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AN EMPIRICAL STUDY ON THE PERFORMANCE OF THREE ALTERNATIVE LINE FEEDING MODES IN A JIT CONTEXT

Mustapha Sali ^a, Evren Sahin ^b

^a PSL, Université Paris Dauphine, DRM UMR 7088,
75016 Paris, France.

^b École Centrale Paris, Laboratoire Génie Industriel,
Grande Voie des Vignes, 92290 Châtenay-Malabry,
France.

mustapha.sali@dauphine.fr

evren.sahin@ecp.fr

Alain Patchong ^c

^c Faurecia, Automotive Seating Technical Center, 91150
Brières-les-Scellés. France.

alain.patchong@faurecia.com

ABSTRACT: *In-plant material supply has gained more interest since product diversity has increased with the growth of mass customization. In such production environment, mixed-model assembly lines are designed to support the production of a large scale of finished products obtained by the combination of alternative variants of components that ensure a specific functionality on the finished product. The availability of the required variant at each stage of the assembly process is critical for the production processes that operate in a just in time (JIT) environment as it's the case for some first tier suppliers in the automotive industry. To ensure the availability of the required parts at each stage of the assembly process, several line feeding modes can be used. Their relative performance depends on several factors like the components' diversity and physical features to name a few. The impact of these parameters on the performance of the line feeding modes is not well known and this issue remains weakly represented in the literature. Using an empirical approach, this study aims to analyse the performance of three line feeding modes (line stocking, kitting and sequencing) according to a set of key parameters. The performance of each line feeding mode is measured as a periodic total cost that includes preparation, picking for the assembly, transportation and storage costs.*

KEYWORDS: line feeding, in-plant material supply, kitting, line stocking, sequencing.

1 INTRODUCTION

In assembly environment, line feeding is the in-plant logistic activity that aims at ensuring the preparation and the delivery of parts from the storage areas, where components are held upstream the assembly line, to the Border of the Line (BoL). Line stocking is the more common line feeding mode used in assembly industries such as automotive and electronics (Bozer and McGinnig 1992; Limère et al. 2012; Hanson and Brolin 2013). Also called continuous replenishment, it consists of stocking all parts used during assembly near their point of use at the BoL, in individual boxes. The replenishment of the stock hold at the BoL is usually performed by a consumption renewal or a kanban call signal. Since the increasing diversity of assembled products makes line stocking cumbersome and sometimes impossible to implement because of space constraints (Boysen et Bock, 2011), new feeding modes such as kitting and sequencing have emerged. Indeed, kitting and sequencing are two modes where only the specific parts needed for a future assembly sequence are prepared and delivered to the workstations rather than stocking all parts at the BoL. Although these modes imply a preparation process that takes place upstream the BoL, they enable to save space at BoL and improve assembly operators working conditions. The use of these approaches is only possible in JIT settings where the assembly sequence of end products is known over a reasonable horizon.

A kit may be viewed as a container which holds a specific assortment of parts that are used in one or more assembly

operations (Bozer et McGinnis, 1992). Hence, a kit holds all or a part of parts required to assemble one unit of end product and may be made up of one or several containers. A kit is qualified as stationary when parts that the containers hold are depleted at a unique workstation on the line. It is qualified as traveling when the containers are delivered at a certain point of the assembly line (usually the beginning of the line) and follow the end product they are associated with in order to support assembly operations performed at several workstations. In our study, we consider the case of traveling kits. Sequencing can be considered as a particular case of stationary kit where the assortment is made of one and only one particular part.

Each line feeding mode has its own operating principles which make it more or less efficient depending on the specific context in which it is applied. Indeed, a given mode has some advantages and drawbacks regarding several quantitative and qualitative performance criteria such as labour cost, operator ergonomics, flexibility for assembly line balancing, end-product quality, etc.

The First Tier Supplier (FTS) we worked with introduced recently kitting and sequencing in several pilot plants as an alternative to line stocking. This was done with the objective of reducing operating costs related to man-hour consumption and space. However, the company currently suffers from a lack of studies describing the relative benefit of implementing kitting and sequencing. Managers are therefore interested in comparing the performance, in terms of average total operating cost, of these three line feeding modes.

In this paper, we extend the existing literature by comparing line stocking, sequencing and kitting in the context of

an FTS that produces car seats in JIT plants. Through an empirical approach, we assess the impact of key parameters on the average total cost, in a deterministic environment. Cost components consist of parts preparation, in plant transportation, storage and picking for assembly costs. Such an approach is intended to provide insights to the company's initial question by identifying conditions that make one mode more efficient than others.

Our paper is organized as follows. Section 2 gives an overview of related literature. Section 3 describes in detail processes associated with each line feeding mode and provides the formulation of the cost considered. Section 4 presents the empirical analysis carried based on a numerical study. To conclude, further research perspectives are discussed in Section 5.

2 LITERATURE REVIEW

An extensive bibliography exists on the area of in-plant material supply covering a large range of topics such as ergonomics (Christmansson et al. 2002; Neumann and Mebdo 2010), packaging optimization and material exposure (de Souza, de Carvalho, and Brizon 2008; Finnsgard et al. 2011), and layout optimization (Gu, Goetschalckx and McGinnis 2010). Our review willingly restricts the focus on studies that assess the performance of several line feeding modes in both qualitative and quantitative ways.

One of the first papers dealing with the issue of line feeding was from Bozer and McGinnis (1992) where authors propose a descriptive model to quantify the trade-offs in terms of material handling, space requirements, and work-in-process between kitting and line stocking. Based on a numerical example, they argue that kitting achieves a better performance in reducing space requirement, average work-in-process and container flow. On the other side, line stocking is better regarding the storage and retrieval criteria. Parts picking activity performed by assembly operators is not taken into account in this study despite the fact that significant differences between feeding modes may exist at this level.

Caputo and Pelagagge (2008) propose a quantitative comparison between three line feeding modes. They provide analytical expressions for work-in-process, material handling, and space utilization under each mode. The model developed considers the case of a single product, which eliminates a part of the complexity observed in real mixed-model assembly lines where end product diversity implies parts diversity with components declined in several variants. This dimension of the problem is evaded by the single product assumption.

Battini et al. (2009) propose an integrated approach to support both centralization and decentralization storage area and line feeding decisions. Authors 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). First, the centralization/decentralization problem is addressed through a search of trade-off between inventory and material handling costs. Then, based on a multi-factorial analysis involving parameters such as lot size, number of compo-

nents, 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 assess the impact of diversity on the performance of line feeding modes.

Based on a study in the electronic industry, Hua and Johnson (2010) enumerate factors that may influence the choice between kitting and line stocking. They formulate various research questions grouped into five areas: product characteristics, storage and material handling, production control, performance impact and implementation. According to authors, the relatively large variety of components would push toward kitting while line stocking would likely be the best option in settings where products use similar components.

The model proposed by Limère et al. (2012) is a Mixed Integer Programming (MIP) that aims at minimizing a total labour cost by affecting components to either line stocking or stationary kitting. Space requirement is assumed to be a constraint with no cost associated. Labour costs cover picking at BoL, kit assembly, transportation, and replenishment of the preparation area. Authors show that, in some few cases, kitting can be preferred to line stocking even if there is no space constraint. However, conditions that make a component a desirable candidate for kitting are not explicitly explored.

More recently, based on two descriptive case studies, Hanson and Brolin (2013) identify the effects of kitting and continuous supply on man-hour consumption, product quality, flexibility, inventory levels and space requirements. Their conclusions suffer from contingency effect issued from the case study methodology that does not cover a large variety of situations.

We can deduce from our review that despite a growing industrial interest concerning the choice of an efficient line feeding policy, few studies focus on the comparison of different alternatives on a quantitative basis. Furthermore, when comparing the contributions of papers analysed, certain conclusions appear to be contradictory. Hua and Johnson (2010) illustrate this situation with the example of company in the automotive industry that switched back between kitting and line stocking modes several times without being sure of which one is best for them. In our study, we extend the existing literature by comparing line stoking, sequencing and kitting modes through an empirical approach. Our contribution aims at clarifying general conditions that make one line feeding mode more efficient than others in order to guide practitioners in their choice.

3 PROCESS DESCRIPTION AND COST FORMULATION

This section aims firstly at describing the processes observed in a FTS plant that assembles seats for automakers, in JIT mixed-model assembly lines. Based on this, we formulate the cost components associated with each line feeding mode.

3.1 General assumptions

Main processes concerned with line feeding are the preparation of parts before assembly, the transportation that is realized by a trolley train delivering parts from the preparation area to the BoL, picking activities realized at BoL and the storage of parts packaged in various forms. 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 declinations in colour and texture are variants.

Figure 1 provides an overview of the overall line feeding processes. Each preparation area is represented by a specific colour. In the preparation areas, shapes represent components and colours 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 the boxes with shapes with a black outline. The first two work stations of the assembly line are also represented. Dotted lines correspond to the moving of operators.

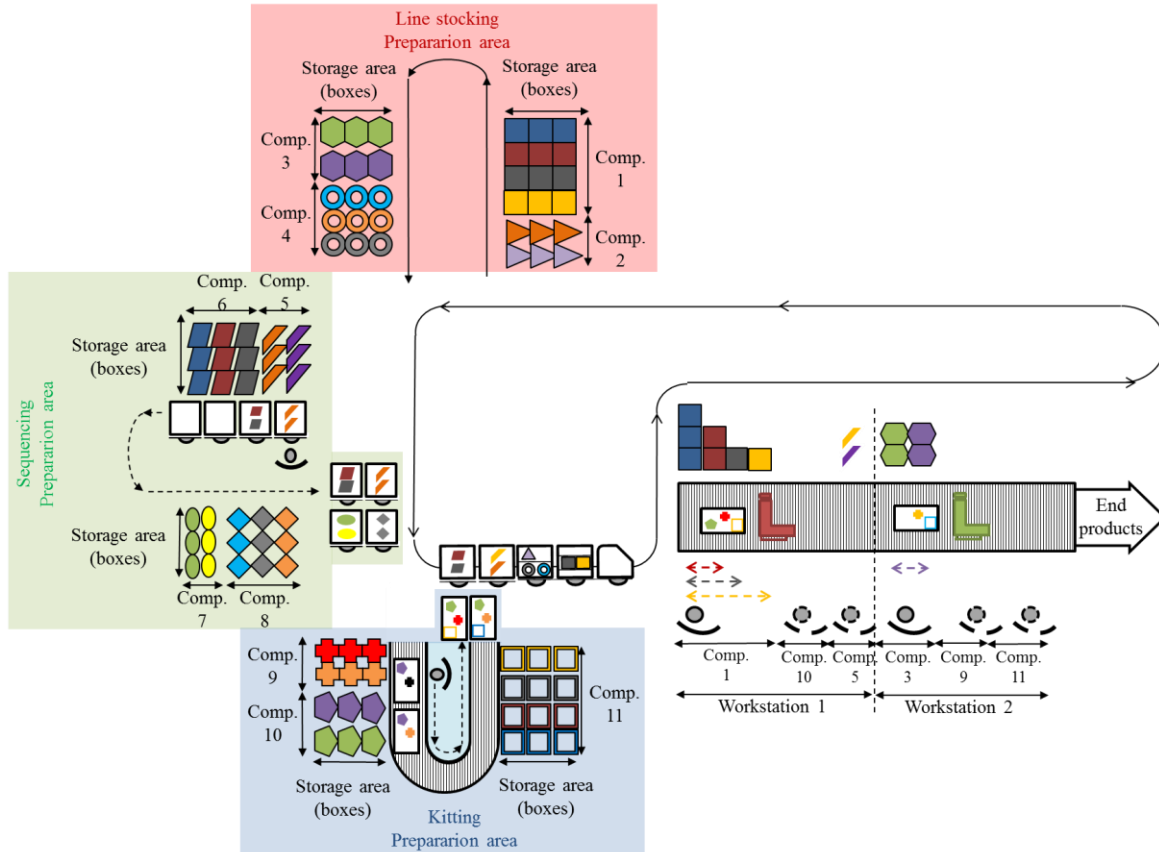


Figure 1. Process description

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. 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 variants of components are stored in boxes that have homogeneous content and from where the transportation of parts towards the BoL is carried by trolley 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 takt that separates two successive deliveries corresponds to the preparation batch size TL , i.e. the number of kits or sequenced variants of the same component prepared simultaneously between two deliveries.

Each preparation realized between two consecutive deliveries consists of four activities. First, a full roundtrip performed in the aisles of the preparation area in order to

collect parts. Then, operators grasp the relevant parts and boxes during the roundtrip. After, operators load parts, boxes and kit containers on the tugger train. Finally, 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 performed by the train, operators visit the aisles (where each aisle represents a zone that contains all variants of components), grasp the needed boxes and load 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 depends on the weight and volume of a single box. Such an efficiency principle also holds when operators unload boxes from the train.

Kitting: kits preparation is performed according to the needs deduced from the 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.

Sequencing: Under this mode, the preparation is quite similar to kitting. Instead of placing variants within a kit container, the preparation of each component is processed individually. The needed variants are grasped and directly placed in specific devices adapted to their shape according to the order of their consumption. These 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 deserve 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.

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 multiple instances of the same variant. For further efficiency, parts are fed to the BoL in the original supplier packaging. 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, 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 containing variants of components 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 when they are in front of them.

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.

3.3 Cost formulation

As presented in the previous section, costs considered in our model are formulated over four cost components that correspond respectively to the preparation before assembly, transportation, storage and picking during assembly. The total average cost associated with a line feeding mode is then obtained by summing all its related cost components. A comprehensive list of notations used in the formulations is provided in the Appendix.

provides a synthesis of the formulations of cost components. Each cost component is referenced with the notation (α, β) where α refers to the line feeding mode and β to the process. When several cost components are related to the same process, letters are added to the reference to avoid any ambiguity. When formulating cost, we consider that all components are supplied to the BoL under the same line feeding mode.

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 .

Mode	Process	Activity	Formula	
Line stocking	Preparation before the assembly	Perform a roundtrip in the preparation area	$\frac{V \cdot C_o}{TL \cdot 2 \cdot v_t} \cdot \sum_k S_k \cdot B'_k$ (1.1a)	
		Grasp the boxes and load them on the tugger train	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} \frac{\tau_{ki} \cdot c_k}{p_k \cdot \theta_{ki}} \cdot t_4$ (1.1b)	
		Unload the boxes from the tugger train at BoL	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} z_k \frac{\tau_{ki} \cdot c_k}{p_k \cdot \theta_{ki}} \cdot t_9$ (1.1c)	
	Transportation	Perform milk-runs to transport the boxes from the preparation areas to the BoL	$\frac{V}{TL} \cdot C_o \cdot m \cdot \frac{D}{v_t}$ (1.2)	
	Picking during assembly	Identify the variant to assemble on the end product	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} z_k \cdot \tau_{ki} \cdot t_{10k}$ (1.3a)	
		Perform a roundtrip between a starting point and the location of the variant to assemble	$\frac{V \cdot 2 \cdot C_o}{v_o} \cdot \sum_k \sum_{i \in S_k} z_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_k} \cdot (i-1) \cdot B'_k$ (1.3b)	
		Pick the variant from its box	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} z_k \frac{\tau_{ki} \cdot c_k}{\theta_k} \cdot t_{11}$ (1.3c)	
	Storage	Store the boxes at the BoL	$\sum_k \sum_{i \in S_k} z_k \cdot \lceil r_{ki} \rceil \cdot A'_k \cdot B'_k \cdot C_{m^2}$ (1.4)	
	Kitting	Preparation before the assembly	Perform a roundtrip in the preparation area	$\frac{V \cdot C_o}{TL \cdot 2 \cdot v_o} \cdot \sum_k x_k \cdot S_k \cdot B'_k$ (2.1a)
			Grasp the parts and fill the kit containers	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} x_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_{ki}} \cdot t_1$ (2.1b)
Load the kit containers on the tugger train			$V \cdot C_o \cdot N_{bac} \cdot t_2$ (2.1c)	
Unload the kit containers from the tugger train at BoL			$V \cdot C_o \cdot N_{bac} \cdot t_5$ (2.1d)	
Transportation		Perform milk-runs to transport the kit containers from the preparation areas to the BoL	$\frac{V}{TL} \cdot C_o \cdot m \cdot \frac{D}{v_t}$ (2.3)	
Picking during assembly		Pick the variant from the kit container	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} x_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_k} \cdot t_6$ (2.3)	
Storage		Store the kit containers in the preparation area	$\frac{TL \cdot A_{bac} \cdot B_{bac} \cdot C_{m^2} \cdot N_{bac}}{2}$ (2.4)	
Sequencing	Preparation before the assembly	Perform a roundtrip in the preparation area	$\frac{V \cdot C_o}{TL \cdot 2 \cdot v_o} \cdot \sum_k y_k \cdot S_k \cdot B'_k$ (3.1a)	
		Grasp the parts and load them on the support devices	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} y_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_{ki}} \cdot t_3$ (3.1b)	
		Unload the parts from the tugger train at BoL	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} y_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_k} \cdot t_7$ (3.1c)	
	Transportation	Perform milk-runs to transport the sequenced parts from the preparation areas to the BoL	$\frac{V}{TL} \cdot C_o \cdot m \cdot \frac{D}{v_t}$ (3.2)	
	Picking during assembly	Pick the sequenced variant	$V \cdot C_o \cdot \sum_k \sum_{i \in S_k} y_k \cdot \frac{\tau_{ki} \cdot c_k}{\theta_k} \cdot t_8$ (3.3)	
	Storage	Store the sequenced parts in the preparation area and at the BoL	$2 \cdot TL \cdot C_{m^2} \cdot \sum_k \sum_{i \in S_k} y_k \cdot \tau_{ki} \cdot c_k \cdot A_k \cdot B_k$ (3.4)	

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.

3.3.1 Line stocking

Preparation before assembly: The average total labour time spent by operators moving in the preparation area is obtained by multiplying the total number of roundtrips by the time required to realize a single roundtrip. The number of roundtrips is given by V/TL . Time required to achieve a complete roundtrip is given by $\sum_k |S_k| \cdot B'_k / (2 \cdot v_t)$. The term

$1/2$ comes from the U-shaped arrangement of the preparation area and the two height storage structure. The cost pertaining to this activity is then given by (1.1a).

During a roundtrip within the preparation area, the operator has to grasp boxes relative to the needed variants and load them on the train. The number of boxes of a variant i of a component k that is consumed during the period considered corresponds to $V \cdot \tau_{ki} \cdot c_k / p_k$. The implicit assumption made is that all variants of a given component have the same physical features.

If we model the possibility for an operator to grasp and load several boxes at the same time, i.e., simultaneously, it is necessary to calculate the average number of boxes of each variant prepared for one delivery. Since the preparation batch size TL is also the number of takts that separates two successive deliveries, it is possible to deduce r_{ki} , the number of boxes of the variant i of component k consumed between two successive deliveries by $r_{ki} = TL \cdot \tau_{ki} \cdot c_k / p_k$. r_{ki} is also the average number of boxes of the variant i of component k that has to be grasped and loaded on the tugger train during a single preparation. If θ'_{ki} represents the average number of boxes of the variant i of component k grasped and loaded at once, it would correspond to the maximum between 1 and the minimum between a'_k and r_{ki} . The value of a'_k depends on the weight and the volume of the boxes. The total cost of grasping and loading boxes on the tugger train is given by (1.1b).

A symmetrical operation is done when operators unload the boxes. The cost of this operation is given by (1.1c).

Transportation: 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. The number of milk-runs m that must be performed per TL takts is given by

$$m = \left\lceil TL \cdot \sum_k \sum_{i \in S_k} r_{ki} \cdot Vol'_k / Y_t \right\rceil$$
. The total average number of milk-runs performed to transport all parts needed for the production of V end products is then given by $m \cdot V / TL$.

The average total transportation cost is given by (1.2).

Picking during assembly: During this process, three elementary operations are done by the assembly operator. After the identification of the right variant to be assembled on the end product is done, a roundtrip is realised between a starting position and the location where the variant is

stored. Finally, the variant to be assembled is grasped. Grasping may involve several parts at a time if the BOM coefficient of the component is greater than one. The mentioned activities are repeated for each variant to be assembled.

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 any variant of a component. The cost of this operation is given by (1.3a) where t_{10k} 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 fixed and that depend on the usage rate of variants. To overcome this difficulty, we approximate the effective movement of the operator. Since products are moving on the line, we consider a different and independent starting point for each component concerned by a specific elementary assembly operation. 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.

The total number of roundtrips depends on the opportunity of picking multiple parts at a time. If θ_k denotes the number of parts picked at once during the assembly, it would correspond to the minimum between a_k and c_k .

The cost related to the movement of operators during the assembly is given by (1.3b)

The grasping cost is given by (1.3c).

Storage: The storage cost is interpreted as an opportunity cost associated with the potential use of available space in the plant. For line stocking, storage cost is related to the storage area required at BoL where boxes are positioned on shelves and within arm's reach of the assembly operator. The number of required square meters at BoL is obtained by summing the ground surface of boxes stored, i.e., $\sum_k \sum_{i \in S_k} \lceil r_{ki} \rceil \cdot A'_k \cdot B'_k$. The storage cost is then obtained by

$$(1.4).$$

3.3.2 Kitting

Preparation before assembly: Kits are prepared in batches of TL in consistency with the length of the JIT window. Information regarding kits to be prepared is provided to operators on a communized picking list for the next TL products.

During the roundtrip in the preparation area, the operator selects for each component the specific variant required for the assembly. Variants are then placed into containers. A U-shaped roller shelf is used to ensure an easy moving

of kit containers. The average total labour time related to the movement of operators within the preparation area is obtained by (2.1a).

During a roundtrip within the preparation area, operators have to grasp the needed variants and to put them in kit containers. 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 model 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 $TL \cdot \tau_{ik} \cdot c_k$.

θ_{ki} , i.e., the average number of parts of the variant i of component k grasped at once during the preparation, is obtained by $\theta_{ki} = \max(\min(TL \cdot \tau_{ik} \cdot c_k, a_k), \min(c_k, a_k))$. Potentially, between two deliveries, an operator has the opportunity to grasp at once the number of parts of the same variant consumed during this period (i.e., $TL \cdot \tau_{ik} \cdot c_k$). The simultaneous grasping is limited by a_k . Thus, the number of parts of the same variant that can be grasped at once corresponds to $\min(TL \cdot \tau_{ik} \cdot c_k, a_k)$. θ_{ki} is the maximum between this value and $\min(c_k, a_k)$ that gives the number of parts that can be grasped at once regardless the value of TL . The cost of grasping variants is calculated using (2.1b).

The loading of kit containers on the tigger train is calculated using (2.1c) Equation (11) where N_{bac} is the number of containers per kit. N_{bac} is calculated according to the maximum volume and weight capacity of a container

$$N_{bac} = \left\lceil \frac{\max(\sum_k \sum_{i \in S_k} \tau_{ki} \cdot c_{ki} \cdot M_k / M_{bac}, \sum_k \sum_{i \in S_k} \tau_{ki} \cdot c_{ki} \cdot Vol_k / Vol_{bac})}{1} \right\rceil. \text{ Note that, the}$$

loading/unloading of several containers at once is made difficult due to the presence of some components' shapes that prevent the stacking of containers. Thus, the loading and unloading of containers are assumed to be performed one by one. The unloading of containers from the tigger train is calculated using (2.1d).

Transportation: The number of milk-runs m that must be performed per TL takts is given by $m = \lceil TL \cdot N_{bac} \cdot Vol_{bac} / Y_t \rceil$. The total average number of milk-runs performed to transport all parts needed for the production of V end products is then given by $m \cdot V / TL$. The transportation cost is given by (2.3).

Picking during assembly: Picking during assembly consists of grasping individual pieces from kit containers to assemble them on end products. In contrast to line stocking, only the needed variants are present within a kit container. Thus, no identification activity is required. Furthermore, unlike the line stocking mode, operators do not have to move to fetch the variant to be assembled. The cost related to this activity is given by (2.3).

Storage: The storage cost associated with kitting concerns the buffer zone where the prepared kit containers are temporarily stored.

As explained before, TL kits are prepared and stored before being loaded on the train. Each kit consists of N_{bac} containers of length A_{bac} and width B_{bac} . Containers are stored on two height storage levels in the buffer zone. Thus, the storage cost is given by (2.4).

3.3.3 Sequencing

Preparation before assembly: Preparation of sequenced parts is done identically to kitting with the use of the same information from the assembly sequence. The only difference is that parts are directly loaded on the train's wagons instead of being positioned within containers. The cost related to the operator movement within the preparation area is obtained by (3.1a).

The cost of picking and loading variants is calculated using (3.1b).

Sequenced parts are unloaded from the tigger train to be placed near their point of use. The cost formulation of this activity differs slightly from the one of the loading activity. θ_{ki} is replaced by $\theta'_k = \min(a_k, TL \cdot c_k)$ as the unloading operation is not related to the consumption rate of variants. The cost of unloading variants at the BoL is calculated using (3.1c).

Transportation: The transportation cost is given by (3.2)

$$\text{where } m = \left\lceil TL \cdot \sum_k \sum_{i \in S_k} \tau_{ki} \cdot c_k \cdot Vol_k / Y_t \right\rceil.$$

Picking during assembly: Since only the needed variants for the assembly are presented at BoL according to their consumption sequence, no identification and movement activities are required for the sequencing mode. The cost related to the picking at the BoL is given by (3.3).

Storage: In a sequencing mode, 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 storage cost is then given by (3.4). We assume that no stacking is possible for sequenced variants.

4 EMPIRICAL ANALYSIS

The description of the different line feeding modes shows significant differences in their *modus operandi*. Hence, each mode has its own cost formulation involving several parameters such as components' physical features, packaging, layout, production and unit time parameters associated with operators' movements. Thus, the research questions asked in this paper can be formulated as follows:

- How can we evaluate quantitatively the impact these various parameters on the performance of line feeding modes?
- What are the conditions that make a particular line feeding mode more efficient, in terms of average total operating cost, compared with others?

To provide answers to these questions, we have opted for an empirical approach which is based on a multi-scenario analysis as detailed in this Section. Indeed, the diversity of parameters and the complexity in formulating some cost components make it difficult to conduct an analytical approach. Hence, Section 4.1 explains the methodology used and Section 4.2 presents the numerical experiments carried out. Finally, Section 4.3 provides insights on results obtained.

4.1 Methodology

Our analysis consists of comparing three situations where components are either exclusively line stocked, kitted or sequenced. Each situation is studied under different scenarios characterized by specific values taken by cost parameters. The average total operating cost pertaining to a given scenario is calculated for three situations that correspond respectively to: all components are line stocked, all components are kitted, all components are sequenced. Comparing these three costs allows then to rank line stocking, kitting, and sequencing options for each scenario. The analysis phase aims to identify, among parameters, which are those that mostly contribute to explain the superiority of one mode over others.

Hence, as a first step, we generate a large number of scenarios that combines different values of parameters. In order to simplify the analysis, some parameters used in the cost formulation are considered fixed. Typically, layout related parameters as well as unit time parameters are directly taken from the FTS JIT plant context we worked with. Other parameters take values in intervals constructed on the basis of the feedback given by company experts. *A priori*, the variable parameters, detailed bellow, are expected to have significant impact on the performance of the line feeding modes.

- Number of components. Each component is spotted by an index k that takes values from 1 to K (which corresponds to the total number of components).
- Number of variants per component. A variant is spotted by an index i that takes values from 1 to I (which corresponds to the maximum number of variants per component). We suppose, under the line stocking mode, that variants are stored at BoL in the order of decreasing usage rates τ_{ki} (i.e., if $I=2$ for k then $\tau_{k1} \geq \tau_{k2}$).
- BOM coefficient. The coefficient c_k is the number of pieces of the same component that is required to perform the assembly of a given end product.
- Component class. Each class is characterized by a set of parameters concerning components' and boxes' physical features. These parameters are typically the weight, volume, length, width of components and boxes as well as the number of pieces contained in a box. To synthesize such features into a single parameter, we define five classes (1, 2, 3, 4 and 5 that corresponds to very big, big, medium, small and very small) of components having different physical characteristics.
- Usage profile. The usage rate τ_{ki} of a variant indicates the percentage of end products, among V products, that needs this variant in their assembly. We consider three

profiles of usage. For each profile, the value of δ gives the distribution of the usage rates for a given set of alternative variants. For instance, for a profile where $\delta=40\%$, we have $\tau_{ki-1}=(1-\delta)\cdot\tau_{ki}=0,6\cdot\tau_{ki}$. The profile indicates whether the difference among the individual usage rates of variants is important (i.e., δ close to 100%) or weak (i.e., δ close to 0%).

- Unusage rate. For a given component, the unusage rate τ_0 indicates the percentage of end products that does not use any variant of this component ($\forall k, \tau_0=1-\sum_{i \in S_k} \tau_{ki}$). Typically, this situation is encountered when a component is optional.
- Delivery and preparation batch size. The parameter TL is an input data for both kitting and sequencing modes. For line stocking, the value it takes is optimized to minimize a function that is the sum of storage and preparation costs. The preparation cost is a monotone decreasing function of TL while the storage cost is a stepwise increasing function of TL . To obtain a convex shape of the function, we linearize the storage cost.

4.2 Numerical study

When combining different values of parameters, we obtain 94050 different scenarios. Hence, Figure 2 shows the percentage of scenarios where each line feeding mode is ranked first, i.e., the mostly preferred one, second or third among 94050 scenarios.

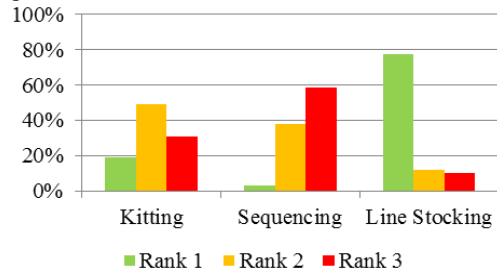


Figure 2: Ranking of the line feeding modes

Line stocking is the least costly mode in more than 77% of scenarios, (which means that the total cost of line stocking is lower than the ones of kitting and sequencing in 72916 scenarios). In near 20% of scenarios, kitting is the best line feeding mode in terms of total cost. Sequencing is ranked in the first position in less than 4% of scenarios.

Figures 3 to 5 characterize scenarios where respectively line stocking, kitting, and sequencing has the minimum total cost compared with the other line feeding modes. Each chart is related to one variable parameter and shows the distribution (in percentage) of values that a given parameter takes in scenarios where the concerned mode dominates the other ones.

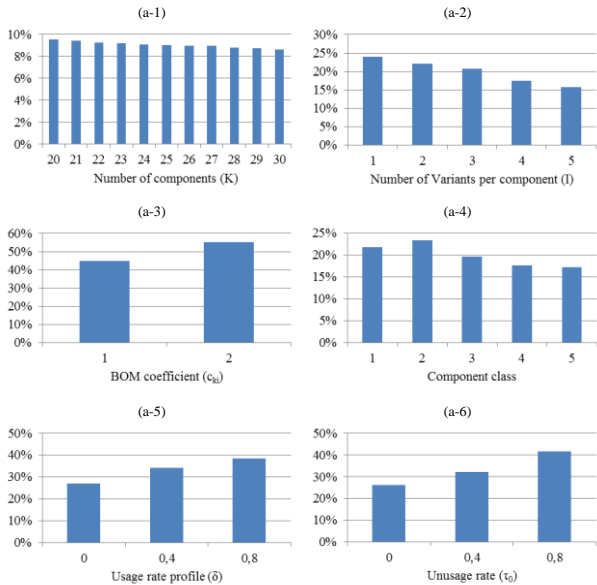


Figure 3: Characteristics of scenarios where line stocking is ranked first

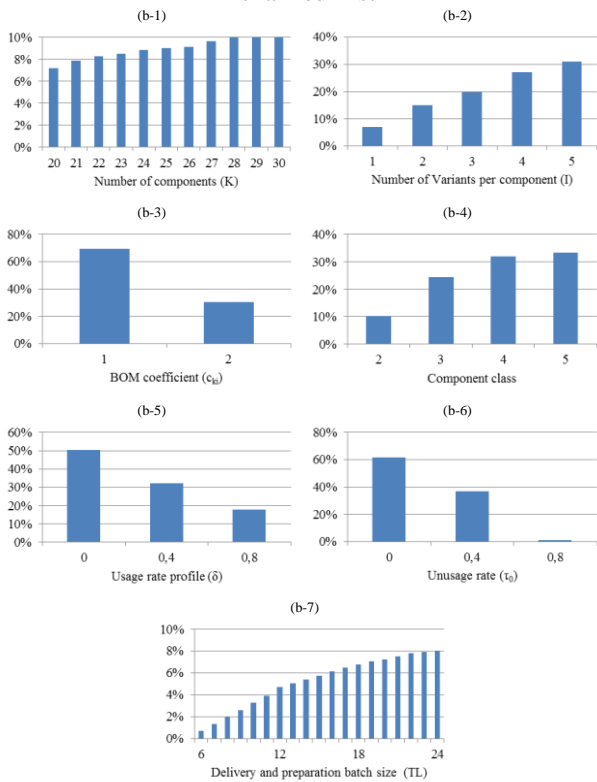


Figure 4: Characteristics of scenarios where kitting is ranked first

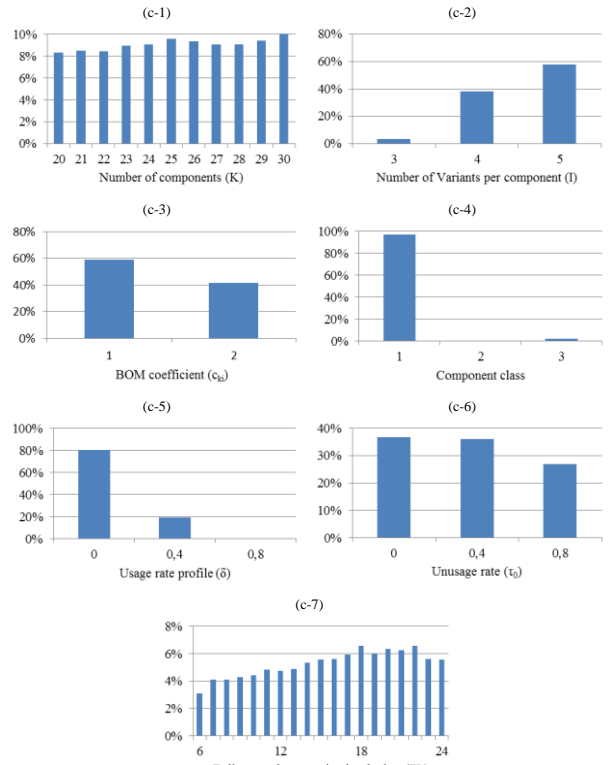


Figure 5: Characteristics of scenarios where sequencing is ranked first

4.3 Interpretation of results

The increase in the number of components increases the total cost pertaining to all line feeding modes. Nevertheless, Chart b-1 of Figure 4 shows that kitting is more interesting in settings where the number of components is important. This observation is consistent with the “free riders” feature reported by Limère et al. (2012). For kitting, when adding a new component, costs related to handling and storage of containers remain stable as long as an additional container is not needed. For line stocking, additional components increase all cost components proportionally. No particular behaviour is observed on Chart c-1 of Figure 5 for scenarios where sequencing is ranked first. Charts a-2, b-2 and c-2 illustrate the effect of variant diversity on feeding modes. Kitting and sequencing are often preferred to line stocking in scenarios where the number of variants per component is high. When the number of variants per component exceeds one, an identification time is necessary during the assembly in the line stocking mode in order to select the right variant among all alternatives. In addition, when a large number of variants are line stocked, walking distances of operators increase especially for voluminous components with uniformly distributed usage rates (i.e., $\delta=0\%$). This is why sequencing becomes more interesting for voluminous components (cf. Chart c-4 of Figure 5) that have a large number of variants (cf. Chart c-2 of Figure 5) and uniform usage profiles (cf. Chart c-5 of Figure 5). The same observation can be made when comparing kitting with line stocking, with the difference that voluminous components are not good candidates for kitting (cf. Chart c-4). Our results show that components pertaining to classes 1 and 2

increase the number of containers per kit and thus loading, unloading and storage costs. In addition, voluminous (and very voluminous) components do not allow batch picking that contribute to reduce the preparation cost. Kitting is often preferred to line stocking in scenarios involving small and very small components that have a large number of variants per component.

As far as the BOM coefficient is concerned, we observe that kitting and sequencing are more efficient than line stocking when $c_k=1$ (cf. Charts a-3, b-3 and c-3). The impact of the BOM coefficient is not the same as the number of components. In the case of kitting and sequencing, when c_k changes from 1 to 2, the total cost behave as if the number of components has doubled. For line stocking, the increase of the BOM coefficient does not necessarily imply an increase of the identification and movement costs associated with assembly operations, for components whose a_k value is greater or equal to c_k .

The unusage rate reduces the walking distance covered by operators at BoL in the line stocking mode. This explains why scenarios where line stocking is ranked first are mostly characterized by a nonzero unusage rate (cf. Chart a-6 of Figure 3).

The increase of the preparation batch size has a positive impact on kitting and sequencing since it allows batch picking as well as a reduction of transportation cost. Since sequencing is preferred for components pertaining to class 1 for which batch picking is not possible, this mode only benefits from the transportation cost reduction when TL increases. For both kitting and sequencing, an excessive increase of TL results in increased storage costs. After a certain value of preparation batch size, the increase of the storage cost is more important than the reduction of the preparation cost. We can see on Charts b-7 and c-7 that the percentage of scenarios starts to stabilize after a certain value of TL . For sequencing, this percentage starts to decrease after $TL=18$.

5 CONCLUSION AND PERSPECTIVES

Benefits and drawbacks of different line feeding modes appear to depend on the characteristics of the production and materials supply environment they are used in. This paper considers this issue by evaluating and comparing the performance of three modes based on a numerical case study in the automotive sector.

Through a description of processes that underlie each line feeding mode, we formulate the associated costs which concern preparation before assembly, transportation, storage and picking during assembly. A multi scenario analysis shows that parameters used in cost formulation play a critical role in the relative performance of line stocking, kitting and sequencing modes. The analysis of scenarios allowed the identification of conditions under which a particular mode would be the least costly one. As such, kitting appears as an interesting alternative for line stocking in the case of small components with high diversity. Sequencing is preferred for voluminous components with high diversity. These general results have to be nuanced

by the significant impact of other parameters such as the usage rate profile and the BOM coefficient.

Our study can be extended in several ways. For instance, a specific in-plant layout or multiple assembly lines would require adjustments of the cost formulation. Also, depending on the location of the plant, unit cost parameters can substantially differ. Additionally, the estimation of unit times pertaining to operators' movements can also be improved by using Methods for Time Measurement (MTM).

To enlarge the comparison, costs pertaining to reverse logistic activities of empty kit containers and boxes may be included to the analysis. Furthermore, the development of new multi-criteria models would enable the consideration of qualitative criteria such as ergonomics, flexibility or product quality. A complementary approach to this empirical study would also consist of developing a decision support allowing the optimal allocation of components to the different line feeding modes in order to minimize operating costs. This would also allow testing the relevance of results obtained in this paper.

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Appendix

Notation	Definition	Unit
K	Number of components	-
k	Component index, $k = 1 \dots K$	-
I	Maximum number of variants per component	-
i	Index for a variant of a given component, $i = 1 \dots I$	-
m	Number of transportation milk-runs per delivery	-
N_{bac}	Number of containers per kit	-
S_k	Set of variants of a component k	-
$ S_k $	Number of variants of a component k	-
c_k	Bill of material coefficient of a component k	-
p_k	Number of parts per box of a component k	-
A_k	Length of a part of a component k	m
B_k	Width of a part of a component k	m
A'_k	Length of a box of a component k	m
B'_k	Width of a box of a component k	m
A_{bin}	Length of a kit container	m
B_{bin}	Width of a kit container	m
Y_t	Capacity of the tugger train	m ³
a_k	Maximum number of parts of the component k that can be handled at once	-
a'_k	Maximum number of boxes of the component k that can be handled at once	-
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
Vol_k	Volume of a part of the component k	m ³
Vol'_k	Volume of a box of the component k	m ³
Vol_{bin}	Volume capacity of a kit container	m ³
M_{bac}	Weight capacity of a kit container	Kg
D	Distance travelled by the train during one milk-run	m
v_t	Velocity of the tugger train	m/s
v_o	Velocity of an operator	m/s
V	Production per period	-
δ	Usage rate profile	-
τ_0	Unusage rate	-
τ_{ki}	Usage rate of the variant i of component k	-
\tilde{r}_{ki}	Number of boxes of the variant i of the component k consumed between two successive deliveries	-
TL	Preparation and delivery batch size	-
t_1	Time needed by the operator to realize a single movement of picking variants during the preparation in a kitting mode	s

t_2	Time needed by the operator to realize a single movement of loading a kit container on the train.	s
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
t_4	Time needed by the operator to realize a single movement of grasping boxes and loading them	s
t_5	Time needed by the operator to realize a single movement of unloading a kit container from the train	s
t_6	Time needed by the operator to realize a single movement of picking during the assembly in a kitting mode	s
t_7	Time needed by the operator to realize a single movement of unloading the sequenced parts at BoL	s
t_8	Time needed by the operator to realize a single movement of picking during the assembly for the sequencing mode	s
t_9	Time needed by the operator to realize a single movement of grasping boxes and unloading them	s
t_{10}	Time needed by the operator to realize a single operation of identification.	s
t_{11}	Time needed by the operator to realize a single movement of grasping line stocked parts for assembly	s
C_{m^2}	Periodic rental cost per square meter	€/m ² /day
C_o	Labour cost per time unit	€/s