Int J Adv Manuf Technol (2014) 72:543–560
DOI 10.1007/s00170-014-5675-0

ORIGINAL ARTICLE

The impact of production mix variations and models varieties on the parts-feeding policy selection in a JIT assembly system

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Received: 12 September 2013 / Accepted: 27 January 2014 / Published online: 20 February 2014

Abstract One of the significant challenges in operating a mix-model assembly system is the feeding of parts to the productive units. In order to avoid production loss, assembly systems require uninterrupted availability of components to feed workstations. On the other hand, the feeding of assembly components has to be performed in a way that minimises the related costs. In the past, the feeding system most widely used was so-called 'line storage' in which the components were stored along the assembly stations in large quantities and were periodically refilled by the central warehouse. Following just-in-time principles, nowadays, assembly system feeding is undertaken by supermarkets, as in decentralised storage areas close to the assembly lines. From such kinds of warehousing, a growing number of manufacturers are adopting two other feeding strategies: the kanban system, which continuously refills the assembly stations through the pull kanban system, or the kitting system, in which kits of components are prepared and delivered following the product through the assembly stations. This paper aims to quantitatively analyse and compare these two recent feeding strategies, considering the production mix variation and the assembled models variety influence. Moreover, kanban-kitting feeding policy and the related optimization issues are considered as hybrid. The findings from an industrial case study and a simulation analysis are also reported. Finally, a decision-making tool that defines a series of 'convenience areas' for the different feeding policies is provided.

Keywords Feeding · Kanban · Kitting · Hybrid · BOM · Production mix · Assembly system

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1 Introduction

In today's market, in order to compete, companies need to offer a wide range of different products. A possible approach is to configure the production system as a multiple mixed-model assembly line system, where each assembly line is capable of producing a great number of variants of a common base product, while the base product is different from one assembly line to another.

One significant challenge within this context is part feeding to the productive units (assembly line stations) [14]. A reliable and flexible parts supply is indispensable because otherwise there is a threat of materials shortages, leading to line stoppages and hundreds of assembly workers being idle. In contrast, enlarged safety stocks near the line impede the assembly process due to the scarcity of space in stations [15] and increase inventory costs. For this reason, the traditional 'line stocking' feeding strategy has increasingly been replaced by reduced assembly line inventory policies such as 'kanban' continuous supply and 'kitting'. In fact, 'line stocking' is based on large containers holding bulk quantities, simply stored along the line and periodically replenished with little handling effort but high space requirements. Moreover, in order to guarantee rapid delivery, assembly system feeding for both kanban and kitting is undertaken through supermarkets. These warehouses are decentralised storage areas scattered throughout the shop floor that serve as intermediate storage for parts required by nearby assembly lines [14]. In this kind of warehouse where handling and picking operations require an ergonomic and fast manner, many special storage tools such as gravity shelves and modular pipes are often used. The stock-keeping units must be easily selected, transported and loaded at each assembly station. In the case of kitting, a kit preparation area is normally present close to the supermarket.

The evaluation and optimization of these two last feeding policies in the supermarket assembly line system is a relatively new research topic and only a few recent contributions are available in the literature. The practical implications for different industrial sectors, especially in just-in-time (JIT) assembly systems, make this topic a relevant research area in operations management. The main features of these two feeding policies are as follows:

- *Kanban continuous supply*: handling operators, sometimes using small towing vehicles connected to a handful of waggons, deliver parts stored in appropriate containers from the supermarket to assembly stations and collect empty containers from them. Typically, delivery is according to a fixed schedule and route for each operator who serves a certain part of the system (i.e. a certain set of assembly stations). After making their deliveries, the handling operators return to the supermarket to refill for their next tour. Thus, decentralised supermarkets can deliver frequent and small loads of parts so that inventory on the lines is reduced and long-distance deliveries from a central receiving store are avoided. Every container is normally associated with a kanban card, a plastic card containing all the information required for the production/supply of the parts of a product at each stage. These cards are used to control production flow and inventory [28]. The assembly stations in such a supermarket/multiple mixed-model assembly line system are refilled through the constant replacement of the parts consumed, pulled by the kanban system.
- *Kitting*: kitting requires that all components of an item be collected before being sent to assembly [21]. The component parts may either be manufactured in-house or purchased from suppliers. Each component is retrieved from a storage location through typical picking operations inside the supermarket and then placed in a container designed to hold all the kit parts. Each kit is associated with a certain model for assembly with a 1:1 correspondence. Once completed, the product kit is moved to the assembly line in accordance with the production sequence. Each operator then assembles the product using the parts contained in the kit in accordance with the assembly cycle. The kit moves together with the product through the assembly stations from the first to the last (travelling kitting). Another possibility is a stationary kit that is delivered to a workstation and remains there until it is depleted.

Figure 1 illustrates the two feeding policies considered.

There are considerable differences between these two feeding policies, both from an operational and cost point of view. With regard to costs, in the feeding of parts, it is possible to consider three main cost types: handling costs, inventory costs and stock-out costs.

Kitting policy enables the materials required to be determined before product assembly. Thus, if the kit is correctly prepared and scheduled, it is possible to avoid stock-out risks (and so stock-out costs). On the other hand, kanban-based continuous supply has a stock-out risk because of the variability in parts consumption, and this can be reduced only through maintaining a high level of safety stock. Kitting requires that each part of the kit is managed through an initial picking activity at the warehouse. This activity certainly increases the handling costs compared with a kanban-supermarket material feeding system in which containers with a certain number of each component type are picked up rather than single pieces. Finally, the average inventory costs at the assembly stations for kanban-based continuous supply tend to be greater than for kitting because of the use of safety and operational stocks close to the assembly stations.

Given these cost trade-offs, it is clear that there are several factors that drive the choice between the two feeding policies, some of these more strategic, others more practical, in terms of the single assembly task.

This study is not intended as a detailed performance analysis of assembly systems, but is aimed at preliminary selection of alternative line-feeding systems in relation to some of these important influential factors for a number of different reasons. A list of the most influential factors in the parts-feeding optimisation problem is presented in Hua and Johnson [21]. As a first point, they affirm that product volume and variety probably play a large role in determining whether a kitting or kanban continuous feeding system is applicable. Moreover, Caputo and Pelagagge [8] affirm that continuous supply becomes unfeasible with increasing product variants owing to capital cost and lack of space at assembly stations.

Because of the acknowledged importance of these factors, this study, taking into account other different influential variables, focuses mainly on the impact of production mix variability and of the models variety (i.e. the assembled product's bill of materials diversity) on the correct feeding policy definition. The aim is to quantitatively define the break-even points of the different feeding strategies according to these variables. The present paper, considering a JIT assembly system fed by a supermarket warehouse, aims to propose a decision-making procedure based on a cost function comparison model, with cost functions being analysed for each feeding policy (kanban, kitting and hybrid). Through a simulation study, it provides a rough but quick and easy tool for the definition of the most appropriate feeding policy as a function of these variables. Hybrid policy design and optimisation represent a further element of the research.

This study continues previous research on kanban-continuous feeding policy optimization [17], also considering the possibility of applying the kitting feeding strategy or a hybrid kanban-kitting feeding strategy.

Summarising, the aims of the study were as follows:

1. to identify and analyse quantitatively some of the factors most influential, like the production mix variation and the

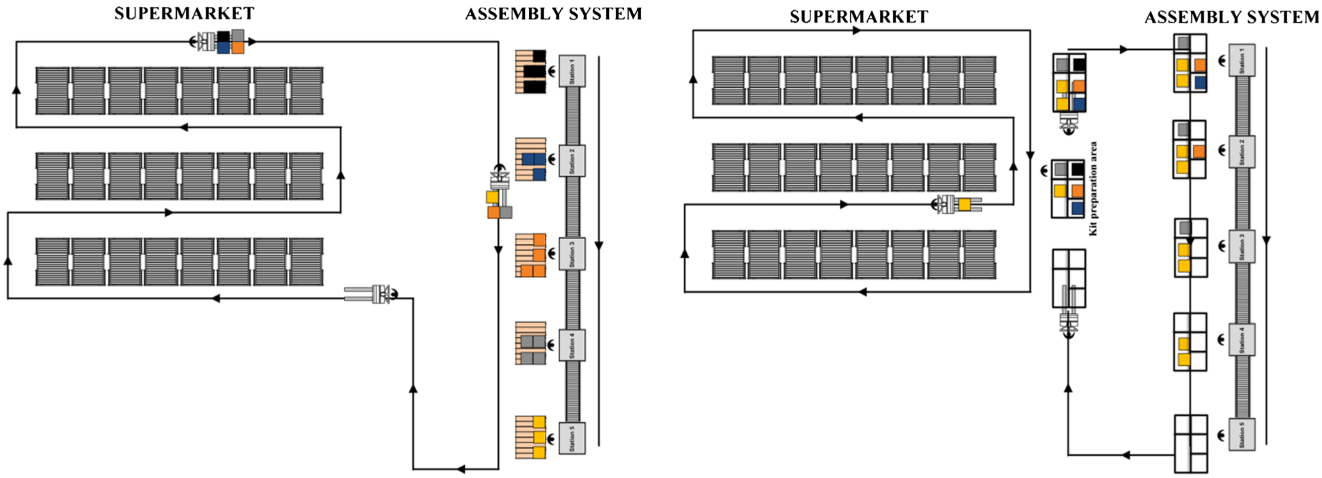

Fig. 1 Kanban continuous supply (*left*) and kitting (*right*)

assembled models diversity in defining the most appropriate feeding policy, and propose feeding policy selection criteria based on a cost function comparison model

2. to provide, through a simulation study, a rapid and easy tool for practitioners for feeding policy selection, based on convenience areas as a function of the performances in picking operations and on variations in parts consumption, that as demonstrated in the paper strongly production mix variability and of the assembled products diversity
3. to propose, as a possibility, a hybrid kanban-kitting feeding policy, highlighting its optimization and demonstrating how, in some cases, this feeding policy can provide a more effective solution than either kanban or kitting alone.

The practical implications of the present study are first the definition of a decision tool to select the proper component feeding method based on a quantitative evaluation of the analysed factors in driving the decision. Secondly, the cost function comparison model considers both single-feeding strategies (kitting or kanban continuous supply) and a hybrid feeding policy (kanban-kitting). The current state of the art in the assembly system components feeding design is relatively poor, especially concerning the quantitative analysis of very important influencing factors [21] like production mix variations and models varieties.

These elements in a JIT-level production environment, as demonstrated in the following sections, play a very important role. This kind of analysis has never been performed before and is a novelty of the present paper. Moreover, the hybrid policy design and optimization represents a further element of originality because just few recent contributions analyse this feeding strategy [8, 24].

The limitations of the proposed study and the further research agenda are provided and discussed in the conclusion section. The remainder of the paper is organised as follows. Section 2 provides a literature review on kanban and kitting feeding policies, focusing on the supermarket assembly line system. Section 3 describes the problem formulation and feeding policy cost models, while Section 4 presents a case study. Section 5 analyses the influence of variations in the bill of materials and production mix on the optimal setting of feeding policies. Finally, conclusions are drawn in Section 6.

2 Literature review

Feeding strategies can be summarised, as by Caputo and Pelagagge [8], in relation to three policies, namely line stocking, kitting and kanban-based continuous supply. In the past, the most widespread was line stocking, in which the components were stored along the assembly stations in large quantities and were infrequently refilled by the central warehouse. However, these days, modern 'lean' production principles have driven resulted in a shift to the other two feeding policies, where the inventory along the assembly lines is greatly reduced and assembly system feeding is undertaken by supermarkets, decentralised storage areas close to the assembly lines. As a result, the present paper is focused on the kitting and kanban continuous supply feeding policies.

2.1 The kanban continuous supply feeding policy

The kanban continuous supply feeding system is typically designed as a supermarkets (a decentralised storage areas scattered throughout the shop floor that serve as an intermediate store for parts required by nearby assembly lines), that refill the assembly stations through the constant replacement of the consumed parts pulled by the kanban system. Parts are stored in container and each container contains only a typology of part. The containers used to stock and move parts from the supermarket to the assembly system are also typically standardised and optimised in line with the parts typology. Every container is normally associated with a kanban card, a plastic card containing all the information required for the supply of the parts of a product at each stage. As consequence, in relation to the kanban continuous supply feeding system, it is possible to identify two main research topics related to: the kanban number optimization and the supermarket design and management. While there are a huge number of contributions about the first topic, the second research topic is relatively young and few papers are available.

The kanban number optimization problem it seems that most kanban implementations set these parameters by rules of thumb or simple formulas [7]. An example of such a formula is the well-known Toyota's $n \leq D \cdot L \cdot (1+\partial)/a$, where n is the number of kanban, D is the consumption rate, L is the supply lead time, a is the stock-keeping unit (SKU) capacity, and α is the positive safety factor [31]. Considering the supermarket/multiple mixed-model line assembly system feeding process, this formulation can sometimes be unable to bring about substantial results because of the parameters used are function of decisions variables that strongly influence the performances and costs of the system. For example, the supply lead time L, that, according to Persona et al. [26], influences also the safety stocks level, is a function of the number of handling operators, that, in this context, is a decision variable that has to be optimised. As demonstrated by Faccio et al. [17] in such production environment, it is possible to find the optimal number of handling operators and the optimal service level to guarantee at the assembly stations, deriving the optimal kanban number.

As reported in literature [28] the contributions in the kanban number optimization problem can be classified by their objectives:

- Maximisation of average cumulative throughput rate (the ratio of total satisfied demand to total generated demand) [32, 33]
- Minimisation of average production lead time (the amount of time spent by a job from entering the system until the completion of all operations) [22, 30];
- Minimisation of average work in progress (the mean of all in-process inventory levels for the products) [9, 29]
- Total costs minimization [25, 27]
- Maximisation of the parts usage rate smoothness in order to avoid the stock-out risk.

According the supermarket concept, this is a relatively young research topic and thus further research is certainly necessary. For Emde and Boysen [15], it is possible to classify these contributions according to timeframe (from long-term strategic to short-term operational), as follows:

1. Location planning, i.e. determining the number/locations of supermarkets, what parts each one has to manage and their assignation to the assembly lines [4, 14].
2. Handling resources definition, i.e. deciding on the number of handling operators (equal if used by the number of tow trains guided by handling operators) assigned to the supermarket and assembly stations served per operator, and where a route, starts and ends in the supermarket [10, 15, 18].
3. Handling operators scheduling and routing, i.e. for any given handling operator and his/her associated route, optimising the point in time for each stopover on any tour along a route [10, 15, 18].
4. Loading, i.e. agreeing on the number and types of a part's SKUs to be loaded per tour [10, 16, 18]. This means deciding for each part for each assembly station of each assembly line the number of parts to manage, or in other words in a JIT pull system for a given SKU capacity, the number of kanban. In this situation, the objective is to optimise the parts level at each assembly station, thus minimising the inventory level but avoiding part stock-outs.

As evidenced by the first part of this section, a large number of research issues concerning supermarkets are strictly related to the kanban system: for example, the definition of handling resources influences the kanban number according to Toyota's formulation.

2.2 The kitting feeding policy

As outlined in the Section 1, kitting parts before assembly operations is a common approach in manufacturing companies. Kitting requires that all components of an item be collected before being sent for assembly. The preparation of kits includes such activities as sorting inside the warehouse, picking, counting, etc. [21]. Kits are normally prepared in a stock area using a 'pick list' generated from the bill of materials for the order and are then delivered to a nearby assembly line according to the production schedule. Since kits are consumed in synch with the takt time, it is easier to schedule kit replenishments than to schedule bulk replenishments [24], avoiding part shortages at the assembly stations [3, 8]. On the other hand, errors in kit preparation and the inclusion of defective parts in a kit may affect assembly operations or the efficiency of the kitting process [8]. Moreover, through the kitting, feeding strategy is possible to achieve a stocks reduction at the point of use [8] and a reduction in time wasted in searching for parts [3] and in the distances covered for the assemblers [20].

Several different research areas relate to the optimization of the kitting feeding policy:

- The problem of picking optimization, including the issue of layout optimization (warehouse position and stocking area optimization) and picking management optimization

- The problem of kit optimization, including related ergonomic aspects
- The problem of kitting scheduling optimization

The first point is a very interesting and wide research topic. A good review is that of De Koster et al. [13]. In terms of layout optimization, the aim is generally to minimise total management and logistics costs, taking into consideration the relations and physical flows between the different zones inside facilities, optimising the number of storage blocks, the location of depots, the length and number of aisles and the introduction of cross-aisles.

Picking management optimization typically aims to minimise the total travel distance or the total picking time [6] through:

- The definition of appropriate picking policies, i.e. 'Picker-to-Part' where unit loads are placed so as to be accessible in order to speed up collection activities, versus 'Part-to-Picker' where unit loads are taken towards the operators working on the partial picking
- The appropriate storage assignment, i.e. random storage, fixed location storage and class-based storage
- The picking sequence optimization, i.e. picking by article (batch picking) or picking by order (order picking).

As demonstrated by Hanson and Medbo [19], in terms of kit optimization, the possibility of presenting parts in a logical order with respect to the assembly order can reduce the searching/sorting time. They demonstrated that kitting can bring about an increase in productivity and line availability, compared with the kanban feeding system, in which parts are presented in containers. Less time is spent walking around searching for components, and the length and cost of training assemblers are reduced [11]. On the other hand, ergonomic issues play a great role in determining which parts should be kitted. In the case of large or heavy parts, kitting is almost obligatory in order to reduce space utilisation and ergonomic impact at the assembly station [5].

Finally, the scheduling of kitting preparation influences the sequencing of production at the assembly lines. It is clear that in a mixed-model assembly line production environment, the sequence has considerable impact on instant workload at the assembly station. The issue of kit preparation scheduling can be addressed by optimising the assembly line sequencing in order to reduce the variability of station workloads, with great benefits for assembly line productivity and the reduction in work-in-progress stock levels [1, 2].

2.3 Hybrid kanban-kitting feeding policy

Hybrid kanban-kitting feeding policy, even if sufficiently diffused in industry, has been not deeply studied in literature and just few recent contributes are available. Normally, once the policy selection is made, all components, apart from exceptions, are supplied with the same method. Nevertheless, improved results can be sometimes obtained when the feeding policy is selected at the single component level. This is also confirmed by industrial experience, where it is thought that there is a break-even point at which kitting is most beneficial, and after that point it turns out as a failure [11]. According to Caputo and Pelagagge [8], although several partitioning criteria can be conceived, in most cases a Pareto ABC classification referring to the economic value of components can be appropriate. Defining the economic value of a component as its unit cost times the demand, components can be ordered according to decreasing economic values. In this way, class A components will have a greater relevance and will be responsible for the greatest flows or WIP and holding costs, while class C will be scarcely relevant. In this way, it is possible to define different feeding policy for different components class. For example kit/kanban/kanban, where most relevant codes (A class) are managed by kitting, while the others (classes B and C) using kanban. Limère et al. [24] developed a feeding policy comparison model at the single-component level, where different production variables are taken into account and where the hybrid feeding policy is a possible result. In the case study they presented, they demonstrated how an optimised component feeding policy can sometimes bring to a hybrid feeding policy, where in the optimal case just 42 % of the parts are kitted, while the others are managed using kanban. As highlighted by Caputo and Pelagagge [8] and demonstrated looking at the Limère et al. [24], in parts-feeding optimization model, even if from a theoretical point of view, the optimal solution would be to find the best policy at the single-component level, this gives rise to a large-scale combinatorial optimization problem which often proves hard to solve in practice. Due to its complexity and its large applicability in industry, further research is certainly needed in this important and new research area.

2.4 Kanban continuous supply versus kitting feeding policy

As described in the Section 1, the first difference between these two feeding policies concerns costs. The typical costs related to the feeding activities are handling costs, inventory costs and stock-out costs:

- The expected stock-out costs for kitting should be lower than those for kanban continuous supply [24]
- The expected handling costs in the parts preparation and supply for kanban continuous supply should be lower than those for kitting
- The expected inventory costs at the assembly stations for kitting should be lower than those for kanban continuous

supply [8] as effect of the reduction/elimination of safety stocks. This effect is more relevant in cases where the same part is used in multiple locations [21, 23].

Hua and Johnson [21] delineated a list of qualitative influencing factors that drive the selection of one of the two different feeding policies. These are, expressed in order of their importance as given by the authors:

1. *the impacts of product and component volume, variety, and size*—related to the production volume and mix and the size and dimensions of components
2. *the impact of component storage and material handling*—related to the storage space required, the quantity of components to be stored at the assembly lines (including safety stock), the handling resources needed to perform the adopted feeding policy, and the associated inventory and handling costs.
3. *the impact of production control*—related to inventory management of components, quality control and the availability of parts at the assembly station.
4. *the impact of system choice on operational performance*—related to the total handling time as the sum of the material handling time of the assembler, the material handling time of the picker in the kit preparations and the time for transporting parts from the kit preparation area to the assembly.

As demonstrated by the literature review, the assembly system parts-feeding problem is related to different operational management research areas such as the optimization of the kanban system or the optimization of picking. In consequence, both kanban and kitting present different optimization levels that could be integrated inside a decision-making procedure that goes from deciding on the most appropriate feeding policy to its optimization.

This study, keeping into account also the different influencing variables, focuses mainly on the impact of production mix variations and models varieties on the parts-feeding policy selection with the aim to quantitatively define the break even points of the different feeding strategies according these variables.

3 Problem formulation and feeding policies cost model

The proposed approach aims to find the optimal feeding policy according to a comparison between the cost functions of each feeding policy (kanban, kitting and hybrid). The proposed cost model is a function of different influencing factors quantitatively defined. As a result, the procedure offers a valid quantitative decision-making tool for operations managers in defining the best feeding policy to adopt, considering also a hybrid kanban-kitting policy and its optimization.

3.1 Notation

In order to describe the procedure, the following notations are introduced:

M	set of all products realised in the system, $m=1,\ldots,M$
I	set of parts necessary for the same system; $i=1,\ldots,I$
L	assembly lines of the system, $l=1,\ldots,L$
$\mathrm{BOM}_{i,m}$	bill of materials of part i related to model m (in parts per product)
Xkit_i	binary vector that is equal to 1 if the part i is managed using kit, 0 otherwise
Xkan_i	binary vector that is equal to 1 if the part i is managed using kanban, 0 otherwise. Xkan_i is equal to 1 where Xkit_i is equal to 0 and vice versa.
$d_{m,l}$	daily expected average model demand for model m on line l (in products per day)
c_m	model value (in Euros per product)
p_m	perceptual incidence of raw materials on the product value c_m (in percent)
Q_l	levelled daily throughput for assembly line l, $Q_l=\sum_m d_{m,l}$ (in products per day)
Q	levelled daily throughput for the whole system, $Q=\sum_l Q_l$ (in products per day)
$\sigma m,l$	standard deviation for model m on line l (in products per day)
$\mathrm{CV}_{m,l}$	coefficient of variation of model m on line l, $\mathrm{CV}_{m,l}\%=\sigma_{m,l}/d_{m,l}$ (in percent)
N_{op}	number of handling operators in the system (in operators)
V_{run}	average speed during the route of the handling operator (in meter per minute)
L_{run}	total length of the route in order to refill all assembly stations of the system starting and ending at the supermarket (in meters)
T_{run}	average run time to cover the total length L, $T_{\mathrm{run}}=L_{\mathrm{run}}/V_{\mathrm{run}}$ (minutes)
T_w	daily working time (in minutes per day)
T_{si}	specific SKU_i time for load/unload operations at the supermarket (in minutes per SKU)
T_L/U_i	specific SKU_i time for load/unload operations on the assembly lines (in minutes per SKU)
$\mathrm{LS}_{i,l}$	service level for part i in assembly line l (adimensional)
$k_{i,l}$	security factor for part i in assembly line l; this refers to the service level $\mathrm{LS}_{i,l}$ considering a

normal distribution pattern of consumption (adimensional)

$\text{kanban}_{i,l}$ number of kanban for part i on line l

SKU_i SKU capacity is the size of the container of parts i in case of kanban system (parts per kanban)

$d_{i,l}$ expected daily average demand for part i on line l, $d_{i,l} = \sum_m \left(\text{BOM}_{i,m} \cdot d_{m,l}\right)$ (in parts per day)

d_i expected daily average demand for part i, $d_i = \sum_l d_{i,l}$ (in parts per day)

c_i part value for part i (in Euros per part)

p_m incidence of raw materials on the product value (in percent)

h_i inventory holding cost index for part i (in percent)

rows/h number of expected hourly rows that one handling operator can dispatch in the picking list (missions per hour)

$C_{1\text{op}}$ cost for one handling operator in the considered period (in Euros per period)

3.2 Parts-feeding policy cost model

Hua and Johnson [21] affirm that products volume and variety play a large role in determining whether a kitting or kanban continuous feeding system is applicable. The proposed analysis, keeping account of other different influential variables, focuses mainly on the impact of the production mix variability and of the assembled product diversity on the correct feeding policy definition. This assembled product diversity is quantitatively taken into account through consideration of the impact of the degree of commonality in the different bills of materials of the models assembled in the system. This element in a JIT-level production environment, as demonstrated in the following sections, plays a very important role. This kind of analysis has never been performed before and is a novelty of the present paper. On the other hand, different levels of production mix variation are considered.

In order to formulate the problem, the following assumptions were made:

- The considered system is composed of a supermarket feeding the assembly stations of a certain number of assembly lines. Each assembly line l is a mixed-model assembly line that is capable of producing a great number of variants of a common base product, while the base product is different from one assembly line to another. For this reason, a certain model m is produced on just one assembly line l. Therefore, there is a univocal correspondence between model m and assembly line l. Set-up times are negligible because of the commonality of assembled models together with the flexibility of manual operators.
- The JIT environment imposes a levelled production. For this reason, in the total daily throughput of each line l, Q_l is considered constant, while the production mix can be variable within a certain range. The average takt time of the assembly line l is considered constant and equal to $1/Q_l$. The mix variation of a certain assembly line is considered to have a normal distribution, i.e. the daily historical demand for model m on line l has a normal distribution. As a result, the pattern of the consumption of the parts for each assembly station is assumed to have a normal distribution and be a function of the bill of materials for each model and model demand.
- The stock-keeping unit (SKU) of part i is the same in every part of the system. Therefore, SKU capacity is a function only of the part. A kanban card is associated with every SKU.
- The workload for handling operators is considered to be equally distributed between them. For this reason, once the number of handling operators has been defined, the parts consumption rate, SKU capacity and average expected supply lead time for each part i is considered to be the same.
- The picking system for the kitting policy is made manually by the handling operators at a certain performance level. It is defined by the rows/h parameter that defines the number of rows in the picking list (i.e. the number of missions) that a handling operator can dispatch in the considered scenario.
- In the hybrid feeding policy, a part can be managed in only one way (kanban or kit) within the whole production system. On the other hand, the handling operators can perform both kitting and kanban feeding.
- It is considered that because of the handling operators' experience or the help/control process in kit preparation (i.e. pick to light system) the errors in kit preparation can be assumed to be equal to zero. On the other hand, to combat the inclusion of defective parts in kits, a common approach in practice, especially in the case of low-size/value parts, is to add redundant parts to the kit containers, without losing the applicability of the proposed approach.
- The container capacity of parts i in the case of the kanban system, SKU_i, takes into account the part size.

The proposed model is based on a comparison between the cost functions of the analysed feeding policy (kanban, kitting and hybrid). Three main cost typologies are considered: inventory costs, handling costs and stock-out costs.

- Inventory costs: Emde and Boysen [15] affirm that in assembly system production environments, it is possible to consider high inventory costs at the assembly stations because enlarged stock levels near the line impede the assembly process because of the scarcity of space at stations. As consequence, the operational stocks at the assembly stations, that change as function of the feeding policy used, are considered in the proposed model with an high inventory holding cost index h_i.

- Stock-out costs: as reported by Limère et al. [24], since kits are consumed in synch with the takt time, it is easier to schedule kit replenishments than to schedule bulk replenishments. In the case of kitting, production mix changes do not create stock-out risk for the kitting feeding policy. On the other hand, considering the kanban continuous feeding policy the stock-out risk increases when the production mix increases.
- Handling costs: the handling cost considered are functions of the necessary handling operators to perform the feeding process. The number of handling operators depends on the adopted feeding policy.

3.3 Kanban continuous feeding cost function

The kanban continuous feeding cost function is derived from Faccio et al. [17].

It is obtained by the minimization of the total kanban cost function (1) for a defined period (i.e. year) composed of inventory costs, handling costs and stock-out costs related to the stock-out risk:

$$C_{\text{tot}}\text{kan} = C_{\text{in}} + C_h + C_{\text{so}} \quad \text{(Euros per period)} \tag{1}$$

where:

$$C_h = N_{\text{op,kan}} \cdot C_{1\text{op}} \quad \text{(Euros per period)} \tag{2}$$

$$C_{\text{in}} = \sum_l \sum_i \text{Xkan}_i \cdot \left[\text{kanban}_{i,l} \times c_i \times h_i\right] \quad \text{(Euros per period)} \tag{3}$$

$$C_{\text{so}} = \sum_l \sum_m \left[d_{m,l} \cdot C_m \cdot (1-p_m) \cdot \text{LT}/2\right] \cdot \text{Xkan}_i \cdot \left[\left(1-\prod_{i \in m} \text{LS}_{i,l}\right) \cdot d_{m,l} \cdot D\right] \text{(Euros per period)} \tag{4}$$

As reported in Faccio et al. [17], the independent variables to be minimised (1) are only:

N_{op},kan number of handling operators in the system that perform the kanban feeding (operators)

$\text{LS}_{i,l}$ service level for part i on the assembly line l (in percent).

The proposed feeding selection procedure considers, for a given scenario, the optimal values of these two variables and consequently the minimum possible cost of the kanban continuous feeding policy for that scenario.

As reported in Faccio et al. [17], the other parameters can be defined as follows:

the expected daily average kanban demand for part i on line l:

$$\text{dK}_{i,l} = \text{Xkan}_i \cdot \left(d_{i,l}/\text{SKU}_\text{i}\right) \text{(kanban)} \tag{5}$$

the average estimated time spent on the loading/unloading operation on the assembly lines:

$$T_{L/U} = \sum_l \sum_i \left(\text{dK}_{i,l} \times T_{L/U_i}\right) \quad \text{(in minutes per day)} \tag{6}$$

the average estimated time spent on the loading/unloading operation at the supermarket:

$$T_S = \sum_l \sum_i \left(\text{dK}_{i,l} \cdot Ts_i\right) \quad \text{(in minutes per day)} \tag{7}$$

estimated turns/day (and as a consequence the average parts supply lead time):

$$\text{round/day}\left(N_{\text{op}}\right) = \frac{T_w \cdot \eta \cdot N_{\text{op,kan}} - \left(T_{L/U} + T_s\right)}{T_{\text{run}} \cdot \lambda} \left(\text{rounds/day}\right) \tag{8}$$

Where λ, as reported in Faccio et al. [17] is the capacity factor ($1 \leq \lambda \leq \infty$), where λ is equal to the number of trips that are averagely necessary for a tow train to complete one kanban delivery mission (λ is equal to 1 if the tow train has a capacity greater than that necessary and equal to 2 if there are averagely necessary two trips, etc.). η is the operator's efficiency ($0 < \eta \leq 1$)

average parts supply lead time:

$$\text{LT} = \frac{T_w}{\text{round/day}} \quad \text{(in minutes)} \tag{9}$$

kanban number, calculated using Toyota's formulation:

$$\text{kanban}_{i,l} = \frac{d_{i,l} \cdot \text{LT} + \text{SS}_{i,l}}{\text{SKU}_\text{i}} \tag{9}$$

where $SS_{i,l}$ is the safety stock on line l for part i, calculated using the formulation by Persona et al. [26]:

$$SS_{i,l} = k_{i,l} \cdot \sqrt{LT} \cdot \sigma_{i,l} \quad \text{(in parts)} \tag{11}$$

so that:

– $k_{i,l}$ is the security factor for part i on line l related to the service level $LS_{i,l}$ according to the normal distribution assumption relating to the part demand;
– LT is the supply lead time calculated as in (15), expressed in days according to the daily working time T_w;
– $\sigma_{i,l}$ is the parts standard deviation, with considers the correlated demand between the model in the case of levelled production (Q_l is considered to be constant) calculated according to Das and Tyagi [12] as:

$$\sigma_{i,l} = \sqrt{\left(\text{Xkan}_i \left(\sum_m \left(\text{BOM}_{i,m} \cdot \sigma_{m,l} \right)^2 + \text{Xkan}_i \left(\sum_m \sum_{z>m} 2\rho \cdot \text{BOM}_{i,m} \sigma_{m,l} \cdot \text{BOM}_{i,m} \sigma_{m,z} \right) \right) \right)} \quad \text{(in parts per day)} \tag{12}$$

Since, in a levelled production JIT environment, the variation in model production quantity influences the production quantity of other models with a negative correlation, we assume that for a given number *Ml* of models assembled in a certain assembly line l, the coefficient of correlation ρ is negative and equal to $\rho = -1/(M_l - 1)$ equal for all models.

In the case of the complete adoption of a kanban feeding policy, $\text{Xkan}_i = 1\ \forall\ i$ *and* $\text{Xkit}_i = 0\ \forall\ i$.

3.4 Kitting cost function

As in the kanban continuous feeding cost function, the kitting cost function (13) is related to a defined period (i.e. year) and composed of inventory costs and handling costs (related to the number of operators employed in the feeding process, , kitting preparation, etc.)

$$C_{tot}\text{kit} = C_{in} + C_h \quad \text{(in Euros per meter)} \tag{13}$$

The cost function for the kitting system does not consider the stock-out cost as an effect of the assumption that the stock-out risk in the case of kitting is considered equal to 0. This assumption is almost real in the case of very rare negative events such as defective parts being included in a kit, errors in kit preparation or a shortage of parts during kit preparation. These events are typically very rare in companies such as those in which lean manufacturing concepts are strongly introduced. As outlined in Section 1, modern lean production principles have resulted in the feeding of components moving far from line-stocking systems to the other two ‘leaner’ feeding policies, kanban and kitting, where the inventory along the assembly lines is greatly reduced. For this reason, these kinds of companies are potentially good candidates for applying the proposed procedure and thus the assumption is not a limitation in the proposed model. In the opposite case, especially when frequent errors in kit preparations occur, an additional stock-out cost should be considered, even in the kitting policy.

3.4.1 Kitting handling costs

$$C_h = N_{\text{op,kit}} \cdot C_{1\text{op}} \quad \text{(in Euros per period)} \tag{14}$$

where $N_{\text{op,kit}}$ is the expected number of handling operators that perform the kitting. This can be derived in a considered period as the ratio between the expected picking missions to dispatch and the number of missions that one handling operator can dispatch. The number of hourly missions that a handling operator can dispatch is rows/h. As highlighted in the literature review, it is clear that the parameter rows/h depends on the level of optimization of the manual picking system considered.

In this paper, the optimization of the picking activity is not considered as part of the proposed procedure. For this reason, rows/h is managed as a variable, where, once the considered case company picking performance is determined, it is possible to derive the relative kitting handling costs.

The number of expected daily picking missions to dispatch (equal to the sum of the picking rows in the picking lists) in the supermarket assembly line system considered is given by the product of the number of parts for each model managed with a kitting policy for the number of models produced daily.

Considering T_w, the daily working time (in minutes per day) and η the human operator’s daily efficiency, the expected number of handling operators needed to perform kitting can be calculated as:

$$N_{\text{op,kit}} = \frac{\sum_i \text{Xkit}_i \cdot Q}{\text{rows}/h \cdot T_w \cdot \eta / 60} \tag{15}$$

3.4.2 Kitting inventory cost

$$C_{\text{in}} = N_{\text{st}}(1+\alpha)\cdot C_{1\text{kit}} \quad (\text{in Euros per period}) \tag{16}$$

where:

- N_{st} is equal to the number of the assembly stations in the system in which is assumed that there is one kit for each
- α is a positive factor that depends on the average queue of completed/work-in-progress kits waiting to be transported at the assembly line. In the case of JIT kit preparation, α can be fixed equal to 0
- $C_{1\text{kit}}$ is the average inventory cost of 1 kit in the assembly system.

Each kit could have a different cost depending of the bill of materials $\text{BOM}_{i,m}$ and of the cost of each part c_i.

The average kit costs also depend on the production mix inside the assembly system. As a result, $C_{1\text{kit}}$ can be derived as:

$$C_{1\text{kit}} = \left(\sum_l \sum_i \left(\text{Xkit}_i \cdot d_{i,l} \cdot c_i \cdot h_i\right)\right)/Q \quad (\text{in Euros per kit}) \tag{17}$$

In the case of complete adoption of a kitting policy, $\text{Xkan}_i = 0\ \forall\ i$ *and* $\text{Xkit}_i = 1\ \forall\ i$.

3.5 Hybrid kanban-kitting cost function

The following feeding policy is composed by merging the continuous kanban feeding system and the kitting system. In the companies that perform the hybrid feeding policy, a part can be managed in only one way (kanban or kitting) within the whole production system. On the other hand, the handling operators can perform both kitting and kanban feeding. This condition is assumed in the paper, with the consequence that:

$$C_{\text{tot}}\text{hybrid} = C_{\text{tot}}\text{kan} + C_{\text{tot}}\text{kit} \quad (\text{in Euros per period}) \tag{18}$$

where parts i that adopt a kanban feeding policy have $\text{Xkan}_i = 1$ and $\text{Xkit}_i = 0$, while parts i that adopt a kitting policy have $\text{Xkan}_i = 0$ and $\text{Xkit}_i = 1$. The two opposite notations are maintained in order to improve the reading comprehension.

For the given whole set of parts to be managed, the problem of finding the optimal sub-set of parts to manage using kanban and the optimal sub-set of parts to manage using kitting is an non-linear optimization problem that can be formalised as follows:

$$\begin{aligned} &\text{Minimize} \quad C_{\text{tot}}\text{hybrid}\left(\text{Xkan}_i, \text{Xkit}_i\right) \\ &\text{Xkan}_i = \{0,1\}, \quad \forall\ i \\ &\text{Xkit}_i = \{0,1\}, \quad \forall\ i \\ &\text{Xkan}_i \neq \text{Xkit}_i \\ &Xkan_i + Xkit_i = 1, \quad \forall\ i \end{aligned} \tag{19}$$

4 Case study: feeding policies comparison

This section of the paper compares the kanban, kitting and hybrid feeding policies starting from the case company shown in Faccio et al. [17].

The case is a worldwide motorcycle manufacturer company that produces a wide variety of products in an Assembly to Order environment. Its 12 models of motorcycles are produced on four assembly lines fed by a unique supermarket. The daily working time is $T_w = 8$h (480 min) and the considered period for the total cost calculation is 1 year with a working time $D = 200$ days. Figure 2 shows the case company's supermarket/multiple mixed-model assembly line system.

Table 1 reports the daily production data $d_{m,l}$ on each model for each assembly line and each model value c_m. The takt time of each line can be derived as takt time=$1/Q_l$ where $Q = 75$ models/day and the average system takt time is one model every 6.4 min. The daily throughput Q_l is considered to be fixed (levelled production). The historical data show that the coefficient of variation for all models is almost the same, and thus $\text{CV}_{m,l}$ is considered the same for all models, namely equal to CV=30 %.

The bill of materials of each model is reported in Table 2, while the parts attributes such as SKU capacity SKU_i and part value *Ci* are reported in Table 3.

Handling operator efficiency from the historical data is η= 75 %. The total length of the route L_{run} is 1,000 m and the average speed V_{run}, considering queues, curves, etc., is 0.5 m/s. The load/unload time on the assembly line T_L/U_i and at the supermarket TS_i are considered to be equal for all parts, namely 1 min/SKU. The average raw materials incidence is p_m=40 % for all models. In order to simplify the problem the service level $\text{LS}_{i,l}$ was chosen to be equal to LS for all parts and assembly lines. The cost for each handling operator is $C_{1\text{op}}$=26,000€/year. The inventory holding cost h_i was chosen to be equal to 65 % in accordance with Emde and Boysen [15]. It is considered a just in time kit preparation, so α can be fixed equal to 0.

The comparison between the three feeding policy cost functions (kanban, kitting and hybrid) according to (1), (13) and (18) is reported in Fig. 3. It reports the total annual cost of the three feeding policies in the function of the rows/h parameter, and for different hybrid solutions, i.e. for different values of Xkan_i and Xkit_i (green lines). The kitting curve is reported in red, hybrid curves in green and the kanban curve in blue.

Looking at Fig. 3, it is clear that the total cost for the kanban feeding policy does not depend on the rows/h parameter because there is no picking activity inside the supermarket for handling operators.

On the other hand, clearly the total costs decrease for both the kitting policy and for the hybrid policy (for the parts managed through kitting) when the rows/h parameter

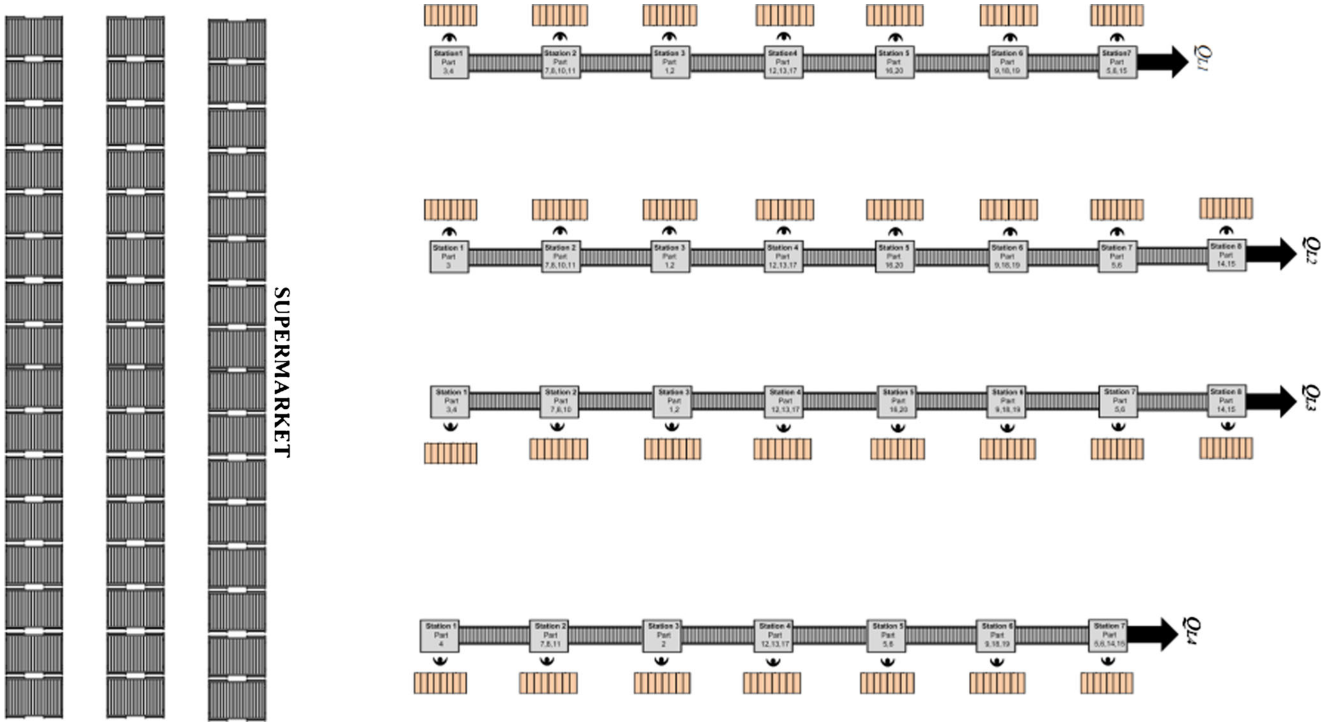

Fig. 2 Supermarket/multiple mixed-model assembly line system comparison environment

increases, because the number of handling operators required decreases. It is important to highlight how, in the case of the hybrid feeding policy, the total annual cost is strongly influenced by the values of $Xkan_i$,$Xkit_i$ (green lines). As a result, in the case of the hybrid feeding policy solution, a very important problem to solve is the optimization of (19).

It is interesting to note that, in this case study, kanban performs better versus kitting in term of total costs until rows/*h* is approximately equal to 43 rows/*h* for each handling operator. The hybrid feeding policy is usually less convenient compared with the other two, but a possible combination of $Xkan_i$,$Xkit_i$ exists that performs better than the other two feeding policies in a narrow range of rows/*h* parameter (approximately 37–45).

The results of the case company are interesting because:

- they demonstrate that it is possible, through the proposed total cost model comparison, to define quantitatively the decoupling points that make one of the different feeding policies preferable as a function of the picking performance in the kit preparation (rows/*h*)
- they demonstrate that the hybrid feeding policy could, in some cases and if optimised, perform better than either the kanban or kitting policies.

5 Influence of assembled production mix variation and models variety on the optimal setting of feeding policies

In a levelled production typical of the JIT environment (Q_l constant), the diversity of the bill of materials between the models assembled in the same assembly line and the production mix variation for a given assembly line are the main drivers of the variation in parts consumption [17].

Table 1 Daily production and model value

Line	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11	m12	Q_l`
L1	4	10	6	0	0	0	0	0	0	0	0	0	20
L2	0	0	0	6	4	5	0	0	0	0	0	0	15
L3	0	0	0	0	0	0	9	3	4	0	0	0	16
L4	0	0	0	0	0	0	0	0	0	6	10	8	24
c_m	6,500	7,500	6,000	6,200	7,000	7,600	8,000	8,200	7,200	7,000	9,000	8,200	75

Table 2 Bill of materials

Parts	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11	m12
1	1	1	1	1	1	0	1	0	0	0	0	0
2	0	0	0	0	0	1	0	1	1	1	1	1
3	1	0	1	1	1	1	0	0	0	0	0	0
4	0	1	0	0	0	0	1	1	1	1	1	1
5	2	0	2	2	2	0	2	2	2	2	0	2
6	0	2	2	0	0	2	2	0	0	0	2	2
7	1	2	0	1	2	0	1	2	0	1	2	0
8	1	0	2	1	0	2	1	0	2	1	0	2
9	6	6	4	0	2	4	4	6	6	0	4	2
10	1	1	0	1	0	1	1	1	1	0	0	0
11	0	0	1	0	1	0	0	0	0	1	1	1
12	1	2	0	1	2	0	1	2	0	1	2	0
13	1	0	2	1	0	2	1	0	2	1	0	2
14	0	0	0	1	0	2	1	1	0	0	2	2
15	2	2	2	0	1	0	0	0	1	2	0	0
16	6	8	4	8	12	10	4	6	6	8	10	6
17	4	4	4	4	4	4	4	4	4	4	4	4
18	4	6	8	4	4	8	4	6	6	4	8	8
19	35	25	20	30	35	45	32	44	28	36	42	54
20	50	30	40	60	65	80	35	45	40	40	55	75

Moreover, product volume and variety are likely to play a large role in whether a kitting or line-stocking system is applicable [21].

Table 3 Parts attributes

Parts	SKU_i	Description	C_i
1	1	Engine A	750
2	1	Engine B	850
3	2	Frame A	780
4	2	Frame B	670
5	5	Carening A	60
6	5	Carening B	80
7	2	Wheels A	150
8	2	Wheels B	130
9	6	Lights	40
10	6	Suspensions A	95
11	6	Suspensions B	75
12	4	Brakes A	150
13	4	Brakes B	120
14	4	Silencer A	90
15	4	Silencer B	70
16	10	Electric Wires	20
17	12	Levers	15
18	20	Buttons	3
19	30	Fasteners	1
20	50	Screw bolts	0.2

The following section, considering the JIT-levelled production environment, aims to extend the results derived from the case company in order to understand the convenience of adopting a certain feeding policy as a quantitative function of the variation in parts consumption which, according to Hua and Johnson's [21] list, is the first element driving the definition of the most appropriate feeding policy.

Secondly, it aims to investigate in what cases the hybrid feeding policy could be preferable. Moreover, because the optimization problem presented in (19) is not simple to solve, the study aims to investigate the correlation between the optimal values assumed by $Xkan_i$,$Xkit_i$ in terms of convenience in applying the hybrid feeding policy and the attributes of the parts involved. In this way, it could be possible to determine some general rules related to the attributes of parts, easily and quickly applicable by operations managers, in order to define the two sub-sets of parts to be managed through kanban and kitting in the case of hybrid policy application.

5.1 Quantitative calculation of variation in parts consumption

As reported in Faccio et al. [17], in the case of levelled production, it is possible to quantify the two elements that mostly influence the variation in parts consumption.

The product mix variation can be summarised using the coefficient of variation index derived as follows:

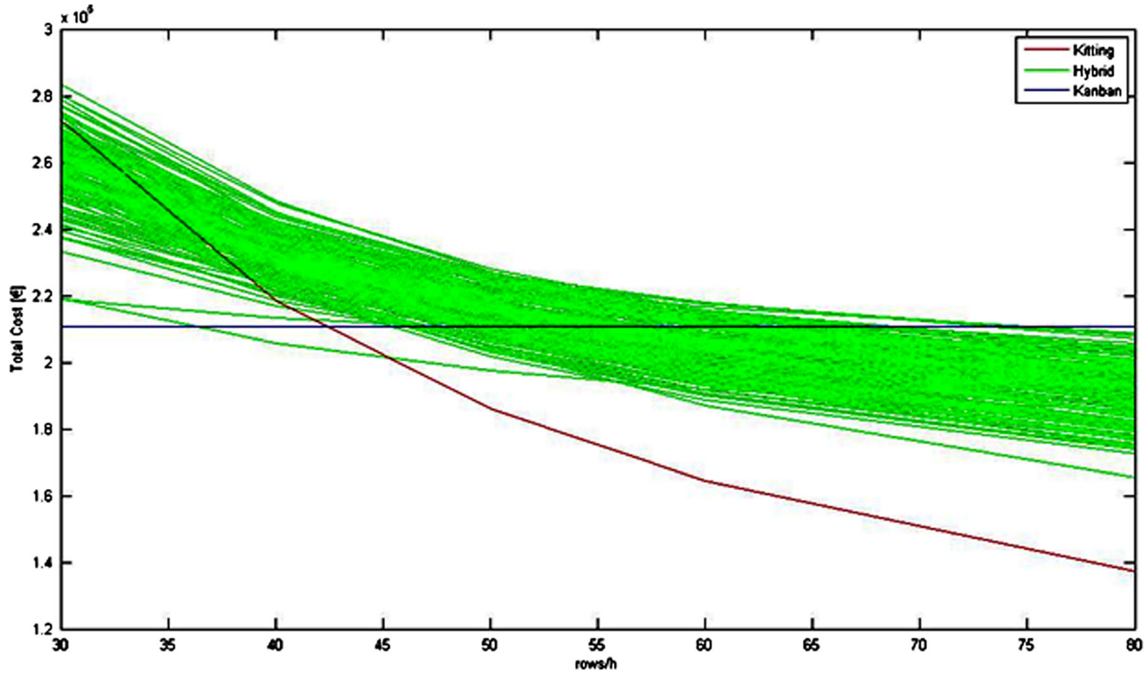

Fig. 3 Total annual cost function in the case of kitting (*red*), kanban (*blue*) and hybrid (*green*) feeding policies as a function of the rows/*h* parameter (performed by one operator) and as function of $Xkan_i$,$Xkit_i$ for the hybrid policy

$$\mathrm{CV} = \frac{\sum_{m,l} \sigma_{\mathrm{m,l}}}{Q} \tag{20}$$

The models variety can be analysed as models diversity (or the commonality) of the different values of $\mathrm{BOM}_{i,m}$. It can be summarised using the model diversity index (div). This is a positive number that increases when diversity between the models increases, and it is defined as:

$$\mathrm{div}_l = \sum_i \frac{\sigma_{i,l}}{\overline{\mathrm{BOM}}_{i,l}} \cdot \frac{1}{I_l} \quad \text{(in percent)} \tag{21}$$

where:

M_l is the number of models assembled on the assembly line l (in our case, M_l=3 $\forall l$)

I_l is the number of parts managed on the assembly line l (in our case, I_l=20 $\forall l$)

$$\overline{\mathrm{BOM}}_{i,l} = \sum_m \frac{\mathrm{BOM}_{i,m}}{M_l} \quad \text{is the average utilization coefficient of part } i \text{ on line } l \tag{22}$$

$$\sigma_{i,l} = \sqrt{\left(\sum_m \frac{\left(\mathrm{BOM}_{i,m} - \overline{\mathrm{BOM}}_{i,l}\right)^2}{M_l}\right)} \quad \text{is the standard deviation of the utilization coefficient of part } i \text{ on line } l \tag{23}$$

It is also possible to define a unique value for the model diversity index for the entire supermarket/multiple mixed-model assembly line system as:

$$\mathrm{div} = \sum_l \frac{\mathrm{div}_l \cdot Q_l}{Q} \quad \text{(in percent)} \tag{24}$$

It is clear that the highest values of the *div* index are given when a certain part *i* is used only in one kind of model *m*. In this case, a low variation in the production mix results in varied parts consumption. By contrast (in the case of levelled production where Q_l=constant), when the utilisation of a certain part *i* is the same for all models

($BOM_{i,m}$ is the same for all models m), div=0 for the considered part i, even with a high variation in the production mix.

As an example, the case company described in the previous section presents the following parameters of variation in parts consumption: CV=30 %, div=52 %.

5.2 Simulation and comparison environment

The diversity of the bill of materials of the assembled models and the production mix variation are the main drivers of the variation in parts consumption in the case of levelled production typical of the JIT environment [17]. Starting from the case company, 1,000 different supermarket/mixed-model assembly line system scenarios were generated, changing only the following input data:

- the bill of materials of the models produced
- the production mix (considering a levelled production equal to Q_l of the case company for each assembly line).

Moreover, for each one of these 1,000 scenarios, as in the case company analysis, different values for the rows/h parameter were considered. In case of the hybrid policy, in addition to different values for the rows/h parameter for each scenario 15,000 possible combinations of $Xkan_i$,$Xkit_i$, were considered and between them the best combination in terms of minimising the total annual costs according to (19) was identified. Each possible combination of $Xkan_i$,$Xkit_i$ was randomly generated.

The simulation study was developed using Matlab software over a period of more than 20 days 24/24 on a Core i3 computer. As result of what reported in Fig. 3 for the hybrid feeding policy, it has been used the Matlab Newton–Raphson optimization tool to find the minimum of (19).

In order to compare the different scenarios, the bill of materials was generated according these constraints:

- for each part i and model m, the difference between the generated $BOM_{i,m}$ and the $BOM_{i,m}$ of the case company was not excessively high (less than 30 %).
- For the given $BOM_{i,m}$ of the considered scenarios, c_i was generated to keep the raw material incidence the same as that for the case company (p_m= 40 %) in order not to change the influence of the value of the raw materials on stock-out costs.

The $BOM_{i,m}$ values were generated in order to obtain div values in the range of 0–80 %. The production mix variations were generated in order to obtain CV values in the range of 0–80 %.

5.3 Simulation results

The simulation study aimed to define the values of the investigated parameters according to which a certain feeding policy should be preferred. The investigated parameters were:

- rows/h, number of expected hourly rows that one handling operator can dispatch in the picking list (in missions per hour)
- div, the model diversity index (16) (in percent)
- CV, production mix coefficient of variation (20) (in percent). For CV, the results were then categorised into three classes: A (0–20 %), B (20–40 %) and C (40–80 %).

The results are a series of ‘convenience areas’ as a function of these parameters that represent a rapid and easy tool for practitioners in order to evaluate which feeding policy should be adopted, just through calculating and measuring these three parameters. It is clear that these convenience areas present different limitations. For example, they take into account just these three parameters and not others. They have been derived starting from the case study in which some data could be relevant in the cost functions (i.e. p_m=40 % perceptual incidence of raw materials on the product value c_m (in percent) that appears in the stock-out costs). On the other hand, they represent a first quantitative decision-making tool able to give practitioners a rapid general indication which, if necessary, should be analysed more closely through the formal application of the proposed cost function comparison model.

The lines presented in Figs. 4, 5, 6 and 7 are derived as trend lines from the entire dataset drawing on the 1,000 analysed scenarios. These lines interpolate the decoupling points, obtained where the cost functions (1) for kanban (1), for kitting (13) and for the hybrid feeding policy (18) assume the same value. The decoupling points are derived by comparing the three feeding policies two by two. Figure 4 shows only the comparison between the kanban feeding policy versus the kitting policy.

The lines represent the decoupling points between kitting (in the upper position) and kanban (in the lower position). The comparison is made as a function of the rows/h (y-axis) parameter and as a function of the variation in parts consumption (div on x-axis and CV, with different lines according to the three classes A, B and C).

The results quantitatively demonstrate that, once the other two parameters are fixed, the kitting area increases when div, CV and rows/h increase.

Even if this result could be predicted, there are different aspects to highlight. Firstly, the results quantitatively demonstrate how, in the case of JIT-levelled production, the commonality of bills of materials of the assembled models strongly influences the definition of the most appropriate feeding

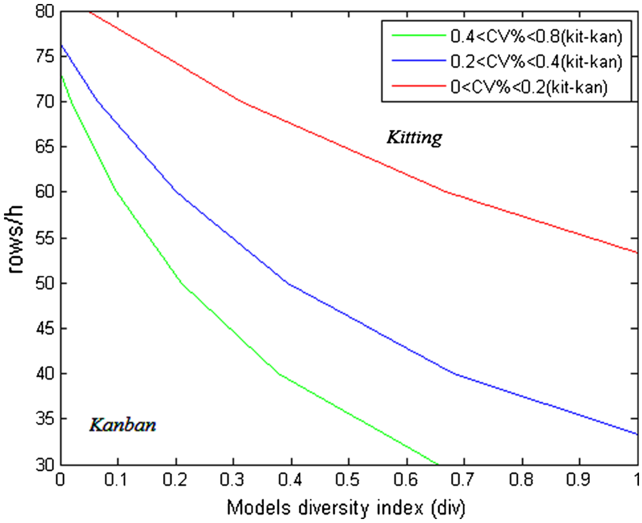

Fig. 4 Kanban convenience area (*lower left*) versus kitting convenience area (*higher up*) divided for different CV values (different lines as reported in the legend) as a function of rows/*h* (*y*-axis) and of div (*x*-axis)

policy and these elements are not evident in many different contributions. Secondly, looking at the curves, it is clear how, in the case of very low variation in the production mix (CV< 20 %), the kanban system is the better solution for the greatest possible combination of row/*h*–div. On the other hand, when the variation of production mix is high (i.e. CV>40 %), the kanban area is largely reduced. Kitting would then be preferred in most cases even if, in the case of a low model diversity index, kanban could perform better even for low row/*h* values.

In Figs. 5, 6 and 7, the comparison also takes into account the hybrid feeding policy. The hybrid feeding policy considered for each one of the 1,000 analysed scenarios is the best hybrid solution that minimises (19) choosing between the 15,000 possible combinations tested in the simulation.

Figure 5 shows the results in the case that 0<CV<20 %, Fig. 6 shows the results in the case that 20<CV<40 %, and Fig. 7 shows the results in that case that 40<CV<80 %.

The hybrid convenience area is represented by the area included in the kitting-hybrid comparison curve and the kanban-hybrid comparison curve.

As highlighted by Figs. 5, 6 and 7, the hybrid feeding policy, when compared with the kanban and kitting policies, presents a convenience area that is not negligible. Comparing Figs. 5, 6 and 7, it is evident that the hybrid convenience area increases when the coefficient of variation CV of the production mix increases. On the other hand, when CV increases, the hybrid convenience area moves from high rows/*h* values (i.e. high handling operator picking performance) to low rows/*h* values. From a div point of view, it seems that for very similar assembled models (i.e. div< 10 %), or very different (i.e. div> 70 %), the hybrid feeding policy is never convenient.

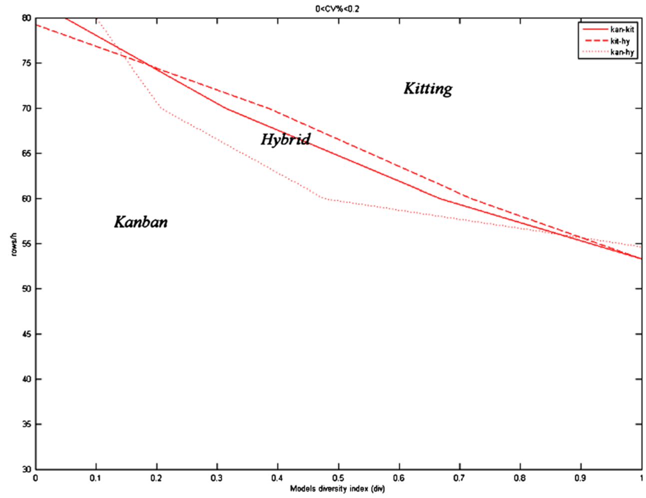

Fig. 5 Kanban, kitting and hybrid convenience areas as a function of rows/*h* (*y*-axis) and as a function of div (*x*-axis) for 0<CV<20 %

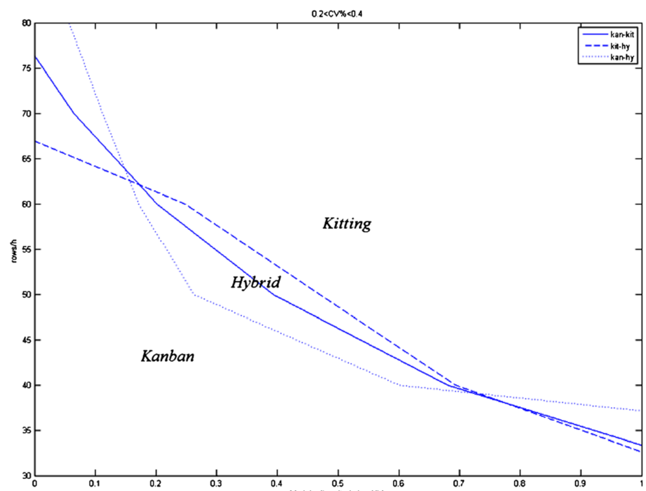

Fig. 6 Kanban, kitting and hybrid convenience areas as a function of rows/*h* (*y*-axis) and as a function of div (*x*-axis) for 20 %<CV<40 %

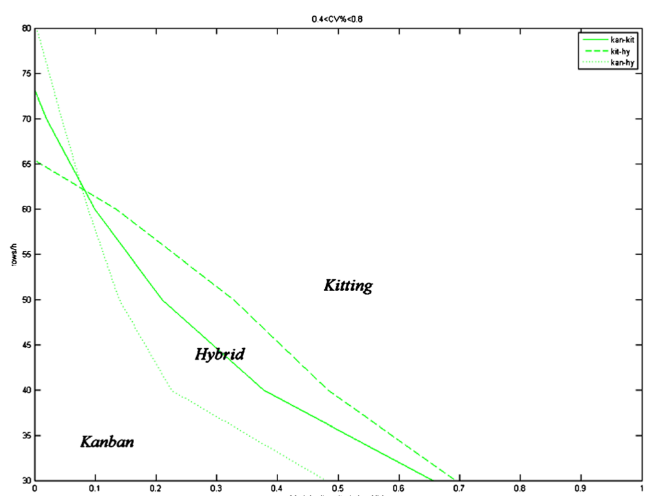

Fig. 7 Kanban, kitting, and hybrid convenience areas as a function of rows/*h* (*y*-axis) and as a function of div (*x*-axis) for 40 %<CV<80 %

Is important to highlight that these results were obtained by considering for each of the 1,000 analysed scenarios just 15,000 possible combinations of Xkan_i,Xkit_i, and choosing from them the best solution according to (19). It is reasonable to assume that the hybrid convenience area should be greater. On the other hand, from the results obtained, testing a single scenario with a larger number of Xkan_i,Xkit_i combinations would not significantly change the minimum hybrid cost function values from those obtained with 15,000 combinations.

Figures 5, 6 and 7 represent a rough but simple decision-making tool in order to evaluate the best feeding policy to adopt between the choice of kanban, kitting and hybrid systems as a function of the three parameters CV, div and row/*h*, with a reasonable certainty margin.

Even if these convenience areas suffer from the limitations described above, is reasonable to think that a practitioner who analyses a certain situation and finds that it lies sufficiently far from the decoupled curves, can assume the result to be the best feeding policy to adopt. On the other hand, it is preferable to apply the proposed cost model using the correct input data as shown in Section 4.

5.4 Hybrid feeding policy optimization: correlation analysis

This part of the research aims to investigate the correlation between the optimal values assumed by Xkan_i,Xkit_i in the case of hybrid feeding policy convenience and the attributes of the parts involved. In this way, it could be possible to derive some general rules related to the attributes of parts in order to define easily and quickly the two sub-sets of parts to be managed through kanban and kitting in the case of hybrid policy application. In fact, as shown in Section 3, the problem of finding the optimal sub-set of parts to manage using kanban and the optimal sub-set of parts to manage using kitting (19) is a non-linear optimization problem, which cannot be solved rapidly.

Once derived the best solution for each of the 1,000 production scenarios in which a hybrid feeding policy would be convenient, the correlation between the optimal Xkit_i vectors (and the related Xkan_i), derived from the 15,000 vectors tested for each scenario, versus the parts attributes (with the *i* index), and some different combinations, was analysed. The results show that the most significant are the following:

- Av_i
- $\mathrm{Av}_i \cdot \mathrm{div}_i \cdot c_i$

where:

- c_i is the part value for part *i* (in Euros per part)
- Av_i represents the average parts utilisation in the bill of materials of the part *i*, calculated as $\mathrm{Av}_i = \sum_m \frac{\mathrm{BOM}_{i,m}}{M}$ (25)
- div_i is the diversity index of the part *i*, calculated as

$$\mathrm{div}_i = \sum_l \frac{i,l}{\mathrm{BOM}_{i,l}\,\_} \times \frac{1}{L} \qquad (26)$$

In our case, M=12 and L=4. The values of these parameters were later normalised with respect to their maximum values in order to compare them in a class analysis. In this way, their values go from 0 to 100 %, and they were collated under an ABC classification so that:

A 0–20 %
B 20–40 %
C 40–100 %.

The final results are reported in Fig. 8, in which the ABC cross-matrix is shown. Each part of the scenarios considered where the hybrid feeding policy would be convenient was placed in one of the nine zones according to the values of Av_i and $\mathrm{Av}_i \cdot \mathrm{div}_i \cdot c_i$, and whether it might be managed through kanban or kitting in the relative optimal Xkit_i vectors (and the related Xkan_i) was traced. All the nine zones contain some parts, with a major concentration in the A class (low values) of $\mathrm{Av}_i \cdot \mathrm{div}_i \cdot c_i$ and in the C class (high values) of Av_i. Figure 8 reports for each one of the nine zones the percentage of parts managed through kanban or kitting in respect of the total parts presented in that zone.

As highlighted by Fig. 8, the parts managed using kitting are concentrated in the CB-CC zone in which more than 85 % of the total parts in the whole matrix are managed through kitting.

As a result, as a general rule and one very quick to apply, it is possible to affirm that, for a given part, once the two parameters defined in Fig. 8 are calculated and normalised (according their maximum):

- if the values lie in a class different than the CB and CC zones, it should be managed using the kanban feeding policy
- if the values lie in the CC zone, it should be managed using kitting

			$\mathrm{Av}_i \cdot \mathrm{div}_i \cdot c_i$		
			0-20%	20%-40%	40%-100%
			A	B	C
Av_i	0-20%	A	AA Xkit<5% Xkan>95%	AB Xkit<5% Xkan>95%	AC Xkit<5% Xkan>95%
	20%-40%	B	BA Xkit<5% Xkan>95%	BB Xkit<5% Xkan>95%	BC Xkit<5% Xkan>95%
	40%-100%	C	CA Xkit<10% Xkan>90%	CB Xkit≈50% Xkan≈50%	CC Xkit>85% Xkan<15%

Fig. 8 Kanban versus kitting ABC cross-matrix in the case of hybrid feeding policy

- if the values lie in the CB zone, it is not possible using this analysis to approximate.

In the proposed cross-matrix analysis 30 % of the parts managed lie in the CB zone. In other words, this approach could solve 70 % of the problem. On the other hand, as a general rule, it can be affirmed that for the CB zone, in which there is no predominance of parts managed by either kanban or kitting, other aspects related to the feeding policies should be analysed, following for example, Hua and Johnson's [21] list.

6 Conclusions and further research

The present paper considers a JIT assembly system fed by a supermarket warehouse. It aims to propose a decision-making procedure based on a cost functions comparison model, considering the cost functions of each feeding policy (kanban, kitting and hybrid). The study, keeping into account other different influencing variables, focuses mainly on the impact of production mix variations and models varieties on the parts-feeding policy definition. The aim is to quantitatively define the break even points of the different feeding strategies according these variables.

An illustrative case of a motorcycle manufacturer was used as a case study. Due to the highly relevant impact on decisions with regard to feeding policy of the product and component volume and variety, a simulation analysis of the bill of materials diversity was developed testing 1,000 different scenarios. A JIT daily levelled production is considered. The results reported in the paper show that:

- It is possible, through the proposed cost function comparison model, to quantitatively define the decoupling points that make one of the different feeding policies preferable as a function of the picking performance in the kit preparation (rows/*h*).
- The hybrid feeding policy could be a possible alternative applicable to a supermarket assembly line system. In some cases it can, if optimised, perform better than either the kanban or kitting policies. The problem of finding the optimal sub-set of parts to be managed using kanban and the optimal sub-set of parts to be managed using kitting has been formalised.
- Through a simulation study, it has been possible to derive a straightforward and quantitative decision-making tool composed of a series of graphics that define different 'convenience areas', able to give practitioners a general indication with a reasonable certainty margin about the best feeding policy definition as a function of the models diversity and production mix variations (div and CV) and of the picking performance (rows/*h*). On the other hand, this analysis demonstrates that the hybrid feeding policy, if compared with the kanban and kitting policies, presents a convenience area that is not negligible and varies according to the variance of div, CV and rows/*h*.
- To find the optimal solution for the hybrid feeding policy at the single component level gives rise to a large-scale combinatorial optimization problem. Authors demonstrated that the hybrid feeding policy optimization problem can be easily solved using a classes based approach, using the cross-matrix provided in the paper for averagely 70 % of the tested cases with a low margin of error.

Future research could include some important aspects. In this paper, the optimization of the picking activity is not considered within the proposed procedure. For this reason, rows/*h* is managed as a variable where, once determined, it is possible to derive the relative kitting handling costs. In a future study, the picking optimization problem could be integrated in the parts-feeding policy selection procedure, as a function of the relative influence of parameters.

Secondly, the proposed cost function comparison model does not consider the impact of system choice on operational performance. The possibility of presenting parts in a logical order with respect to the assembly order through kitting can reduce the searching/sorting time (and so the assembly time). To include this aspect in the cost functions, especially for a complex assembly, could be reasonable. On the other hand, the possibility of controlling certain component attributes (i.e. shapes, colours, flaws, etc.) before assembly, as part of the picking activities performed for kitting, could be included in the cost functions. Stoppages in continuous assembly due to defective components can sometimes be very burdensome from a costs perspective.

Actual industrial trends in the optimization of supermarket/multi-mixed assembly line systems are often driven by rules of thumb. Research in this field is many times not able to provide effective methodologies and procedures to practitioners. In this context, researchers, especially through simple but effective approaches, can play a very important role in helping companies to achieve high efficiency levels.

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