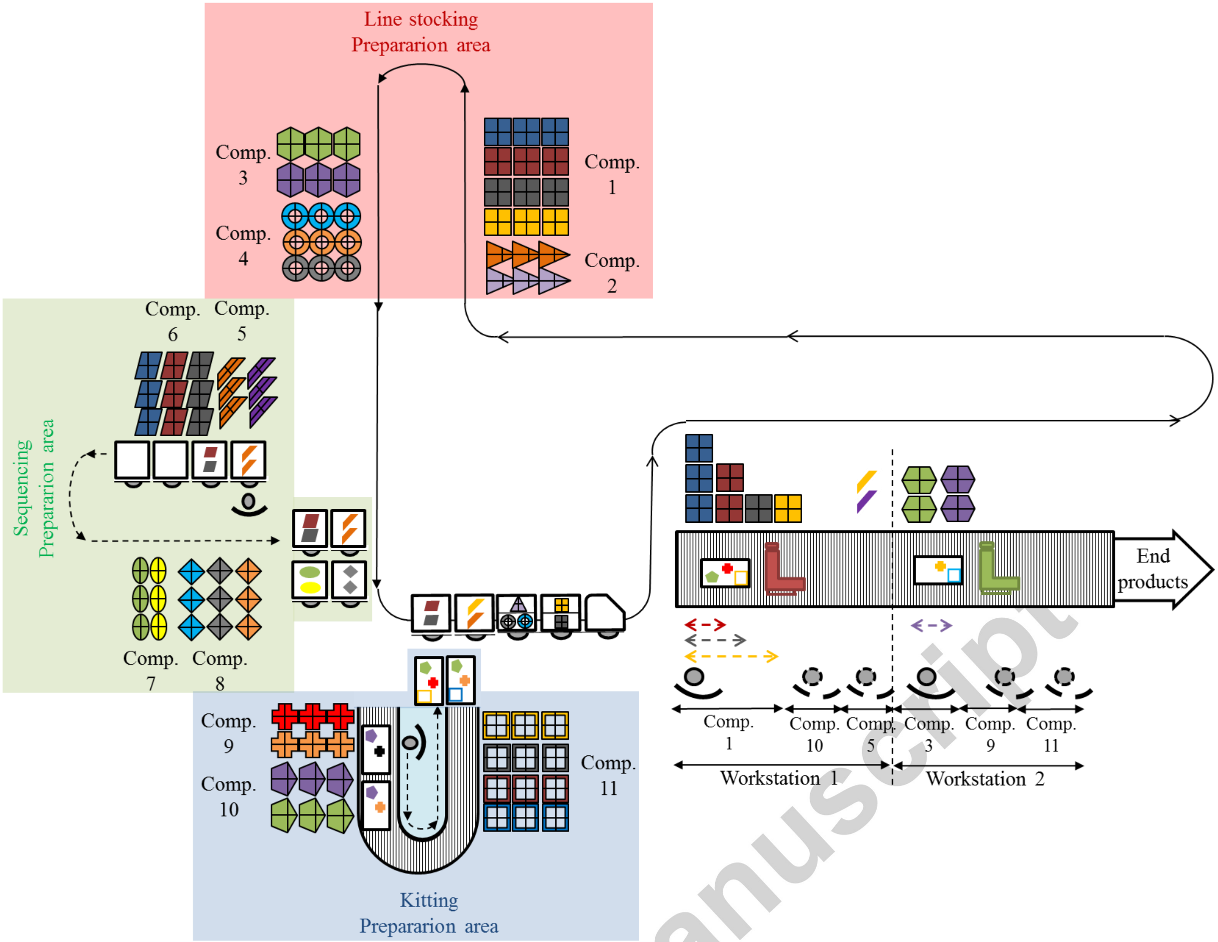

Figure 1. Process description

Each workstation pertaining to the continuous flow seat assembly line is dedicated to the assembly of a set of components. For instance, components 1, 10 and 5 are assembled in workstation 1 while components 3, 9 and 11 are assembled in workstation 2. An elementary assembly operation realized in a workstation concerns the assembly of a single specific variant of a given component on the end product. Products move on the assembly line conveyor from a workstation to another at a constant speed. Hence, elementary operations are performed while the product to be assembled is in motion. The distance separating two products on the line is defined to be consistent with the takt time requested by the customer. One takt corresponds to the time interval that separates two consecutive products assembly. Our model assumes that a given component is assigned to one and only one elementary operation and that a given variant is associated with one and only one component. An operator is responsible for the elementary operations of one and only one workstation.

3.2. Specific assumptions

3.2.1. Preparation before assembly

The preparation area refers to the location where each variant of the components is stored in a dedicated boxe and from where the transportation of parts towards the BoL is carried by tugger trains (cf. Figure 1). The replenishment of the preparation area has no impact on our model since it is performed in exactly the same way whatever the line feeding mode used.

Preparation operations are performed between two successive train deliveries. The number of takts that separates two successive deliveries corresponds to the preparation batch size, i.e. the number of kits or sequenced variants of the same component prepared between two deliveries. The available information in a JIT context restricts values that the preparation batch size can take for both kitting and sequencing modes. If we consider that a kit is made up of a single container, on Figure 1, the preparation batch size is 2 since kit containers and sequenced parts are prepared two by two. In our model, the preparation batch size, denoted by TL, is considered as an input parameter of the problem.

Each preparation realized between two consecutive deliveries consists of four activities: i) a full roundtrip performed in the aisles of the preparation area in order to collect parts, ii) operators grasp the relevant parts and boxes during the roundtrip, iii) operators load parts, boxes and kit containers on the tugger train, iv) operators unload parts, boxes and kit containers at BoL.

According to the layout configuration of the studied plant, we assume that each line feeding approach has its own (separated) preparation area as represented on Figure 1.

Line stocking: Under this mode, the replenishment of the stock in BoL is performed by a consumption renewal or a kanban call-signal each TL takts. Thus, during a preparation, only certain parts have to be replenished. While doing the roundtrip with the tugger train within the aisles of the line stocking preparation area, the train conductor visits the aisles (where each aisle represents a zone that contains all variants of components), stops in front of the needed boxes, grasps them and loads them on the train. The average number of boxes of each variant prepared for one delivery depends on the average consumption of the variant during TL takts and the number of parts per box. When the number of boxes of the same variant to deliver at BoL is greater than one, the possibility for an operator of grasping and loading several boxes at the same time, i.e. simultaneously, depends on the weight and volume of a single box. Such an efficiency principle also holds when operators unload boxes from the train to put them on the BoL near their point of use.

Kitting: Kits preparation is performed according to the needs deduced from the TL forthcoming products scheduled for assembly. A kit is a collection of variants of various components required to assemble one unit of end product. It may be made up of one or several containers. Thus, during a preparation, only the needed variants of each component have to be replenished. While doing the roundtrip in the preparation area, operators visit the aisles, grasp the needed variants and place them within a kit container. When TL is greater than one and/or the BOM (Bill of Materials) coefficient of a component is greater than one, the operators have the possibility of grasping simultaneously several pieces of the same variant to improve efficiency. Containers of the TL prepared kits are then placed in a buffer zone waiting to be loaded one by one on the tugger train. Containers are unloaded from the train and placed at the beginning of the line. On Figure 1, $TL = 2$ and a kit is made up of a single container.

Sequencing: Under this mode, the preparation is quite similar to kitting. Instead of placing several variants within a kit container, the preparation of the variants needed for each component is performed individually. Indeed, the needed variants are grasped and put according to the sequence of their consumption on the assembly line, in specific handling devices adapted to their shape. These devices differ from kit containers, and are specific to each component in order to facilitate the handling operations of its variant. Hence, the devices, installed on carriages, are stored in a buffer zone before being attached to the tugger train. Sequenced parts are unloaded from the train at the BoL near their point of use.

3.2.2. Transportation

At the end of the preparation, a tugger train realizes one or several milk-runs to transport to the BoL a mix of line stocked, kitted and sequenced parts, at a regular frequency of TL takts.

A milk-run is a complete loop performed around the assembly line to supply all workstations that starts (and ends) at a fixed loading point located at the preparation areas. The distance travelled by the train during a single milk-run is known and assumed to be independent of the number and location of delivery points.

A tugger train is an internal transportation mean that consists of a locomotive, driven by an operator, and several wagons arranged in their order of delivery. A tugger train has a finite capacity in terms of total volume of items (measured in m^3) it can transport during a single milk-run. Several milk-runs may thus be necessary for one delivery. The number of milk-runs required per delivery is deduced from the volume prepared (which is directly related to the preparation batch size TL) and train capacity.

3.2.3. Picking during assembly at the border of line

Picking during assembly consists of grasping parts from where they are stored at BoL to assemble them on end products.

Line stocking: As explained before, in contrast with kitting and sequencing, line stocked parts are supplied to the assembly workstations in boxes where each box contains several pieces of the same variant. For further efficiency, parts are fed to the BoL in the original supplier packaging, i.e. they are not re-packaged. A consumption renewal or a kanban call signal controls the replenishment of boxes. In order to grasp parts needed for assembly, operators have to identify the right variant to be assembled and to realize a roundtrip between a starting position and the location where the variant is stored. Grasping may involve several parts at a time if the BOM coefficient of the component is greater than one. As such, the mentioned elementary activities are repeated for each variant to be assembled.

Kitting and Sequencing: Under these modes, travelling kits and sequenced variants are positioned close to the assembly operator, which reduces significantly operators' walking distance to fetch parts. Additionally, in contrast with line stocking, only the needed variants are available, thus, no identification activity is required. Hence, picking operations at the BoL are greatly simplified by the preparation process realized upstream.

3.2.4. Parts storage

In preparation areas, boxes are stored in the same manner regardless of the line feeding mode used. Hence, the required storage space in preparation areas has no impact when comparing the different modes. As explained before, one of the advantages of kitting and sequencing over line stocking is the reduced stock of parts at BoL. While in line stocking, full boxes are stored at the BoL, in the two other modes this stock is significantly reduced by storing only few items at the line (in the sequencing mode) and no items (in the case of travelling kits moving on the assembly line conveyor). Especially in a situation of high product diversity, this is an important advantage, as the need to have a huge amount of different variants at the BoL would lead to an enormous plant if all parts are to be stored at the BoL (Medbo 2003).

Line stocking: For line stocking, storage concerns BoL boxes that are positioned on shelves and within arm's reach of assembly operators.

Kitting: For kitting, storage concerns the buffer zone in the preparation area where the prepared containers are temporarily stored.

Sequencing: For sequencing, two locations are concerned by storage. First, when the preparation is completed, sequenced parts are stored in a buffer zone waiting to be transported to the assembly line. Second, sequenced components are stored near their point of use at the BoL. The required space is calculated considering the surface on the floor of individual parts.

4. Modeling

The aim of our model is to assign each component to the more appropriate feeding mode so that the average total cost over all components is minimized. Hence, based on the process description made in the previous section, a Mixed Integer Programming (MIP) model is developed to assign each individual component to one alternative line feeding mode in order to minimize the average total cost. To formulate the MIP, we first introduce the primary and auxiliary decision variables, formulate the objective function and finally present the constraints.

The mathematical model presented in this section is closely related to the process which is described in Section 3.

4.1. Decision variables

We assume that a given component is used in one and only one work station. Furthermore, variants of a same component are assumed to have the same physical features and are delivered to the BoL under the same mode. These assumptions enable to take the best assignment mode selection decision at component level. Hence, to a component k we associate three binary decision variables denoted x_k , y_k and z_k defined as follows:

- $x_k = 1$ if the component k supplied to the BoL under the kitting mode, $x_k = 0$ otherwise
- $y_k = 1$ if the component k supplied to the BoL under the sequencing mode, $y_k = 0$ otherwise
- $z_k = 1$ if the component k supplied to the BoL under the line stocking mode, $z_k = 0$ otherwise

In addition to the principal decision variables, two auxiliary integer decision variables are introduced in the model.

- N_{bac} is the number of kit containers that form a kit. The value of this auxiliary variable depends on values taken by variables x_k. The relationship between N_{bac} and x_k is expressed as a constraint (cf. Section 4.3.1)
- m is the number of transportation milk-runs performed for one delivery. The value of m depends on the total volume transported per delivery. The relationship between m and the principal decision variables is expressed as a constraint (cf. Section 4.3.3)

4.2. Objective function

To formulate the objective function to minimize, we first formulate cost components related to each process. The objective function is then formulated as the sum of these components. Indeed, the processes described in Section 3.2 have shown that each line feeding mode operates according to some specific rules. Thus, costs associated with the processes would be different for each mode. Hence, this section first derives the detailed expressions of cost components.

Hence, Table 1 provides a synthesis of the cost components also studied in (Sali and al. 2015). Each cost component is referenced with the notation (α, β) where α refer to the process and β to the line feeding mode. When several cost components are related to the same process letters are added to the reference to avoid any ambiguity. A comprehensive list of notations used in the formulations is provided in the Appendix.

The selection of the best line feeding mode is a tactical decision in the company. Thus, in our model, cost components should be interpreted as average values over a reference mid-term period. All cost components are finally expressed on the basis of a daily period where the quantity of end products to be assembled on the line is V.

We consider one constant operator cost rate per hour, i.e. C_o, although in practice wages of assembly operators and logisticians can differ.

Process	*Mode*	*Activity*	*Formula*
Preparation before the assembly	Line stocking	Perform a roundtrip in the preparation area	$\frac{V \cdot C_o}{TL \cdot 2 \cdot v_t} \cdot \sum_k z_k \cdot \lvert S_k \rvert \cdot B'_k$ (1.1*a*)
		Grasp the boxes and load them on the tugger train	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} z_k \cdot \frac{\tau_{ki} \cdot c_k}{p_k \cdot \theta'_{ki}} \cdot t_4$ (1.1*b*)
		Unload the boxes from the tugger train at BoL	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} z_k \frac{\tau_{ki} \cdot c_k}{p_k \cdot \theta'_{ki}} \cdot t_9$ (1.1*c*)
	Kitting	Perform a roundtrip in the preparation area	$\frac{V \cdot C_o}{TL \cdot 2 \cdot v_o} \cdot \sum_k x_k \cdot \lvert S_k \rvert \cdot B'_k$ (1.2*a*)
		Grasp the parts and fill the kit containers	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} x_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_{ki}} \cdot t_1$ (1.2*b*)
		Load the kit containers on the tugger train	$V \cdot C_o \cdot N_{bac} \cdot t_2$ (1.2*c*)
		Unload the kit containers from the tugger train at BoL	$V \cdot C_o \cdot N_{bac} \cdot t_5$ (1.2*d*)
	Sequencing	Perform a roundtrip in the preparation area	$\frac{V \cdot C_o}{TL \cdot 2 \cdot v_o} \cdot \sum_k y_k \cdot \lvert S_k \rvert \cdot B'_k$ (1.3*a*)
		Grasp the parts and load them on the supporting devices	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} y_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_{ki}} \cdot t_3$ (1.3*b*)
		Unload the parts from the tugger train at BoL	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} y_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta'_k} \cdot t_7$ (1.3*c*)
Transportation	All	Perform milk-runs to transport the kit containers, the sequenced parts and the boxes from the preparation areas to the BoL	$\frac{V \cdot D \cdot C_o}{TL \cdot v_t} \cdot m$ (2)
BoL picking	Line stocking	Identify the variant to assemble on the end product	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} z_k \cdot \tau_{ki} \cdot t_{10k}$ (3.1*a*)
		Perform a roundtrip between a starting point and the location of the variant to assemble	$\frac{V \cdot 2 \cdot C_o}{v_o} \cdot \sum_k \sum_{i \in S_k} z_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_k} \cdot (i-1) \cdot B'_k$ (3.1*b*)
		Pick the variant from its box	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} z_k \frac{\tau_{ki} \cdot c_k}{\theta_k} t_{11}$ (3.1*c*)

	Kitting	Pick the variant from the kit container	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} x_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_k} t_6$ (3.2)
	Sequencing	Pick the sequenced variant	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} y_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_k} t_8$ (3.3)
Storage	Line stocking	Store the boxes at the BoL	$\sum_k \sum_{i \in S_k} z_k \cdot \lceil r_{ki} \rceil \cdot A'_k \cdot B'_k \cdot C_{m^2}$ (4.1)
	Kitting	Store the kit containers in the preparation area	$\frac{TL \cdot A_{bac} \cdot B_{bac} \cdot C_{m^2}}{2} \cdot N_{bac}$ (4.2)
	Sequencing	Store the sequenced parts in the preparation area and at the BoL	$2 \cdot TL \cdot C_{m^2} \cdot \sum_k \sum_{i \in S_k} y_k \cdot \tau_{ki} \cdot c_k \cdot A_k \cdot B_k$ (4.3)

Table 1. Cost components associated with the objective function

For ease of understanding, the following paragraphs give the general ideas behind expressions provided in Table 1.

4.2.1. Preparation before assembly

In $(1.1a)$, $(1.2a)$ and $(1.3a)$ the average total labor time related to the operator movement within a preparation area is obtained by multiplying the total number of roundtrips performed (V/TL) by the time required to make a roundtrip. The term $1/2$ comes from the U-shaped configuration of the preparation area and the two height storage structure. Indeed, the traveled distance (back and forth) in a linear configuration with single height storage is divided by 2 if a U-shaped configuration is introduced, and divided again by 2 if a two height storage is adopted. For line stocking, the tugger train velocity v_t is used in formula $(1.1a)$ while the operator velocity is used for kitting and sequencing in $(1.2a)$ and $(1.3a)$.

During a roundtrip within the preparation area, the operator has to grasp the relevant items and load them on the train. In line stocking, the average number of boxes of a variant i of a component k that is consumed between two successive train deliveries corresponds to $r_{ki} = TL \cdot \tau_{ki} \cdot c_k / p_k$ where τ_{ki} is the usage rate of variant i (i.e. the percentage of end products that use this variant), c_k the BOM coefficient of component k and p_k the number of parts in a box containing variants of component k. Formulas $(1.1b)$ and $(1.1c)$ give respectively the loading and unloading costs of boxes in a line stocking mode. θ'_{ki} introduces the possibility for an operator to grasp and load several boxes simultaneously. It is calculated as the average number of boxes handled at once. θ'_{ki} is at least equal to one, and at most equal to r_{ki}. When r_{ki} is greater than the maximum allowed number of boxes of component k that can be handled at once, θ'_{ki} becomes equal to a'_k. In short, $\theta'_{ki} = \max(\min(r_{ki}, a'_k), 1)$.

In kitting and sequencing, the number of pieces of a variant i of a component k that is consumed during one reference period corresponds to $V \cdot \tau_{ki} \cdot c_k$. In order to introduce the possibility of picking several pieces of the same variant at the same time, we calculate the average number of pieces of each variant prepared for one delivery, which is given by $TL \cdot \tau_{ik} \cdot c_k$. In picking cost equations $(1.2b)$ and $(1.3b)$, θ_{ki} corresponds to the average number of parts of the variant i of component k grasped at once during the preparation. It is obtained by the expression: $\theta_{ki} = \max(\min(TL \cdot \tau_{ik} \cdot c_k, a_k), \min(c_k, a_k))$. On one hand, an operator has the opportunity to grasp (at once) the number of parts of the same variant consumed between two deliveries (i.e., $TL \cdot \tau_{ik} \cdot c_k$). This number is limited by a_k that corresponds to the maximum number of parts of the component k that can be handled at once. Thus, the number of parts of the same variant that can be grasped at once corresponds to $\min(TL \cdot \tau_{ik} \cdot c_k, a_k)$. On the other hand, the number of parts of the same variant that can be grasped at once (regardless its consumption between two deliveries) is at least equal to $\min(c_k, a_k)$.

Costs related to loading and unloading of kit containers on the tugger are respectively given by $(1.2c)$ and $(1.2d)$ where the decision variable N_{bac} indicates that these costs are proportional to the number of containers handled.

The cost of unloading sequenced parts is given by $(1.3c)$. Since this activity is not related to the consumption rate of variants, the opportunity of unloading multiple parts in the same time is given by $\theta'_k = \min(a_k, TL \cdot c_k)$.

4.2.2. Transportation

Since transportation is shared between line stocking, kitting and sequencing, this cost is common to all line feeding modes. The total transportation time is obtained by multiplying the total number of milk-runs performed over the period considered by the time required for a single milk-run. In formula (2), m represents the number of milk-runs that needs to be performed each TL takts (i.e. each delivery), V/TL the number of deliveries necessary over the considered period and D/v_t the duration of a single milk-run. The value of the auxiliary variable decision m depends on the total volume transported per delivery.

The time spent by the tugger train in the line stocking preparation area is taken into account in the preparation time related to the line stocking mode.

4.2.3. Picking at the border of line

Similarly to grasping activities performed at preparation areas, the cost pertaining to grasping operations during assembly is given by $(3.1c)$, (3.2) and (3.3) for respectively line stocking, kitting and sequencing. In these formulas, θ_k is the number of parts picked at once during the assembly. It corresponds to the minimum between a_k, the maximum allowed number of parts of the component k that can be handled at once, and c_k the BOM coefficient of component k.

For line stocking, two additional elementary operations are performed during BoL picking operations. First, operator responsible for the assembly identify of the right variant to be assembled on the end product $(3.1a)$. Then, he/she realizes a roundtrip between a starting position and the location where the variant is stored at the BoL $(3.1b)$.

The identification of the variant which has to be assembled on the end product is necessary when the operator has to choose the right variant among several alternatives. Such a choice exists when there is more than one variant associated with a given component or when end products do not use systematically this component. Thus, the unit time needed by the operator to identify a variant of a component k is t_{10k} that has a nonzero value t_{10} if $|S_k| \geq 2$ or $\sum_{i \in S_k} \tau_{ki} < 1$.

The cost associated with the movement of fetching the needed variant for assembly is difficult to model faithfully. Indeed, the movement of the product on the conveyor combined with the movement of the operator implies going back and forth between points that are not easily identifiable. To overcome this difficulty, we approximate the effective movement of the operator in formula $(3.1b)$. Indeed, since products are moving on the line, we consider a different starting point for each elementary assembly operation and the related component. This point corresponds to the location where the first variant of the component is stored. The operator makes a roundtrip between this starting point and the location of the needed variant for the assembly. In order to minimize the total distance travelled by operators, we assume that variants are displayed at the BoL according to a descending order of their usage rates (i.e. fast moving variants first and then slow movers). In formula $(3.1b)$, if the component k is line stocked, the term $V \cdot \frac{\tau_{ki} \cdot c_k}{\theta_k}$ gives the number of two-way trips made by the operator between a starting point and the location of variant i. The starting point of the operator corresponds to the location of the most consumed variant. When variants are displayed at the BoL according to a descending order of their usage rates (i.e. i is equal to 1 if it refers to the most consumed variant, 2 if it refers to the second most consumed variant, etc.), the distance that separates the starting point of the operator and the location of any variant i of a component k is given by $(i-1)\cdot B'_k$.

4.2.4. Parts storage

The storage cost is interpreted as an opportunity cost associated with the potential use of available space in the plant. It represents the penalty that corresponds to the unoccupied square meters which can be used for other purposes or disposed of in the case of a plant leasing contract for example. The storage cost is obtained by multiplying the number of occupied square meters on the floor by a periodic rental cost per square meter.

For line stocking, storage cost given by (4.1) is related to the storage area required at BoL.

For kitting, since there is no storage at BoL, only the space required to store the prepared kits waiting for delivery is taken into account in (4.2). Containers are stored on two level shelves to reduce the impact on the floor.

For sequencing, the two storage locations (i.e. preparation area and BoL) are taken into account in formula (4.3).

4.3. Constraints

Constraints considered in our model can be classified into model consistency constraints, takt time constraints, layout constraints, and capacity constraints.

4.3.1. Consistency constraints

(1) $\forall k, \quad x_k \in \{0,1\}, \quad y_k \in \{0,1\}, \quad \forall k, z_k \in \{0,1\}$ principal decisions variables are binary

(2) $N_{bac} \in \mathbb{N}, \quad m \in \mathbb{N}$ auxiliary decisions variables are integer

(3) $\forall k, x_k + y_k + z_k = 1$ ensures that each component is assigned to one and only one mode

(4) $\forall k, N_{bac} \geq x_k$ a kit is made up of at least one container when a component k is kitted

4.3.2. Takt time constraints

(5) $$\frac{D}{v_t}+\frac{1}{2\cdot v_t}\cdot\sum_k z_k\cdot|S_k|\cdot B'_k+TL\cdot\sum_k\sum_{i\in S_k} z_k\cdot\frac{\tau_{ki}\cdot c_k}{p_k\cdot\theta'_{ki}}\cdot t_4+TL\cdot\sum_k\sum_{i\in S_k} z_k\frac{\tau_{ki}\cdot c_k}{p_k\cdot\theta'_{ki}}\cdot t_9+$$

$$TL\cdot N_{bac}\cdot t_2+TL\cdot N_{bac}\cdot t_5+TL\cdot\sum_k\sum_{i\in S_k} y_k\cdot\frac{\tau_{ki}\cdot c_k}{\theta'_k}\cdot t_7\leq\frac{TL\cdot T}{V}$$ the time spent by the tugger train in the BoL, the preparation areas and during the roundtrip must not exceed the time after which each workstation has to be served (i.e. TL takts). The number of transportation milk-runs performed for one delivery (i.e. m) does not appear in the constraint since there is no restriction on the number of tugger trains that may be used for the same delivery.

(6) $$\frac{1}{2\cdot v_o}\cdot\sum_k x_k\cdot|S_k|\cdot B'_k+TL\cdot\sum_k\sum_{i\in S_k} x_k\cdot\frac{\tau_{ki}\cdot c_k}{\theta_{ki}}\cdot t_1\leq\frac{TL\cdot T}{V}$$ the time spent by operators to prepare the kit containers must not exceed TL takts

(7) $$\frac{1}{2\cdot v_o}\cdot\sum_k y_k\cdot|S_k|\cdot B'_k+TL\cdot\sum_k\sum_{i\in S_k} y_k\cdot\frac{\tau_{ki}\cdot c_k}{\theta_{ki}}\cdot t_3\leq\frac{TL\cdot T}{V}$$ the time spent by the operators to prepare the sequenced parts must not exceed TL takts

(8) $$\forall n, \sum_{k\in S_n}\sum_{i\in S_k} z_k\cdot\tau_{ki}\cdot t_{10k}+\frac{2}{v_o}\cdot\sum_{k\in S_n}\sum_{i\in S_k} z_k\cdot\frac{\tau_{ki}\cdot c_k}{\theta_k}\cdot(i-1)\cdot B'_k+\sum_{k\in S_n}\sum_{i\in S_k} z_k\frac{\tau_{ki}\cdot c_k}{\theta_k}t_{11}+$$

$$\sum_{k\in S_n}\sum_{i\in S_k} x_k\cdot\frac{\tau_{ki}\cdot c_k}{\theta_k}t_6+\sum_{k\in S_n}\sum_{i\in S_k} y_k\cdot\frac{\tau_{ki}\cdot c_k}{\theta_k}t_8\leq\frac{T}{V}$$ for each workstation, the time allowed for picking during assembly must not exceed the working available time (i.e. the takt time)

4.3.3. Layout constraints

(9) $\forall n, \sum_{k \in S_n} y_k \cdot B_k + z_k \cdot |S_k| \cdot B'_k \le \zeta_n$ for each workstation, the total frontal distance used by line stocked and sequenced components must not exceed the available length

(10) $\forall k, \forall i, \ z_k \cdot \lceil r_{ki} \rceil \cdot A'_k \le \xi$ the depth storage of each variant of line stocked components stored at BoL must not exceed the available depth

(11) $\forall k \ y_k \cdot TL \cdot A_k \le \xi$ the depth storage of sequenced components stored at BoL must not exceed the available depth

(12) $B_{bac} \cdot N_{bac} \le d$ the number of containers per kit must respect the available space between two successive end products moving on the assembly line

4.3.4. Kit containers and transportation capacity constraints

(13) $\forall k, x_k \cdot c_k \cdot M_k \le M_{bac}$ a component cannot be kitted if its weight multiplied by its BOM coefficient exceed the maximum weight of a kit container

(14) $\forall k, x_k \cdot c_k \cdot Vol_k \le Vol_{bac}$ a component cannot be kitted if its volume multiplied by its BOM coefficient exceed the maximum volume of a kit container

(15) $\sum_k x_k \cdot c_k \cdot M_k \le N_{bac} \cdot M_{bac}$ the total weight of a kit must be lower than the maximum weight of a kit container multiplied by the number of containers per kit

(16) $\sum_k x_k \cdot c_k \cdot Vol_k \le N_{bac} \cdot Vol_{bac}$ the total volume of a kit must be lower than the maximum volume of a kit container multiplied by the number of containers per kit

(17) $\sum_k y_k \cdot Vol_k \cdot c_k \cdot \sum_{i \in S_k} \tau_{ki} + N_{bac} \cdot Vol_{bac} + \sum_k z_k \cdot \sum_{i \in S_k} \frac{\tau_{ki} \cdot c_k}{p_k} \cdot Vol'_k \le \frac{m}{TL} \cdot Y_t$ the number of milk-runs per delivery must be enough so that the total volume to be transported each delivery respects the tugger train capacity.

5. Case Study Analysis

In the first part of this section, we analyze the optimal solution obtained with data provided by the car seats assembly company. A summary of the input data used in the numerical analysis is provided in the Appendix[1]. In the second part, we compare the solution obtained by the optimization model with some other practical scenarios of interest for the company.

5.1. Analysis of the optimal solution

A seat used for medium range cars consists of about 40-50 components. Seat diversity mainly stems from the combination of variants associated with components. In the case considered, the number of variants per component varies from 1 to 5. Hence, 44 components are concerned by the line feeding optimization problem, leading to an optimization problem of 132 binary variables and 2 integer variables. The resulting MIP is solved in a few seconds on a standard computer.

The optimization results in 20 components that are assigned to the line stocking mode, 19 components that are kitted and 5 components that are sequenced (cf. first column of Table 3). Figure 2 shows the repartition of the total cost according to cost components (left side) and to line feeding modes (right side). As such, preparation before the assembly and BoL picking represent nearly 80% of the average total cost.

[1] The complete dataset is available on : http://dx.doi.org/10.13140/RG.2.1.5127.3685

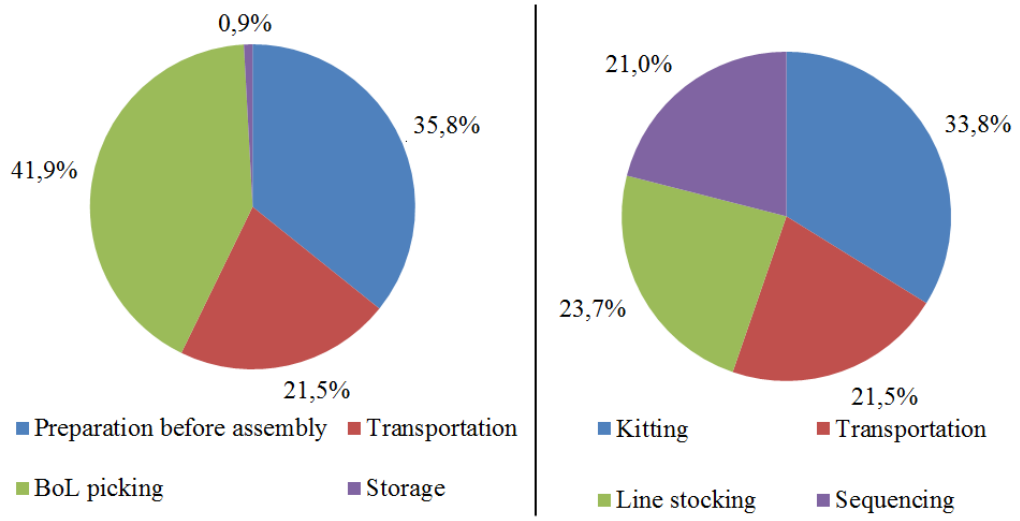

Figure 2. Line feeding cost repartition in the optimal solution

The optimal solution shows that kitting and sequencing up to a certain degree is suitable in order to decrease the total cost and/or to satisfy constraints of the model. Indeed, these two modes offer significant cost reduction especially for BoL picking and parts storage processes. To prevent the relatively more important preparation costs of kitting and sequencing (in comparison with line stocking) from canceling out the gain in operator efficiency at BoL, components that are kitted or sequenced have some specific features.

Hence, by analyzing the optimal assignment of components according to two impacting parameters that are component volume and diversity, several conclusions can be drawn. Indeed, Figure 3 shows that kitting and sequencing modes are preferred to line stocking for components that have a number of variants greater than one. Components with high diversity need only one space in the kit container whereas much space is freed up at the BoL if variants associated with such components are not line stocked. When the number of variants per component exceeds one, an identification time is necessary during the assembly under the line stocking mode in order to select the right variant among all possible alternatives. In addition, when a large number of variants is line stocked, walking distances of operators increase especially for voluminous components whose variants have uniform usage rates. This explains why sequencing becomes more interesting for such big components that have a large number of variants uniformly consumed. Voluminous components would increase the number of containers per kit and thus loading, unloading and storage costs. In addition, such components do not allow batch picking that contributes to reduce the preparation cost. Hence, such components are not kitted. Kitting is often preferred to line stocking for small components that have a large number of variants per component. Choosing kitting for high diversity components enables to free up space at BoL. These results support insights provided by Hua and Johnson (2010) that identify component variety as an influencing factor regarding the choice between kitting and line stocking. Indeed, according to the authors, a large variety of components pushes towards kitting while line stocking is preferred in settings where products use similar components.

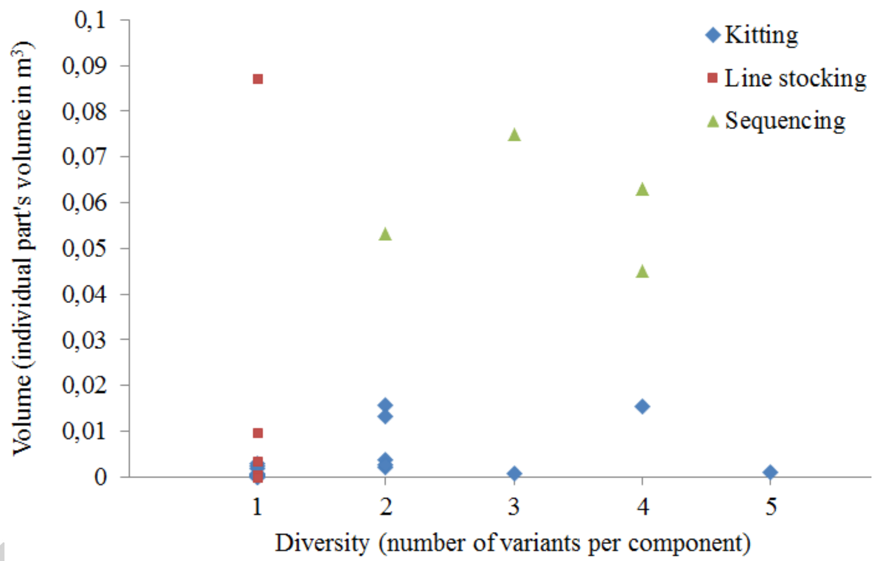

Figure 3. Optimal assignment according to components' volume and diversity

The global behavior of the MIP consists of filling the kit container starting from high diversity components to lower ones. If free space remains in the container, additional components can be kitted. Those are "opportunistic components" named "free riders" by Limère and al. (2012). Since the relative cost of kitting decreases when the number of parts in the kit container increases, free riders are typically the smallest components with low diversity. However, the constraint analysis (constraints (11) and (12)) shows that line stocking is preferred for some components even if there is remaining space in the kit container. These components have typically small size, low diversity, high consumption rate, high BOM coefficient and hold a large number of pieces per box. For such components, line stocking costs are lower than kitting costs even if they can benefit from "free riding". For instance, components that are in this case are screws, nuts and bolts.

It should be noted that additional numerical experiments we carried out reveal that in addition to component volume and diversity, other parameters can tip the scales in favor of one mode over others in the optimal assignment. Consider, for example, the usage rate of a component which is obtained by the sum of usage rates of its variants. A low usage rate would not allow batch picking even if variants are small. In the same time, for a given component, the effect of having a high diversity can be neutralized by the usage profile of variants associated with this component. Indeed, when the usage rate of a component is close to 100% and the usage rate of one of its variants strongly dominates the others (i.e. one of the variants of the component is much more used than others), the walking distance at BoL would be significantly reduced leading to the line stocking mode to be preferred to sequencing or kitting modes. The inherent complexity of the model with different influencing parameters justifies the use of a mathematical model instead of simple assignment rules that would ignore some subtleties.

In the case studied in Figure 3, these additional parameters were less impacting the optimal assignment. This enabled to discuss the results according to the two most influencing factors that are the volume and diversity parameters. Indeed, in this case, the usage rates of variants are well balanced and only a few optional components have a low usage rate.

5.2. Comparing the optimal solution with other assignment scenarios

The aim of this section is to compare the performance of the optimal solution with other assignment scenarios that are of interest for the company we worked with. Some of scenarios are simple assignment rules, while others illustrate common beliefs on the fact that kitting is always preferable to line stocking or vise-versa. This leads to 5 scenarios to be considered. Hence, the performance of each scenario is evaluated by calculating the average total cost it generates and then compared to the optimal solution. To have comparable results, all scenarios respect constraints presented in Section 3.3.

In scenario 1, since production managers seek more flexibility in order to re-balance the line in case of demand variations, they tend to push towards an increased percentage of kitted components (il faut expliquer dans l'intro que parmi les avantages du kitting, il y a aussi cet avantage). Indeed, in the actual assignment used in the plant, more than 50% of components are kitted, which leads to use two kit containers per kit.

Scenario 2 proposes an assignment that maximizes the use of the available space at the BoL by maximizing the number of line stocked components while minimizing the total average cost. In order to model Scenario 2, we first solve the optimization model by setting $t_4 = t_9 = t_{10} = t_{11} = 0$ in order to identify components that would be line stocked as well as those that are kitted and sequenced under conditions that are in favor of the line stocking mode. Then, based on the assignment obtained, we evaluate the average total cost pertaining to this scenario by setting t_4, t_9, t_{10}, and t_{11} to their initial values.

The last three scenarios aim at maximizing the use of kit containers' capacity in different ways. Hence, in Scenario 3, kit containers capacity is optimally used by choosing components that present the highest potential of cost savings if they are kitted. In order to calculate the cost related to Scenario 3, we first solve the optimization model by setting $t_1 = t_2 = t_5 = t_6 = 0$

in order to identify components that would be line stocked as well as those that are kitted and sequenced under conditions that are in favor of the kitting mode. Then, based on the obtained assignment, we evaluate the average total cost pertaining to this scenario by setting t_1, t_2, t_5, and t_6 to their initial values. In Scenario 4, kit containers are filled by prioritizing components having the highest number of variants. In this scenario, the kit container is filled starting from components having the highest diversity. If two components have the same diversity, the kit container is filled starting from the one with the lowest volume. If a component cannot be kitted, it is skipped and the next component is considered and so on until the kit container is completely full. Remaining components are assigned to sequencing if their number of variants is greater than 1, and to line stocking otherwise.

In Scenario 5, kit containers are filled starting from components having the lowest weighted volume (i.e. part's volume multiplied by its BOM coefficient). This rule aims at maximizing the number of kitted components and the use of kit containers' capacity in terms of volume (the weight constraint is not a blocking constraint in our case).

In Scenarios 4 and 5, the number of kit containers is set to one, as in the optimal solution, to measure how these simple rules can substitute for the optimization model by providing close solution in terms of total average operating cost.

The principles and motivations underlying the consideration of each scenario are summarized in further detail in Table 2.

Scenario n°	Name	Design principle	Motivation
1	Current assignment	Using the assignment presently used in the plant under study	Evaluate potential savings with respect to the optimal solution
2	Promote line stocking	Maximizing the use of the BoL available space while minimizing the total average cost	Challenge the widespread belief considering that line stocking is the best line feeding mode.
3	Promote kitting	Maximizing the use of kit containers' capacity while minimizing the total average cost	Challenge the widespread belief considering that kitting is the best line feeding mode.
4	Diversity prioritization	Maximizing the use of kit containers' capacity by assigns components to kitting starting from those with the	Evaluate the possible use of a simple assignment rule inspired from figure 3 with component's

		highest diversity	diversity as a principal criterion.
5	Volume prioritization	Maximizing the use of kit containers' capacity by assigns components to kitting starting from those with the lowest volume.	Evaluate the possible use of a simple assignment rule inspired from figure 3 with component's volume as a principal criterion.

Table 2. Assignment scenarios

The performance of each scenario is compared to the optimal solution, in terms of cost and component assignment, under the same input data. Table 3 summarizes results obtained where cost differences (in comparison to the optimal cost) are given in percentage. For instance, "Actual assignment", is 10,7% more expensive than the "Optimal assignment". The Table also provides the number of components assigned to each mode in each scenario. Components assigned to the same mode over different scenarios are not necessarily the same ones.

			Optimal assignment	Scenario 1: Actual assignment	Scenario 2: Promote line stocking	Scenario 3: Promote kitting	Scenario 4: Diversity prioritization	Scenario 5: Volume prioritization
Difference in total operating cost			-	10,7%	4,3%	7,4%	7,6%	9,9%
Cost components	Preparation before the assembly		-	37,3%	-16,9%	39,6%	32,5%	46,7%
	Transportation		-	0,0%	0,0%	0,0%	0,0%	0,0%
	BoL picking		-	-6,6%	25,1%	-15,9%	-9,5%	-16,5%
	Storage		-	12,9%	-24,5%	-16,1%	0,7%	9,2%
Decision variables	Assignment (number of components)	Line stocking	20	7	37	5	8	0
		Kitting	19	23	4	34	30	35
		Sequencing	5	14	3	5	6	9
	Number of kit containers		1	2	2	2	1	1
	Number of milk-runs per delivery		1	1	1	1	1	1

Table 3. Comparison of assignment scenarios

From Table 3, two direct observations can be made:

- As expected, the transportation cost does not vary from one scenario to the other: in all cases, the tugger train has to transport the same quantity of parts that is spread over a different repartition of alternative line feeding modes. The number of milk-runs per delivery is the same for all scenarios.

- The storage cost represents only 1% of the total cost in the optimal solution (cf. Figure 2). This cost component can be neglected when comparing the assignment scenarios.

In scenario 1, managers tend to push towards an increased percentage of kitted components, which increases the number of kit containers used and thus the preparation cost. Such a choice leads to a sub-optimal solution where a potential of 10,7% savings can be achieved in comparison with the optimal model.

Scenario 2 is more costly than the optimal solution mainly because of BoL picking operations cost. Since more components are line stocked in this scenario, assembly operators walk larger distances to fetch and identify the variants. However, because of cost reduction at the preparation process before assembly, this scenario is the closest one to the optimal solution, with a potential of 4,3% of savings. This result is as expected intuitively. Indeed, nearly 70% of the components have no diversity, which make them good candidates for the line stocking mode. In the optimal solution, the “free riding” phenomenon pushes toward kitting some of these components to reduce the total operating cost.

Scenario 3 has a potential of 7,4 % savings when comparing with the optimal solution. Increasing the number of kitted components increase the preparation cost which is only partially compensated by the decrease of picking cost at BoL.

The last two scenarios are inspired from the categorization shown on Figure 3. Unsurprisingly, scenario 4 is more expensive than scenario 3. However, the small difference in costs and the similarity of assignments for these two scenarios, demonstrates the importance of the diversity parameter while maximizing kit containers’ capacity utilization.

Scenario 5 provides results that are relatively far from the optimal solution with a potential of 9,9% of savings, which denotes the importance of considering the diversity parameter in the assignment.

6. Sensitivity Analysis

In addition to the numerical study carried out, this section conducts a sensitivity analysis of results obtained when the constraints impacting kitting and line stocking are progressively relaxed. Basically, parameters that are relaxed are the allowed BoL available space, i.e. the parameter ζ_n in constraint 5 (cf. Section 4.3.2), and the volume that a kit container can hold, i.e. the parameter Vol_{bac} in constraints 10 and 12 (cf. Section 4.3.3).

In order to analyze the impact of ζ_n on the optimal assignment, we progressively increase the value of workstations' length by increments of one meter starting from the first value where a feasible solution exists. To simplify the analysis, we assume that all workstations have the same allowed length, i.e. $\zeta_n = \zeta, \ \forall n$. As reported on Figure 4, when all other parameters are kept equal to their initial values, a feasible solution exists for $\zeta \geq 2$. The final value considered where $\zeta = 9$ corresponds to the workstation length that can (physically) allow an assignment where all components are line stocked, if it is optimal to do so.

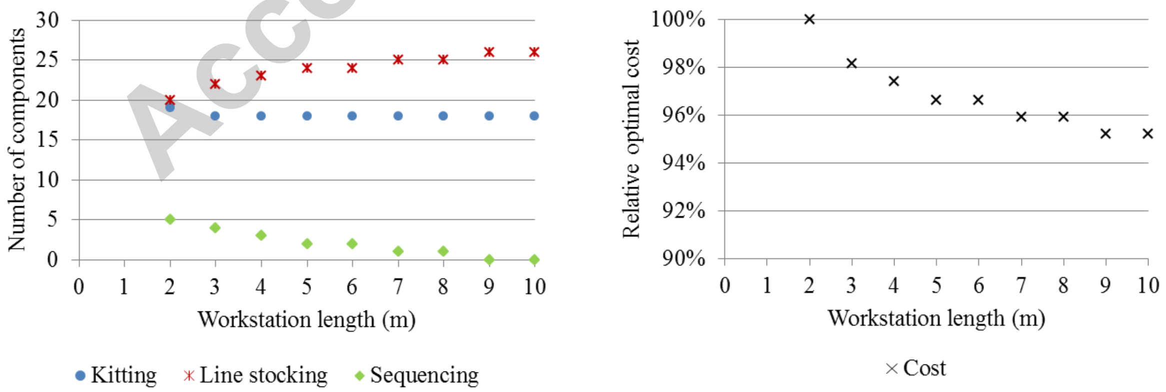

Figure 4. Optimal assignments according to the workstation length

The left part of Figure 4 shows the number of components assigned to each line feeding mode for the values of ζ considered. As expected, the number of line stocked components increases when the BoL space constraint is relaxed. It reaches its maximum value for $\zeta = 9$. Even if this value potentially allows an assignment where all components considered can be line stocked, we observe that a significant number of components, i.e. 40%, remain kitted. Conversely, as ζ increases, the number of sequenced components decreases progressively until no component is assigned to this mode for large workstation lengths. Hence, the evolution of the mix of line stocked, sequenced and kitted components when ζ increases shows that kitting remains economically interesting in comparison with line stocking even for high values of ζ. This emphasizes the fact that a hybrid solution would lead to a lower optimal cost than a strategy where all components would be line stocked.

The right part of Figure 4 represents the evolution of savings achieved when ζ increases. The optimal cost pertaining to the case $\zeta = 2$ is considered as a reference point and the optimal cost associated with each value of ζ is compared with this point. Hence, the minimum cost is obtained for a workstation length of 9 meters where a savings of 4,8% is observed. However, the lengthening of the workstations would probably induce new layout configuration and work organization that may counterbalance the cost savings.

To analyze the impact of kit container volume on the optimal assignment, we start by setting the maximum weight that a kit container can hold to a huge value so that the constraint on kit container capacity concerns only the volume. Then, we progressively increase the volume capacity of a kit container by increments of 0,06 m^3 starting from the first value where a feasible solution exists, i.e. $Vol_{bac} = 0{,}06$. All other parameters are set equal to their original values. The final value considered for Vol_{bac} corresponds to a kit container capacity that can allow an assignment where all components are kitted, if it is optimal to do so.

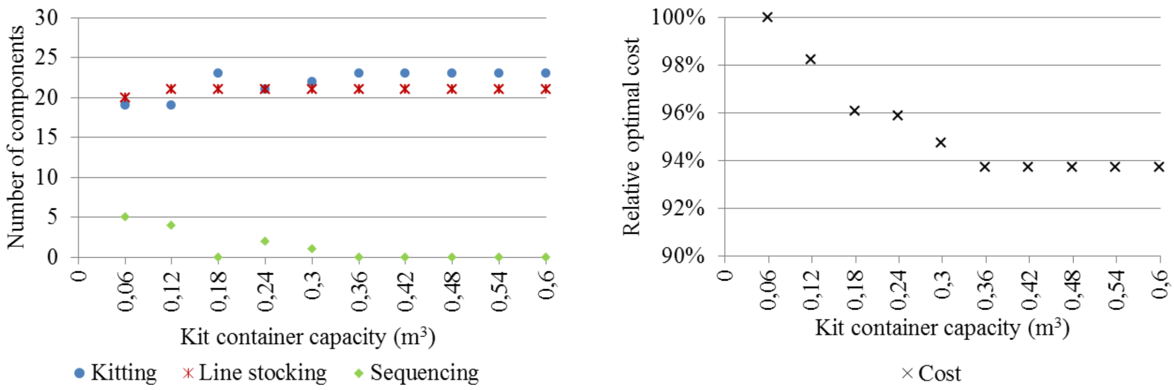

Figure 5. Optimal assignments according to the kit container capacity

The left part of Figure 5 shows the number of components assigned to each line feeding mode for each value of Vol_{bac} considered. For small kit container volume, the evolution of assignments looks non intuitive, explained by transfers that occur between the different line feeding modes: increasing the kit container capacity can offer the opportunity of kitting a voluminous component having high diversity while removing from the container smaller components that have less diversity. After a certain value of the kit container capacity, the number of kitted components reaches its maximum value while the number of line stocked components remains stable. Even for high values of Vol_{bac}, we observe that a significant number of components, i.e. 47%, remain line stocked. The number of sequenced components decreases progressively until no component is assigned to this mode for high kit container capacities.

The behavior of the optimal assignments when kit container capacity increases shows that line stocking at a certain level remains economically beneficial. This shows also that, despite the "free riding" effect, line stocking can be preferred to kitting.

The right part of Figure 5 illustrates the evolution of the optimal cost when kit container capacity increases. Hence, the minimum cost is obtained for a kit container capacity of 0,36 m^3 where a savings of 6,3% is observed. However, when the kit container capacity is increased, the resulting cost reduction can be counterbalanced by the deterioration of ergonomic conditions and higher space requirements on the line due to the increase of the interspace d between two end-products on the line conveyor.

The progressive decrease of the number of sequenced components observed on Figure 4 and Figure 5 show that the sequencing mode is rather used to achieve feasible solutions and plays the role of adjustment variable to satisfy the constraints of the model.

7. Conclusion

Kitting, sequencing and line stocking are different line feeding modes that are commonly used in assembly industries. The lack of quantitative decision making models regarding the choice of the more efficient (less costly) mode for a given set of components has pushed practitioners to adopt simple rules. Our contribution challenges such rules by proposing a comprehensive mathematical model regarding the choice of the most appropriate mode for each individual component.

Even if the proposed model is developed within the context of the automotive industry, it can be easily transposed to other industries, such as electronic, that also operate under JIT mixed-model assembly lines. Thus, our approach is generic and can be tailored to capture the particular settings regarding a specific situation (i.e. layout configuration, characteristics of components and variants, transportation mode used, plant physical constraints, etc.).

Based on a case study carried out in a first tier supplier plant assembling car seats for automakers, we have shown that cost savings up to 10% can be achieved by using the solution provided by the optimization model. To complete the study, we have quantified the sensitivity of the optimal cost regarding two factors that were expected as being the most impacting ones regarding the choice of the line feeding mode. Results show that these factors, which are the kit container capacity and the allowed BoL space, have significant impact on the cost, especially in constrained production environments. Furthermore, for a given kit container volume, once a hybrid policy is reached, this equilibrium is maintained even if the value of the allowed BoL space is increased. This counter-intuitive result challenges the common understanding which would expect an increased number of line stocked components when the allowed space becomes larger.

This study can be extended in several ways. First, the types of line feeding modes considered in the study can be enriched by considering stationary kits and batch supply. Secondly, the cost pertaining to additional processes such as the repackaging of goods received from suppliers or reverse logistic activities can be considered in the objective function to refine the model. Also, the preparation batch size, which is considered as a given parameter in our model, could be considered as a decision variable in a nonlinear model. Another interesting extension would be the consideration of investment costs in the study since the implementation of a given line feeding mode can require some specific equipment. Indeed, in practice, in parallel to evaluating operational costs, practitioners often explore innovative solutions that would increase efficiency even more such as the use of more sophisticated sequencing racks or new pick to light technologies, etc. The consideration of such investment costs would be complementary to the operating costs already identified in this study and would lead to more exhaustive models.

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Appendix: list of parameters and the associated values

Notation	Definition	Unit	Value in case study[1,2]
K	Number of components	-	44
k	Component index, $k = 1...K$	-	1…44
I	Maximum number of variants per component	-	5
i	Variant index, $i = 1...I$	-	1…5
N	Number of work stations	-	10
n	Workstation index, n=1...N		1…10
D	Distance travelled by the train during one milk-run	m	200
V	Production per period	-	480
T	Duration of the production period	s	28800
TL	Preparation and delivery batch size	-	6
Vol_{bac}	Volume capacity of a kit container	m^3	0,06
M_{bac}	Weight capacity of a kit container	Kg	10
A_{bac}	Length of a kit container	m	0,4
B_{bac}	Width of a kit container	m	0,6
ζ_n	Available length at workstation n	m	1,8-2
ξ	Available depth at BoL	m	30
d	Interspace between two consecutive end products on assembly line	m	1,4
Y_t	Capacity of the tugger train	m^3	5,85
v_t	Velocity of the tugger train	m/s	1,38
v_o	Velocity of an operator	m/s	1
t_1	Time needed by the operator to realize a single movement of picking variants during the preparation in a kitting mode	s	1,9
t_2	Time needed by the operator to realize a single movement of loading a kit container on the train.	s	1,3
t_3	Time needed by the operator to realize a single movement of picking and loading variants during the preparation in a sequencing mode	s	1,4
t_4	Time needed by the operator to realize a single movement of grasping boxes and loading them	s	1,75
t_5	Time needed by the operator to realize a single movement of unloading a kit container from the train	s	1,3
t_6	Time needed by the operator to realize a single movement of picking during the assembly in a kitting mode	s	1,1
t_7	Time needed by the operator to realize a single movement of unloading the sequenced parts at BoL	s	1,4
t_8	Time needed by the operator to realize a single movement of picking during the assembly for the sequencing mode	s	1,3
t_9	Time needed by the operator to realize a single movement of grasping boxes and unloading them	s	1,75
t_{10}	Time needed by the operator to realize a single operation of identification.	s	0,5
t_{11}	Time needed by the operator to realize a single movement of grasping line stocked parts for assembly	s	1,73
C_{m^2}	Periodic rental cost per square meter	€/m^2/day	0,2
C_o	Labour cost per time unit	€/s	0,0083
S_k	Set of variants of a component k	-	-
S_n	Set of components assembled in workstation n	-	-

$\lvert S_k \rvert$	Number of variants of a component k	-	-
c_k	Bill of material coefficient of a component k	-	[1;6]
p_k	Number of parts per box of a component k	-	[4;800]
A_k	Length of a part of a component k	m	[0,005;0,7]
B_k	Width of a part of a component k	m	[0,005;0,6]
A'_k	Length of a box of a component k	m	[0,2;1]
B'_k	Width of a box of a component k	m	[0,09;1,2]
a_k	Maximum number of parts of the component k that can be handled at once	-	[1;4]
a'_k	Maximum number of boxes of the component k that can be handled at once	-	[1;2]
θ_k	Number of parts of the component k picked at once during the assembly	-	-
θ'_{ki}	Average number of boxes of the variant i of component k handled at once	-	-
θ_{ki}	Average number of parts of the variant i of component k picked at once during the preparation	-	-
θ'_k	Average number of sequenced parts of the variant i of component k unloaded at once	-	-
M_k	Weight of a part of the component k	Kg	[0,002;9,913]
M'_k	Weight of a box of the component k	Kg	[1,1; 136,133]
Vol_k	Volume of a part of the component k	m^3	[0,0000003;0,087]
Vol'_k	Volume of a box of the component k	m^3	[0,005;1,176]
τ_{ki}	Usage rate of the variant i of component k	-	[0,05;1]
r_{ki}	Number of boxes of the variant i of the component k consumed between two successive deliveries	-	-

[1] Values of parameters concerning components are given in ranges of variation.

[2] Values of calculated parameters are not provided and replaced by "-".