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A decision model for selecting parts feeding policies in assembly lines

Antonio C. Caputo Pacifico M. Pelagagge Paolo Salini

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Antonio C. Caputo
Department of Engineering, University of Roma Tre, Rome, Italy, and
Pacifico M. Pelagagge and Paolo Salini
Department of Industrial Engineering, Information and Economics, University of L'Aquila, L'Aquila, Italy

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Abstract

Purpose – The purpose of this paper is to develop an optimization model allowing the choice of parts feeding policy to assembly lines in order to minimize total cost.
Design/methodology/approach – An integer linear programming mathematical model is developed to assign the optimal material feeding policy to each part type. The model allows choice between kitting, line stocking and just in time delivery policies.
Findings – The choice of assembly lines feeding policy is not trivial and requires a thorough economic comparison of alternatives. It is found that a proper mix of parts feeding policies may be better that adopting a single material delivery policy for all parts.
Research limitations/implications – The model is aimed at single-model assembly lines operating in a deterministic environment, but can be extended to the multi-model line case. While relevant quantitative cost drivers are included, some context-related qualitative factors are not included yet. The model assumes that information about product structure and part requirements are known and that a preliminary design of the assembly system has been carried out.
Practical implications – Production managers are given a quantitative-decision tool to determine the optimal mix of material supply policies at an early decision stage.
Originality/value – Respect previous simplified literature models, this approach allows to quantify a number of additional factors which are critical for successful implementation of cost-effective parts feeding systems, allowing comparison of alternative policies on a consistent basis.

Keywords Cost estimation, Kitting, Assembly lines parts feeding, Just in time, Line storage, Linear programming optimization
Paper type Research paper

Nomenclature

a_k	container base dimension, first direction (m);
b_k	container base dimension, second direction (m);
c_k	container vertical dimension (m);
C_c	container equivalent daily unit cost (€/day);
C^E	equipments equivalent capital cost (€/day);
C_{FS}	floor space unit cost (€/m^2 day);
C^M	personnel daily cost (€/day);
C_{op}	daily cost of a worker (€/day);
C^S	space occupation cost (€/day);
C_{SRU}	equivalent daily cost of storage rack per unit volume (€/m^3 day);
$C_{std\ i}$	daily unit holding cost of ith component (€/piece day);
C_V	daily equivalent vehicle unit cost (€/vehicle day);
C_{VMR}	daily equivalent unit cost of tugger train performing milk runs (€/vehicle day);

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C_{VRS}	daily equivalent unit cost of vehicle replenishing the supermarket (€/vehicle day);
C^{WIP}	holding cost of the work in process (€/day);
D	daily demand for finished products (units/day);
h	daily shift working hours (h/day);
k	number of operators to move a kit or to transport a load to the line;
L	length of one-way transport route from kitting department to line start (m);
L_{BWS}	operator walking distance at the workstation in case of line storage (m);
L_{MR}	average length of the milk run (m);
L_{WH}	average distance between warehouse and supermarket (m);
L_{WS}	average distance of the workstation from the warehouse (m);
L_{WSK}	operator walking distance at the workstation in case of kitted parts (m);
LT	containers lead time in kanban policy (h);
M	number of workstations;
N	number of different components in a finished product;
$n_{cont\ kit,i}$	number of equivalent containers in a kit required to hold components of type i;
n_i	multiplicity of ith components in a finished product;
n_{ij}	number of items i utilized at station j per each unit of finished product;
n_{sl}	number of stackable containers on the shop floor;
Nop_{Av}	maximum available operators number;
NS_i	number of workstations utilizing part i;
p_i	weight of the ith component (kg);
p_{max}	maximum allowed weight of a container (kg);
Q	number of parts simultaneously picked from a storage location in the warehouse;
$S_{j,\ av}$	floor space available at workstation j (m^2);
S_{KS}	floor space available at first workstation for kits storage (m^2);
t_{fr}	time to fraction bulk component cartons in warehouse (s/carton);
t_{pb}	time to pick a piece from bulk container (s/piece);
t_{pick}	picking time for a single kitted item (s/piece);
$t_{r/s}$	time to locate and reach components in the warehouse (s/part type);
v_i	volume of the ith component;
V_c	volume of a components container ($a_c \times b_c \times c_c$, being a_c, b_c, c_c the container dimensions) (m^3);
V_k	volume of a kit container ($a_k \times b_k \times c_k$, being a_k, b_k, c_k the dimensions of the container) (m^3);
V_O	operator walking speed (m/s);
V_V	transport vehicle velocity (m/s);
$X_{i,p}$	decision variable;
Z_i	equivalent number of parts that can fit into a container;
α_{ij}	integer numer of containers of part i at workstation j;
η_{op}	average workers efficiency;
ω	number of containers transported simultaneously; and
ω_{WH}	number of container simultaneously moved from warehouse to supermarket.

Indexes

i	component index (1 to n);
j	station index (1 to M); and
p	policy identifier.

1. Introduction

Design and management of assembly lines requires decisions about the way components and subassemblies are delivered to assembly stations. This issue attracted interest from academic researchers in recent times as reviewed by Kilic and Durmusoglu (2015) and

Boysen *et al.* (2015). The main alternative is between kitting and continuous supply. The latter, in turn, may include line storage (LS) and just in time (JIT) supply, so that at least three distinct policies are available. Other specialized solutions, like sequencing, or synchronized parts supply and e-Kanban, as used for instance in Toyota Set Parts Supply System (Jainury *et al.*, 2014), will not be dealt with here.

The selection among such policies is often a matter of qualitative judgment, influenced by product and production system structure, operational constraints, company-specific practices and tradition, but it strongly affects the performances of the assembly system. In fact, while the basic implied trade-off is labor cost vs space occupation and WIP holding cost, even additional factors, such as degree of quality control and assembly support, flow control and visibility issues, ergonomics, material security, obsolescence, compatibility with large product variety and frequent mix variations, ease of implementation, etc., may favor one policy respect another in a specific manufacturing context, as discussed by Caputo and Pelagagge (2011) and Hanson (2012). Nevertheless, Hua and Johnson (2010) note that considerable confusion exists in the scarce literature on kitting vs line stocking decisions, with some research showing kitting to be superior to LS and other research, in similar manufacturing environments, showing just the opposite (Ding, 1992; Carlsson and Hensvold, 2008; Field, 1997; Henderson and Kiran, 1993; Sohal, 1997). Many industries show a lack of knowledge about where and when each type of system should be used, and may switch several times from kitting to LS without being sure which system is best for their environment. For instance, Limère and Van Landeghem (2008) report that in a company for a total of 3,500 part numbers, 52 percent of the parts were supplied to the line in bulk, 31 percent was sequenced at the supplier and the remaining 12 percent was repackaged or kitted internally. However, no clear quantitative basis could be given for this allocation. This is mainly caused by a scarcity of comparative research on factors influencing the choice of kitting respect other parts feeding methods, and the fact that a comprehensive methodology to assist in this system decision is not yet mature despite recent research efforts in the academic community.

In order to contribute to a solution of this problem, in this work an optimization method based on a mathematical programming approach is proposed. The model defines the optimal assignment of feeding policy to each component type, by selecting among the three cited policies, and factoring in workers cost, investment costs, work in process (WIP) holding cost as well as floor space occupation cost, in order to minimize the total materials supply cost.

The paper is organized as follows. At first the three considered policies are described and compared. Then an overview of currently available methods for planning and selecting parts feeding policies is presented by discussing the related literature. Subsequently a formulation of the decision problem is carried out and an integer linear programming model is developed for optimal allocation of components to feeding policies. A case study including a sensitivity analysis is then analyzed, showing the application of the proposed methodology to a large-sized industrial problem taken from the automotive industry. Comments on managerial implications and directions for future research conclude the paper.

2. Line feeding policies

2.1 Kitting

In kitting (Brynzér, 1995; Brynzér and Johansson, 1995; Bozer and McGinnis, 1992; Caputo and Pelagagge, 2011) all parts required to assemble one unit of the end product are grouped together and placed into a kit container. Kits prepared in a stockroom are delivered to the assembly line according to the production schedule. Figure 1 shows a scheme of a kitting system. Kits may be transported to the first station of the line and then move along the line together with the product being assembled (traveling kit concept). Otherwise individual kits holding the parts assortment required by single workstation can be delivered to each workstation (stationary kit concept).

2.2 Continuous supply (LS and JIT)

In case of continuous supply, every different part type is instead supplied to the assembly line in an individual container holding multiple units of the same item, so that a convenient stock of all parts used at a workstation is always available. Apart from the logic used to control material flows, LS and JIT parts supply mainly differ for the amount of transported material, the size of containers used and the handling frequency. Small-sized containers may be moved in JIT fashion to the assembly stations from a supermarket area, replenished by the central storage facility, adopting a kanban-based policy (JIT; Figure 2). Otherwise, components containers holding bulk quantities are simply stored along the line and periodically replenished (LS; Figure 3). The trade-off between unit load size and materials supply efficiency in continuous supply policies has been explored by Hanson and Finnsgård (2014).

Figure 1. Scheme of a kitting system (with traveling kits)

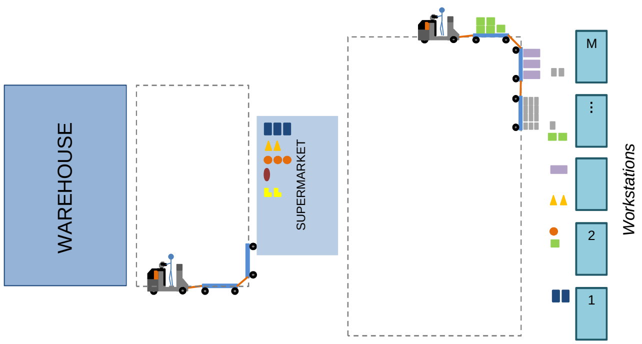

Figure 2. Scheme of JIT delivery from a supermarket

2.3 Policies comparison

Overall, in kitting systems material flow through the shop floor is simplified as only kits need to be moved to the assembly line instead of individual components containers, and WIP may be reduced at the point of use. However, order picking associated with kit preparation is labor intensive, thus an increased workforce is required. Kitting offers opportunity for better quality and productivity as parts are readily available, checked and pre-positioned, and this supports the assembler's work. In fact, items are presented in a logical order and can be removed quickly from the container. Less time is spent walking around searching for components, and in correctly prepared kits part shortages are eliminated. Finally, kitting supports high-mix and low-volume production, provided that kits are properly supplied to workstations according to the assembly schedule. JIT or LS, instead, save the order picking labor required for kitting and guarantee continuous availability of stock at the assembly line, at the expense of a greater space utilization on the shop floor, and higher WIP along the assembly line. The JIT approach allows to somewhat reduce WIP respect line stocking but requires more frequent handling of small-sized containers.

The main drawback of both continuous supply approaches is that parts are stored at their point of use, meaning that a station has to store enough quantity of all the component it utilizes for every product configuration. If the same component is used in multiple stations it has to be stored separately at each station, and this could be simply unfeasible owing to space scarcity.

Although there is much debate about the relative merits of each feeding policy, given that each solution may have both advantages and disadvantages in respect of each performance measure (Hanson, 2012), Table I offers an overall comparison of kitting vs continuous supply.

3. Review of methods for selecting parts delivery policy

3.1 Qualitative approaches

In recent times a growing interest has been witnessed in the literature about qualitative criteria for selecting material handling approaches to deliver components to assembly lines. Wänström and Medbo (2008) and Hanson (2009) discuss, from a general perspective, the design options for material supply systems and the impact that material feeding design and packaging practices have on the performance of assembly systems. They take an operator-centered perspective and focus on organizational and ergonomic aspects.

Fredriksson (2006) discusses operational issues related to the assembly of modular products, including material supply. Johansson *et al.* (2006) and Johansson and Johansson (2006) take the concurrent engineering perspective to analyze the interaction of material

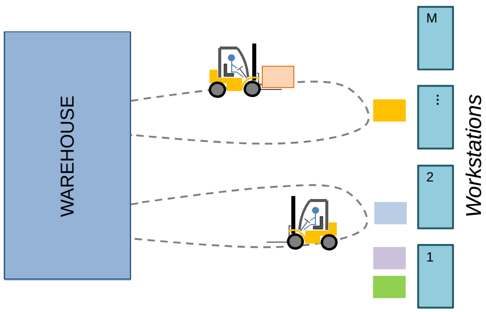

Figure 3.
Scheme of line storage system

	Kitting	Continuous supply (JIT and LS)
Picking labor	Higher	Lower
Line-side space occupation	Lower	Higher
Space occupation for materials preparation	Higher	Lower
WIP at workstations	Lower	Higher
Degree of quality control	Higher	Lower
Support of assembly task	Higher	Lower
Ergonomic quality	Higher	Lower
Compatibility with large-sized parts	Higher	Lower
Compatibility with high-mix and low-volume production	Higher	Lower
Ease of implementation	Lower	Higher
Material flow simplification	Higher	Lower
Stock availability at workstations	Lower	Higher
Flexibility	Higher	Lower
Control and visibility	Higher	Lower

Table I. Comparison of feeding policies performances

supply system design with the product development process, while Johansson (2009) evaluates the role of information management in design and operation of material supply systems. Hua and Johnson (2010) discuss factors affecting the kitting vs line stocking choice highlighting research questions still to be addressed, while Limère and Van Landeghem (2008) outline a conceptual decision model for selection of line feeding systems. In more general terms Hanson (2012) and Hanson and Brolin (2012) discuss in great depth most factors affecting the choice between kitting and continuous supply, also providing empirical evidence from in-plant experiments. However, the above papers have a qualitative approach.

3.2 Quantitative approaches

Quantitative analysis, instead, has been at first restricted to a direct comparison of kitting vs line stocking. Bozer and McGinnis (1992) develop a descriptive model useful for system design, adopting simplified cost models which neglect some factors which may impact on system cost (i.e. human resources requirements, equipment cost or the economic value of WIP). Carlsson and Hensvold (2008) extended the Bozer and McGinnis model to compare kitting with continuous supply, also allowing the possibility of arbitrarily choosing the delivery mode of each component, but do not take part size and weight into proper account and do not expicitly distinguish between JIT delivery and LS. They include an application in a Caterpillar factory. Medbo (1999) discusses the design of kitting systems, Caputo *et al.* (2015a) develop a detailed planning model for kitting systems, while Kilic and Durmusoglu (2012) provide a linear programming model to optimize operating parameters of kitting systems in order to minimize WIP and labor costs. Cottyn *et al.* (2008) as well as Govaert *et al.* (2011) propose a simple model to plan an integrated kitting and LS feeding systems superseding traditional fork lift material handling. Planning models for continuous supply systems, both JIT and LS, are instead developed by Caputo *et al.* (2015b). Faccio (2014) compares kitting and JIT solutions, even considering hybrid policies, while Sali *et al.* (2015) compare kitting, LS and sequencing solutions. Limère and Van Landeghem (2009) presented a simplified cost model for parts supply in the automotive industry from the perspective of the whole logistic flow, from suppliers to assembly line, allowing to determine break-even conditions between kitting and line stocking. Battini *et al.* (2009)

compare trolley to work station, pallet to work station and kit to assembly line approaches by developing analytical expressions for the time to feed the assembly line. They utilize simulation and factorial analysis to integrate the centralization/decentralization storage decision with the selection of feeding policies. They also present a case study where break-even points are obtained as a function of lot size. Caputo and Pelagagge (2008, 2011) extend the Bozer and McGinnis (1992) approach by explicitly taking into account human resources requirements, equipment cost and WIP holding cost. Moreover, in considering continuous supply they discriminate between bulk storage and JIT supply. They also suggested to adopt an ABC class-based approach to develop hybrid feeding policies where the entire set of components is partitioned into homogenous classes and a specific feeding policy is assigned to each class. They provide heuristic criteria for developing meaningful hybrid policies and a mathematical model to compare costs of alternative policies. Their work is subsequently extended (Caputo *et al.*, 2010) by allowing to assign a different feeding policy (i.e. kitting, LS or supermarket-based JIT) to each single item so that components sharing the same feeding policies could be then aggregated into homogenous groups irrespective of their original ABC class. A genetic algorithm is at first used to optimally allocate the three feeding methods to each component type in order to minimize overall cost (Caputo *et al.*, 2010), but mathematical programming techniques associated with more detailed cost modeling have been subsequently used (Caputo *et al.*, 2012, 2013). Vijaya Ramnath (2010) and Vijaya Ramnath *et al.* (2010) develop a multiple criteria decision support systems to choose the material handling method in assembly systems based on quantitative and qualitative factors, mainly focussing on kitting vs JIT options. Limère *et al.* (2012) utilize a linear programming model to make an optimal assignment of parts to kitting or line stocking policies, and successively extend that model to account for variable operator walking distances (Limère *et al.*, 2015). Nevertheless, they neglect the JIT alternative and only consider workers cost related to picking, transportation, kit preparation, material replenishment. Limère *et al.* (2013) also develop a simulation model to analyze performances of kitting or LS systems feeding assembly lines.

An overall comparison of the most relevant planning models comparing two or more policies and/or providing selection criteria is given in Table II, pointing out that most of the earlier models neglect many relevant cost issues. Moreover, in some cases cost estimation is simplistic while in other cases only technical parameters are computed (i.e. operators time consumption, occupied space, etc.) but a cost estimate is not developed, thus impairing a thorough cost assessment. In particular the table shows that most existing models focus on labor cost but neglect equipment cost. In general each single model may include some cost items but miss other ones, so that no model includes all cost items at the same time. This also prevents to carry out a meaningful comparison between earlier models in any specific instance.

Overall, despite previous research efforts, one concludes that a systematic approach to the optimal selection of material supply systems based on detailed cost models, addressing all main factors affecting the choice, and including all policy options has not yet been presented, and the problem of assigning part types to delivery policies remains an open question for academic and industrial research.

4. Model description

4.1 Modeling assumption and notation

The model is based under the hypothesis of one warehouse with a single I/O point, and a single-product assembly line consisting of *M* workstations arranged serially. The assembly

Table II. Comparison of literature models

	JIT	Line storage	Kitting	Optimization	Container cost	Transport equipment.	Storage equipment	WIP holding cost	Kit preparation	Line picking	Supermarket replenishment	Shop-floor space	Transport labor
Bozer and McGinnis (1992)		•	•		(•)			(•)				•	
Carlsson and Hensvold (2008)		•	•					(•)	•	•		•	(•)
Caputo and Pelagagge (2008, 2011)	•	•	•		•	•	•	•	•			•	•
Battini *et al.* (2009)	•	•	•						•	•			•
Limère and Van Landeghem (2009)		•	•			•		•	•			•	•
Vijaya Ramnath (2010)		•	•					•				•	•
Faccio (2014)	•		•					•	•				•
Caputo *et al.* (2010)	•	•	•	GA	•	•	•	•	•			•	•
Limère *et al.* (2012)		•	•	LP					•	•	•		•
Limère *et al.* (2015)		•	•	LP					•	•	•		•
Caputo *et al.* (2012)	•	•	•	LP	•	•	•	•	•			•	•
Sali *et al.* (2015)		•	•						•	•		•	•
This work	•	•	•	LP	•	•	•	•	•	•	•	•	•

Notes: LP, Linear programming; GA, genetic algorithm. ( ) indicate that only number of items or time consumed is computed instead of costs; • the item indicated in the column is included in the paper indicated in the row line has a constant daily production volume and the considered time horizon for cost estimation is one day. We also assume that each component can be used on multiple workstations. Material handling personnel is distinct from line staff which is in charge of assembly operations only. A kit is here defined as a unit load holding all the components required to assemble one unit of the finished product. However, materials composing a single kit may be put into one or more separate containers according to weight and space limitations. Kits are prepared one at a time and delivered from the kitting area located at the warehouse I/O station to the first station of the line, then they travel along the line together with the product being assembled (traveling kit). Multiple kits can be accumulated at the start of the line.

In JIT and line stocking systems, each workstation has its own containers available, and containers are not shared among multiple workstations. In JIT policy material is resupplied at each station with a lead time (LT) in separate containers dedicated to each component type. The required number of containers, therefore, depends on the daily consumption of parts and the replenishment LT. In line stocking each station holds separate containers (usually one) for each distinct component it uses, periodically resupplied at time intervals which depend from the adopted containers capacity. Constant-speed vehicles or walking operators are used to transport kit containers and components containers. However, different kind of vehicles, and containers sizes, can be used for different feeding policies. Even containers or bins size can be made different for each component type. For sake of simplicity the current formulation assumes a single container size for each policy, but containers sizes could be easily differentiated according to component type. From the modeling point of view this would only change the number of parts a container holds, which is an input data to the model. This also implies that in LS policy the lot size is not subject to optimization, as it is dictated by components unit volume and by the choice made about dimensions of the containers holding components. Nevertheless, issues related to the choice of the unit load size have been discussed for instance by Hanson and Finnsgård (2014) who state that "Based on the case study, it is clear that the efficiency of the in-plant materials supply is not proportional to the size of the unit loads. There are fundamental differences between how large pallets, compared to smaller unit loads, are delivered, meaning that the increased delivery frequency required for smaller unit loads does not necessarily result in an increased man-hour consumption." This suggests that even working with predefined lot sizes may not be a significant limitation of this model.

Empty containers are returned back to the central warehouse for replenishment. Exceptional items, such as those very cumbersome and heavy, requiring special handling care, are not included in the analysis.

In this model one and only one feeding policy is assigned to each type of component needed for assembling the end product, and the assignment is made in order to minimize a cost-based objective function. Binary decision variables are $x_{ip} \in [0, 1]$, where $i = 1$ to N is the component type identifier, and $p = (1, 2, 3)$ is the policy identifier with the following meaning, namely, in a kitting policy $p = 1$, in a LS policy $p = 2$, and in a JIT (kanban-based) policy $p = 3$. A decision variable has value $x_{ip} = 1$ in case policy p is assigned to component i, and $x_{ip} = 0$ elsewhere. Cost items included in the model are personnel cost (this includes operators needed to fraction bulk cartons and pick components in the warehouse, to deliver materials to the workstations, as well as workforce engaged in kits preparation and picking time at the line), investment cost (containers, storage racks and transport vehicles), WIP holding cost (proportional to the average level of inventory at the stations), and space occupation cost which is proportional to the floor space occupied by accumulated stock at the workstations and specific floor space cost. Please note that investment cost includes no building cost, so that shop-floor space occupation cost is accounted as a separate item to avoid double count.

Owing to the formulation adopted when building the optimization model, either resource sizing and cost functions are expressed in marginal (or incremental) terms, i.e. as the additional contribution to resource consumption and overall cost when the ith part type is assigned to a given policy. In this manner, irrespective of the chosen part type-policy assignment, the overall cost is simply computed by summing over all part types their individual cost contribution. In particular, we define $C^M_{i,p}$ the marginal workforce cost (€/day) incurred when policy p is selected to deliver component type i. $C^E_{i,p}$ the marginal equivalent investment cost (€/day) incurred when policy p is selected to deliver component type i. $C^{WIP}_{i,p}$ the marginal WIP holding cost (€/day) incurred when policy p is selected to deliver component type i. and $C^S_{i,p}$ the marginal space occupation cost (€/day) incurred when policy p is selected to deliver component type i. Below the equations utilized to estimate cost items are derived respectively for kitting ($p = 1$), LS ($p = 2$) and JIT (p = 3).

4.2 Computation of marginal workforce cost

4.2.1 Kitting policy. In a kitting policy the equivalent number of kit containers required to hold parts of type i per unit end item is:

$$n_{cont\ kit,\ i} = max\left(\frac{v_i\, n_i}{V_k}; \frac{p_i\, n_i}{p_{max}}\right) \tag{1}$$

which depends on containers volume (V_k) or their allowed weight (p_{max}) as well as the unit weight (p_i), the volume (v_i) and the consumption of parts (n_i) per unit end item of the ith part type. Unless the same containers are reused twice or more each day, the total equivalent number of containers required to manage the ith part for a daily production D is $n_{cont\ kit,i}\, D$.

Workers are required to locate and reach components at their storage locations in the warehouse to feed the kitting area, to pick individual parts and place them into kit containers and to move containers from the kitting area to the start of the line. The average time to reach the storage location of ith part and return to the kitting area is ($t_{r/s}$) and can be estimated according to the adopted picking policy and warehouse configuration. We can also assume that when reaching a warehouse location the operator can pick a quantity of parts of type i enough to complete Q separate kits (with Q integer and $\geqslant 1$) in order to avoid returning to that warehouse location for each new kit to be prepared, or that a single trip to a warehouse location allows to retrieve Q different part types that are stored in nearby locations. Kitting operation can be quite time consuming, as it generally includes the following operations, namely, counting/weighting of parts to ensure that the right number is included in the kit; preparation of components before insertion in the kit (i.e. cutting to measure, package removal, cleaning and quality control); kit preparation (insertion of parts in the right sequence and in the proper housing slot, including correct positioning control); compilation of missing component list for subsequent kit completion. Average time t_{pick} required to pick and kit one unit of a part type can be measured or computed resorting to traditional time studied methods. As far as kit transportation is concerned, instead, the equivalent number of daily moves for the ith part type (from the warehouse to the line with full containers and from the line to the warehouse with empty containers) , being ω the number of container simultaneously transported by the material handling vehicle, is $2\, n_{cont\ kit,i}\, D/\omega$. We assume that each trip involves k operators and that the one-way trip time is L/V_V, estimated on the basis of plant layout (L is the distance between kitting area and the line first workstation) and material handling vehicle average velocity (V_V). The time required to pick components at the workstation by line operators $(n_i\ D)\ 2\ L_{WSK}/V_O$, is also included as it may change according to the material handling policy. In this case V_O is the operator's walking velocity, who needs to travel two times the trip L_{WSK} from the assembly position to the kit storage point at the workstation. Time to search for the right part is neglected as parts are already ordered and properly presented to the picker.

From the above assumptions the number of daily workers required to prepare and transport kits can be computed assuming that each operator works a daily shift of h hours and has an efficiency η_{op}. Then the number of workers times their wage rate C_{op} (€/day), allows to compute the marginal personnel cost for ith part type allocated to a kitting policy:

$$C_{i,1}^{M} = C_{op}\left\{\frac{\left[\frac{t_{r/s}}{Q}+\left(t_{pick}+\frac{2L_{WSK}}{V_O}\right)n_i\right]D+\left[\left(\frac{2Lk}{V_V}\right)\frac{Dn_{cont\ kit,\ i}}{\omega}\right]}{\eta_{op}h}\right\} \tag{2}$$

4.2.2 LS policy. In a LS or JIT policy, containers dedicated to a part type are moved from the warehouse, or from a supermarket area in case of JIT policy, to the workstation utilizing that part. Conceptually the main difference is the size of containers and the resulting frequency of handling moves. In both cases $Z_i = min\left(V_c/v_i; p_{max}/p_i\right)$ is the equivalent number of parts of type i which fit in a container. For simplicity here we assume that size V_c of a container is specific of the feeding policy, i.e. that size is different in case of JIT or LS policies, but is the same for all types of parts handled with a given policy as previously assumed. However, the user is free to specify a specific container size for any type of part if needed. Obviously Z_i changes, for any given part type, according the container size and weight limits associated to each policy. It follows that the number of equivalent containers to be moved daily toward station j in case the ith part type is assigned to one of the two above policies (with zero buffer stock) becomes $(D\ n_{ij}/Z_i)$, where n_{ij} is the number of items of the ith component utilized at the jth station per unit finished product ($n_{ij}=0$ if component i is not utilized at station j). Therefore $(D\ n_{ij}/\omega\ Z_i)$ is the equivalent number of daily trips to replenish station j with components i, assuming that ω is the number of container simultaneously transported by the material handling vehicle. In case of LS usually $\omega=1$. The one-way trip time to reach the generic workstation, located at an average distance L_{WS} from the warehouse is L_{WS}/V_V. We assume that a time t_{fr} is required to fraction bulk containers in the warehouse to fill part containers to be handled to the line. In case an entire SKU or pallet is moved to the line $t_{fr}=0$. Time to pick parts at the workstation is $(n_i\ D)\ (t_{pb}+2\ L_{BWS}/V_O)$, where L_{BWS} is the one-way walking distance from the assemply position to the storage point of bulk containers at the workstation, while t_{pb} is the time needed to search and pick each part from the bulk storage. Therefore, the marginal personnel cost for ith part type allocated to a LS policy, to replenish all stations using a given part type and pick parts at the workstations is:

$$C_{i,2}^{M} = C_{op}\left\{\frac{\left[\left(t_{r/s}+t_{fr}+2\,\frac{L_{WS}}{V_V}\,k\right)\sum_j\left(\frac{Dn_{ij}}{Z_i\omega}\right)\right]+\left[\left(t_{pb}+\frac{2L_{BWS}}{V_O}\right)n_i\,D\right]}{\eta_{op}\,h}\right\} \tag{3}$$

4.2.3 JIT policy. In a JIT policy the structure of this cost item is similar, but replenishment of the supermarket has to be considered. Moreover, parts containers are moved from the supermarket to workstations utilizing a tractor-trailer performing a milk run, i.e. a closed circle path of length L_{MR} connecting the supermarket with the set of stations to be visited. As far as time to pick components at the workstation is considered, the same values t_{pb} and L_{BWS} used for LS case have been maintained, as both type of containers are likely to be stored nearby and in both cases dedicated containers are used where components are placed in a random manner. In case that the distance between warehouse and supermarket is L_{WH}, and that ω_{WH} containers are simultaneously moved between warehouse and supermarket, $\sum_j \left(D\, n_{ij}/Z_i\, \omega_{WH}\right)$is the equivalent number of daily trips required to replenish the supermarket with the *i*th part type (usually $\omega_{WH} \ll \omega$), while $2\ L_{WH}\ k\ /V_V$ are the man-hours required to perform a two-way trip between warehouse and supermarket. Again ($t_{r/s}$) is the time required to reach the storage location inside the warehouse, while (t_{fr}) is the fixed time needed to fraction the SKU and replenish the ω_{WH} containers to be moved to the supermarket:

$$C_{i,3}^{M} = C_{op}\left\{\frac{\left[\left[t_{r/s}+t_{fr}+\left(2\frac{L_{WH}}{V_V}k\right)\right]\sum_j\left(\frac{Dn_{ij}}{Z_i\omega_{WH}}\right)\right]+\left[\left(\frac{L_{MR}}{V_V}k\right)\sum_j\left(\frac{Dn_{ij}}{Z_i\omega}\right)\right]+\left[\left(t_{pb}+\frac{2\ L_{BWS}}{V_O}\right)n_iD\right]}{\eta_{op}\ h}\right\} \tag{4}$$

Please note that in Equations (3) and (4) the values of $t_{r/s}$, t_{fr} , k, Z_i and ω depend from the chosen policy, given the different size of containers and material handling devices utilized in LS or JIT contexts.

4.3 Computation of marginal investment cost

Equipment cost C^E is the sum of containers cost and capital investment of storage (i.e. containers) and transport equipment (i.e. fork lifts, manual carts, tractor/trailers, etc.). Operating cost of transport equipment (energy and maintenance) are neglected here, but can be included in the equivalent daily cost (C_V) of the vehicle if needed.

4.3.1 Kitting policy. In a kitting policy the investment includes kit containers and kits transportation vehicles. The marginal daily investment cost is:

$$C_{i,1}^{E} = C_c\left(Dn_{cont\ kit,\ i}\right)+C_V\left(\frac{2L}{V_v h}\frac{D\,n_{cont\ kit,\ i}}{\omega}\right) \tag{5}$$

where C_c is the container daily equivalent unit cost, while L is the one-way trip length from the kitting area to the line start and V_v the vehicle average velocity. We assume that each set of kit containers is used only once a day and replenished the next day.

4.3.2 LS policy. In a LS policy the investment includes storage containers, containers transportation vehicles and storage racks at the workstations. Containers cost is computed as the number of containers required to transport and hold parts at the workstations times the unit container cost. In LS a single container per part type is usually left at each workstation utilizing that component, while NS_i is the number of different workstations utilizing the *i*th part type. However, we double the containers number to account for the fact that while containers are left at the workstation an equal number is being replenished at the warehouse allowing to swap an empty container for a full one. Racks, having a daily cost per unit volume C_{SRU}, are instead needed only to hold the containers transported and left at the workstation. The amount of rack space depends from the unit container volume V_C. The equivalent number of vehicles needed to transport part containers at the workstation, considering that the vehicle can transport ω containers simultaneously (with $\omega \geqslant 1$ and integer), is computed as the ratio of the required daily transportation hours (i.e. number of required equivalent trips $\sum_j (D\, n_{ij}/\omega\, Z_i)$ times the two-way trip duration $(2L_{WS}/V_V)$ to the available daily work hours (h):

$$C_{i,2}^{E} = C_c 2NS_i + C_V \left(\frac{2\, L_{WS}}{V_v h} \sum_j \left(\frac{Dn_{ij}}{Z_i \omega} \right) \right) + C_{SRU}\; NS_i V_c \tag{6}$$

4.3.3 JIT policy. In case of a JIT policy the computation is similar, but multiple daily replenishments of smaller sized containers are required, so that the same container can be used more than once. The average equivalent number of containers left at the *j*th workstation, to ensure the desired parts throughput, is linked to the replenishment LT through Little's law $(D\, n_{ij}\, LT/Z_i)$.

However, given that a dedicated container is used for each part type, an integer number of containers α_{ij} (at least equal to 1) should actually remain at the workstation for each part type assigned to this policy. Therefore, the equivalent number of containers is to be rounded to the next integer ($\alpha_{ij} = 0$ if *i*th component is not used at the *j*th workstation):

$$\alpha_{ij} = \left\lceil \frac{Dn_{ij}\, LT}{Z_i} \right\rceil$$

In this case too the overall number of containers is doubled because empty containers are swapped with full containers coming from the supermarket:

$$C_{i,3}^{E} = 2C_c \sum_j \alpha_{ij} + C_{VRS} \left(\frac{2L_{WH}}{V_V h} \sum_j \left(\frac{Dn_{ij}}{Z_i\, \omega_{WH}} \right) \right) + C_{VMR} \left(\frac{L_{MR}}{V_v h} \sum_j \left(\frac{Dn_{ij}}{Z_i\, \omega} \right) \right) + C_{SRU}\; V_c \sum_j \alpha_{ij} \tag{7}$$

In Equation (7) (C_{VRS}) is the equivalent daily cost of the vehicle replenishing the supermarket, while (C_{VMR}) is the equivalent daily cost of the tugger train performing milk runs to replenish workstations.

4.4 Computation of marginal WIP holding cost

4.4.1 Kitting policy. In case of a kitting policy, the first workstation holds ω kits, while each of the remaining *M*-1 stations holds one traveling kit. It is assumed that C_{stdi} is the daily unit holding cost of *i*th part type, which is expressed as the monetary value of the component times the daily carrying cost per unit value of WIP. Considering that at the start of the line each kit holds the entire multiplicity n_i of the *i*th part type included in one unit of the end product, while it is empty at the end of the line, the average number of parts at each workstation is $n_i/2$, except at the first workstation where it is $n_i\omega/2$, then the holding cost of the average amount of WIP, is:

$$C_{i,1}^{WIP} = \frac{1}{2} C_{stdi}\; n_i (M - 1 + \omega) \tag{8}$$

4.4.2 LS policy. In case of LS the holding cost of the WIP is the holding cost of the average material amount in the containers along the line. For the ith part type fed to a generic workstation the average amount of WIP is $Z_i/2$, given that each container holds a maximum of Z_i items and assuming that a single container is left at the workstation (otherwise this value is multiplied by ω). This average WIP should be multiplied for the number of different workstations holding the part type. Therefore:

$$C_{i,2}^{WIP} = \frac{1}{2} NS_i (C_{stdi}\, Z_i) \tag{9}$$

4.4.3 Kitting policy. In a JIT policy the average amount of components held in the α_{ij} containers at the jth workstation, each one having a capacity of Z_i pieces, is $Z_i\, \alpha_{ij}/2$ so that in the entire line:

$$C_{i,3}^{WIP} = \frac{1}{2} C_{stdi}\, Z_i \sum_j \alpha_{ij} \tag{10}$$

4.5 Computation of marginal space occupation cost

4.5.1 Kitting policy. As far as space requirements on the shop floor are concerned, in case multiple kits are transported and accumulated at the first station, the marginal space consumption cost is the unit daily floor space cost (C_{FS}) times the marginal occupied floor space:

$$C_{i,1}^{S} = C_{FS} \left[\frac{(a_k b_k)\, n_{cont\ kit,i}\, \omega}{n_{sl}} \right] \tag{11}$$

where n_{sl} is the number of containers which can be stacked in a column and a_k and b_k are the length of the kit containers base sides.

Space occupied by the single traveling kit at the workstations instead can be neglected, as kits often travels together with the partially assembled parts over the same material handling system. If this is not the case, space occupation cost at the other (M-1) workstations can be computed according to Equation (11) but assuming $\omega = 1$ resulting in an overall cost:

$$C_{i,1}^{S} = C_{FS} \left[\frac{(a_k\, b_k)\, n_{cont\ kit,i}}{n_{sl}} \right] (M - 1 + \omega) \tag{12}$$

4.5.2 LS policy. In case of LS we assume that up to n_{sl} containers having a base area ($a_c \times b_c$) can be stacked and that a stack can be composed of containers holding different part types. The allocation of a part type to a LS policy implies the space occupation of at least one additional container (assuming only one container per part type is held at each workstation utilizing that part), but this results in the increase of the actual footprint on the shop floor only when the overall number of containers exceeds a multiple of n_{sl}. In this case, in fact, a new stack has to be erected or a new column of storage rack has to be added. To keep the model linear we adopted the following formulation for the marginal space occupation cost, even if this expression slightly underestimates the actual space occupation as long as the number of containers is lower than an integer multiple of n_{sl} or in case that stacks of containers at different workstations are ideally aggregated.

However, the larger the number of part types to be stored at workstations the lower is the error. To avoid this problem, however, instead of computing the space occupation contribution of each item stored lineside at each workstation and summing each individual contribution, the overall pallet volume of items assigned to LS policy at a workstation can be computed and translated into an overall floor space occupation given the maximum allowed stacking height. This cumulative footprint can be used to compute space occupation cost and to verify that allowed storage floor space is not exceeded. This approach would require slight modifications to the model under discussion. However, in the current formulation, assuming that only one container per part type is used at each workstation holding that part ($\omega = 1$) then:

$$C_{i,2}^{S} = C_{FS}\, NS_i \left[\frac{(a_c\, b_c)}{n_{sl}} \right] \tag{13}$$

4.5.3 JIT policy. Finally, in a JIT policy, being α_{ij} the number of containers to be stored at the jth workstation for a part type, and being n_{sl} the stack height, the marginal space occupation cost is assumed as:

$$C_{i,3}^{S} = C_{FS} \left[\sum_{j} \frac{(a_c\, b_c)\, \alpha_{ij}}{n_{sl}} \right] \tag{14}$$

In this case too the previous warning of possible cost underestimation applies as well as the above cited alternative formulation. Furthermore, in case of kitting the space occupied by the supermarket could be acconted for by simply multiplying the terms in square brackets of Equation (14) by a coefficient $\xi > 1$ which accounts for the extra percent space consumed at the supermarket by the stock of a given ith item.

4.6 Optimization model

After defining the above expressions for marginal costs and resource consumption, the integer linear programming optimization model can be stated as:

$$\text{Minimize} \sum_{i=1}^{N} \sum_{p=1}^{3} \left(C_{i,p}^{M} + C_{i,p}^{E} + C_{i,p}^{WIP} + C_{i,p}^{S} \right) x_{i,p} \tag{15}$$

subject to:

$$\sum_{i \in J} \left\{ x_{i,2} \left[\frac{C_{i,2}^{S}}{C_{FS}} \right] + x_{i,3} \left[\frac{C_{i,3}^{S}}{C_{FS}} \right] \right\} \leqslant S_{jAv} \tag{16}$$

$$\sum_{i=1}^{N} x_{i,1} \left[\frac{C_{i,1}^{S}}{C_{FS}} \right] \leqslant S_{KS} \tag{17}$$

$$\sum_{p=1}^{3} x_{i,p} = 1 \tag{18}$$

$$x_{i,p} \in (0, 1) \tag{19}$$

In this model Equation (15) is the overall daily cost function and its components are computed resorting to Equations (2) to (14). Equation (16) states that for each workstation j (with $j = 1, 2, \ldots, M$), given the set J of component types used at a generic jth workstation, the actual occupied space for parts storage (represented by the left hand term) is less or equal to the available floor space ($S_{j,av}$) at the station. This constraint is applied only with reference to the floor space consumed for stocking parts containers (in case of JIT or LS policies) as the space occupied by the single traveling kit is considered to be negligible. Constraint (17) ensures that space occupied by kit containers at the first workstation is consistent with available space S_{KS} for multiple kits storing at the start of the line. This check does not apply to other station because kits enter the line one at a time and only one kit is present at any time at any workstation. Constraint (18) imposes that only one policy is assigned to any part type and that each part type is assigned to a delivery policy. Finally, Equation (19) imposes that any decision variable can only have 0 or 1 values.

When the model is not used for long range planning of new assembly systems, but rather to reorganize the material supply systems of existing facilities, then plant managers may also have the additional requirement of not hiring new operators. If this applies then the following constraint can be included in the model formulation:

$$\frac{1}{C_{op}} \sum_{i=1}^{N} \left[x_{i,1} C_{i,1}^{M} + x_{i,2} C_{i,2}^{M} + x_{i,3} C_{i,3}^{M} \right] \leqslant Nop_{Av} \tag{20}$$

In the above equation the left hand term represents the overall number of operators needed to feed all the components with the allocated policies, while the right hand term represents the available number of operators.

5. Case study

In order to show the capabilities of the method a case study from the automotive sector has been considered. The case study refers to a final assembly line for industrial vehicles. The line is composed of 96 workstations. Each vehicle is assembled using 1,785 different part types. The multiplicity of a given part type can change in the 1-34 range, while each station utilizes from 13 to 28 different part types. Part types have a weight range from 5 g to 25.53 kg, and a volume variable between 23 and 560 cm^3. Unit cost of parts ranged between 0.1 and 127.7 €. The overall component value of an end product is 41,280 € and its weight 4,496 kg. Figure 4 shows the frequency distribution of parts weight, volume and cost.

The single-model assembly line has a throughput of 18 end units per day. Storage space at workstation is limited to a length along the line of 8 m, with a depth of 3 m, while at the first station the available storage floor area is 40 m^2. A scheme of the line layout is depicted in Figure 5.

Additional system data and assumed parameters are resumed in Table III. WIP cost includes only the point of use holding cost, as no obsolescence cost was relevant in this context.

The daily carrying cost per unit value of WIP (C_{stdi}) is computed assuming a specific capital holding cost of 0.25 €/€ yr. Warehousing cost is not included as it is the same for all policies, exception made for picking cost which changes according the selected policy. Labor cost is based only on utilized man-hours cost, instead of the contracted availability. Overhead and supervision costs are neglected. The model was implemented in Matlab computing environment and solved resorting to its Optimization Toolbox. When running

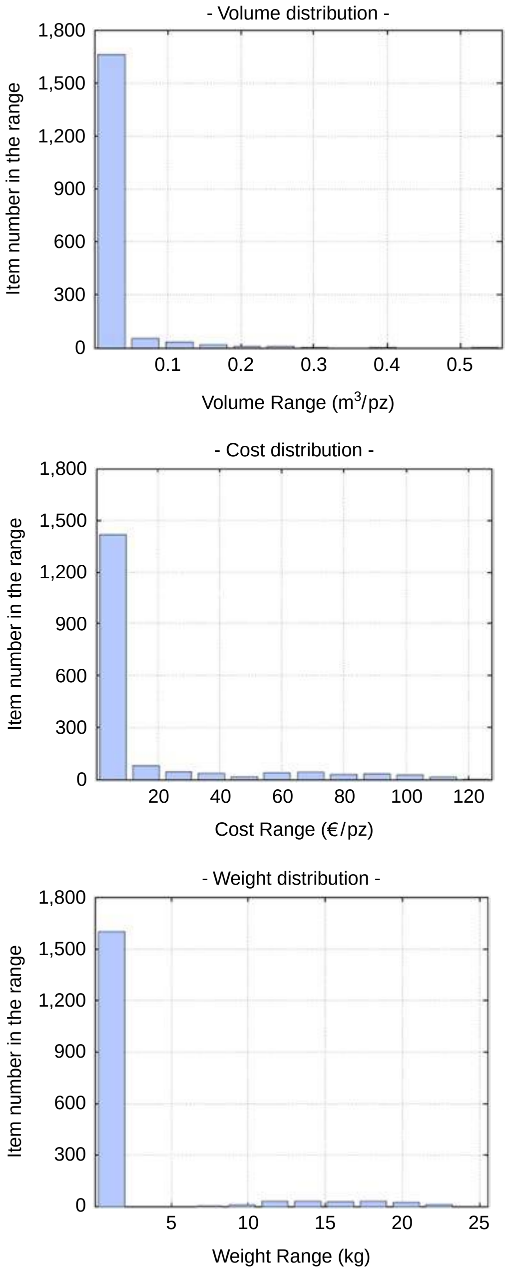

Figure 4.
Frequency distributions of component characteristics

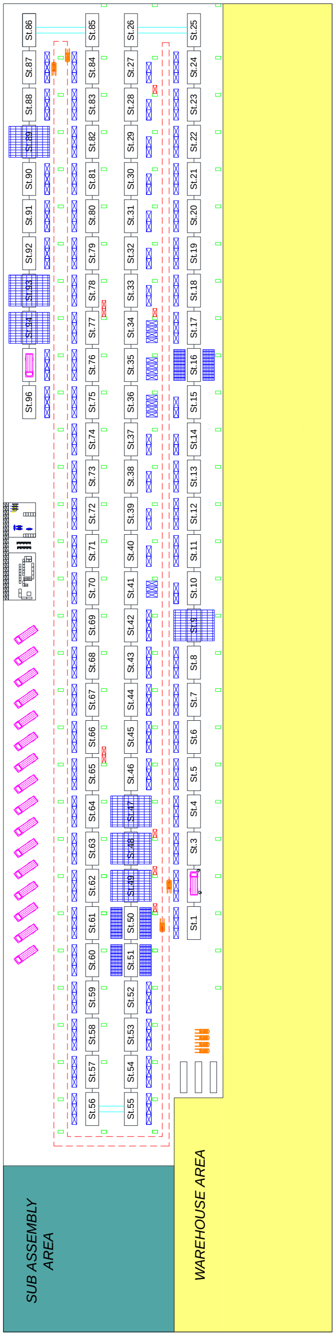

Figure 5.
Assembly line layout

Table III.
Assumed parameters and scenario data

C_c	0.05 €/day
C_{FS}	1.5 €/m^2 day
C_{op}	30 €/h
C_{SRU}	0.075 (LS), 0.05 (KA) €/m^3 day
C_V	15 (KI), 13.64 (LS),
C_{VMR}	22 €/day
C_{VRS}	18 €/day
D	18 units/day
h	8 h/day
k	2 (KI), 1 (LS and KA)
L	100 m
L_{BWS}	2.5 m
L_{MR}	500 m
L_{WH}	40 m
L_{WS}	200 m
L_{WSK}	1.5 m
LT	4 h
n	1,785
n_{sl}	5 (KI), 6 (KA), 2 (LS)
p_{max}	50 kg (KI), 400 kg (LS), 20 kg (KA)
Q	6
S_{jAV}	16 m^2 (32 m^2 at first station, S_{KS})
t_{fr}	30 s/carton (0 for line storage)
t_{pb}	2 s/part
t_{pick}	3 s/component
$t_{r/s}$	60 s/trip
V_c	1.44 m^3 for LS ($a_c = 1.2$ m, $b_c = 1.2$ m, $c_c = 1$ m) and 0.018 m^3 (KA) ($a_c = b_c = 0.3$ m, $c_c = 0.2$ m)
V_k	0.062 m^3 ($a_k = b_k = 0.5$ m, $c_k = 0.25$ m)
V_O	0.7 m/s
V_V	2,800 (KI), 2,400 (LS), 2,500 (KA) m/h
η_{op}	0.8
ω	15 (KI), 300 (KA), 1 (LS)
ω_{WH}	20

the model the following optimal assignment of delivery policies to component types is obtained, namely, 9.4 percent of components are to be delivered in JIT manner adopting a kanban-based policy; 79.4 percent of components are to be stocked at the workstations; while the remaining 11.2 percent of components should be kitted. This optimal strategy is much more cost effective than any pure policy, using a single delivery mode for all components, as shown in Table IV.

Table IV also compares the theoretical optimal cost solution obtained by the solver and the subsequent feasible solution where all variables which must have an integer value (i.e. number of workers, number of vehicles, number of containers stacking columns on the shop floor, etc.) have been rounded up to the integer while verifying that constraints are still satisfied. Table V, instead, shows the percent increase of daily cost, workers and occupied floor space of single policies respect the optimized one. As shown in the table, an optimal supply policy assignment in this case study allows a cost reduction of about 11-28 percent respect pure policies, thus confirming the effectiveness of the proposed method.

Figure 6, instead, shows the subdivision of cost item according to the various supply policies. The figure shows that labor is the single most relevant cost and especially affects kitting. Labor cost was found always to be much higher than WIP cost.

It is interesting to note that the higher workforce required for kitting is compensated in other policies by a rather similar requirement for workers, so that, overall, kitting has a number of workers not very much higher than LS and JIT. However, it should be noted that labor cost does not reflect only the trade off between kitters and material handlers, because cost of picking at the line is also included and penalizes the latter policies respect kitting. WIP holding cost instead is more relevant in LS. However, in this case holding cost is relevant even for a kitting policy, given the large number of workstations and the high component value inside a kit. Instead, the WIP holding cost in case of JIT is quite low, confirming the effectiveness of this policy in limiting the

	Total cost Ideal solution (€/day)	Total cost feasible solution (€/day)	Number of workers	Total occupied floor space (m^2)
Kitting	16,510.29	16,630.68	59	311.33
Line storage	18,428.57	18,680.67	54	1,133.40
Just in time	14,930.85	15,185.80	57	207.99
This work	12,862.33	13,476.48	52	171.57

Table IV. Optimization results and comparison with single delivery policies

	ΔCost (%)	ΔOperators (%)	ΔSurface (%)
Kitting	+19	+11.9	+44.9
Line storage	+28	+3.7	+84.9
Just in time	+11	+8.8	+17.5

Table V. Relative comparison of single policies performance respect optimal solution

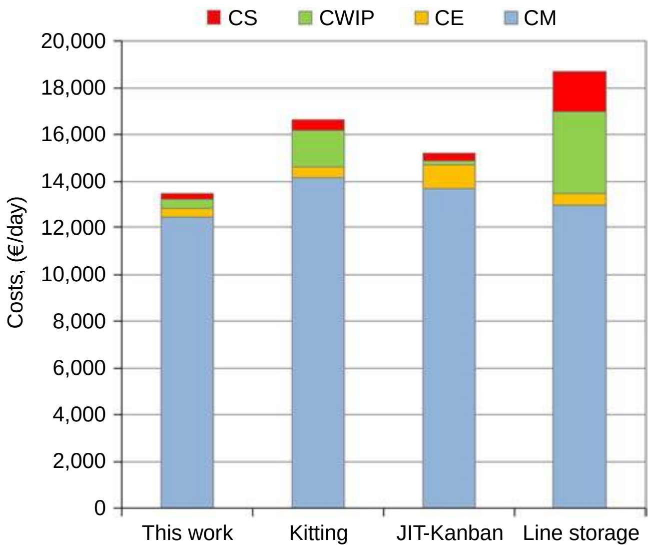

Figure 6. Cost allocation by policy

parts storage requirements, but at the expense of a higher cost for frequent material handling as witnessed by the higher workforce cost respect LS. The highest equipment cost is for a JIT policy, but results confirm that investment costs are not a critical issue in the material management choice, especially when amortized over a suitable number of years. The highest space occupation cost is for LS. Some of those results confirm the general trends in literature findings, but others are counterintuitive. This is probably caused by the complexity of this case study, which is not representative of the typical industrial assembly application where smaller sized consumer goods having a much lower parts number have to be managed in shorter lines. Nevertheless, the results justify the importance of careful analysis of alternative material feeding policies, as the balance among options is very case specific. Anyway, for any cost item the optimal solution is characterized by lower values respect all other competing policies.

In order to test solution stability and the system behavior, a sensitivity analysis has been performed. Figure 7 depicts the variation of percentage of parts assigned to each policy when space occupation cost increases from 0.75 to 2.25 €/m^2 day. One would expect that a rising space occupation cost would progressively penalize a LS solution in favor of the other policies. However, the opposite happens, with LS increasing the percentage of items assigned at the expense of JIT, while kitting remains stable. This is an example of a counterintuitive behavior. Nevertheless, aggregate cost data may mask the underlying phenomena, which are more complex. In fact, Figure 8 shows the trend of actual occupied surface when the specific surface cost increases, showing that while the cost per unit surface increases the overall occupied space decreases, as could be expected. In particular, space occupied by components fed by LS policy reduces from about 110 to about 96 m^2.

The fact that the percentage of items fed by LS increases while actual space occupation lowers means that the sytem is responding by changing the items allocated to that policy without necessarily changing the overall number of part types allocated to that policy. Therefore, the reallocation of items to policies when economic parameters change may lead to counterintuitive results at level of aggregated data.

The same behavior shows when the hourly labor rate increases (Figure 9). The percentage of items fed with apparently more workforce – consuming policies (kitting and JIT) increases while the number of parts assigned to LS reduces. Again, the overall

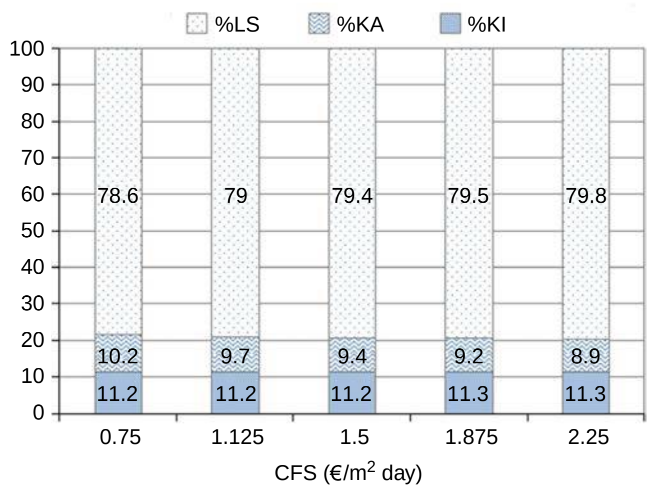

Figure 7.
Influence of space occupation cost on percentage of items assigned to a policy

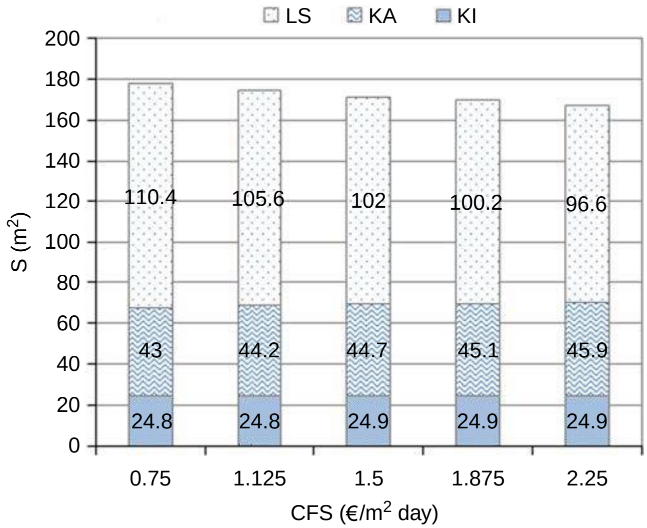

Figure 8.
Variation of occupied space vs specific space occupation cost

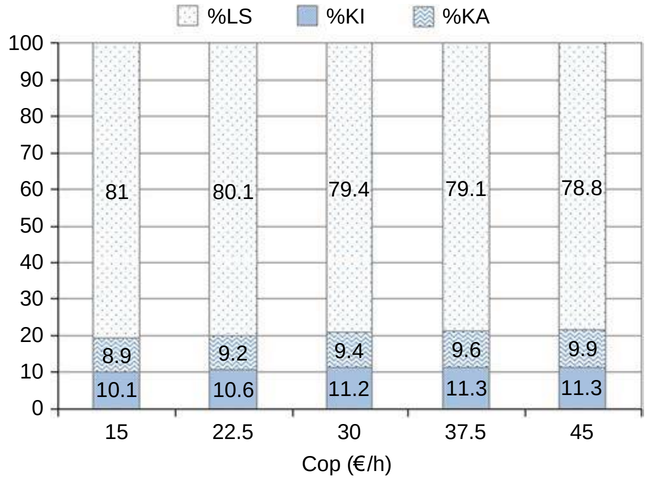

Figure 9.
Influence of labor cost on percentage of items assigned to a policy

workforce cost masks the trade-off between kitting cost and transportation cost, and a reassignment of part types to feeding policies occurs, so that when labor rate is maximum the actual number of workers is slightly reduced respect the other cases (51 respect 52) as shown in Figure 10. Overall, the system correctly reacts to changes in economic parameters while seeking cost minimization, but this does not necessarily result in an intuitive change of the relative distribution of part types among the three policies.

Finally, Figure 11 shows the variation of percent components assignment to policies when the daily production rate increases. In this case the higher the production rate the fewer components are stored at the line side, while both kitting and JIT delivery increase the percentage of parts assigned.

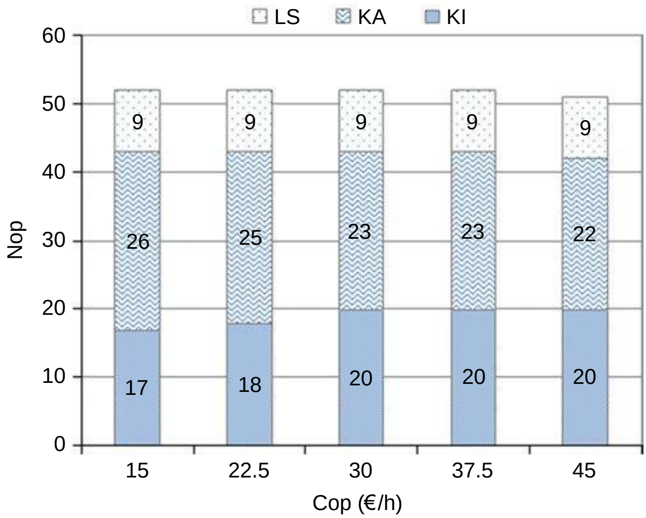

Figure 10.
Influence of labor cost on number of workers assigned to a policy

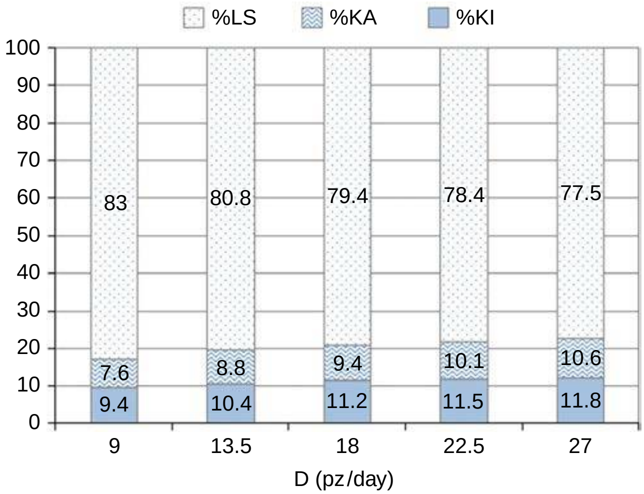

Figure 11.
Influence of demand rate percentage of items assigned to a policy

However, in the given application context the sensitivity analysis shows that the optimal solution is relatively stable in terms of overall percentage of parts assigned to the various policies, and in the overall costs subdivision, so that errors in the estimation of model parameters are not likely to have a relevant effect. Instead it appears that it is the product and assembly system structure that determines the overall balance among competing policies. Nevertheless, the model reassigns single components to each policy according to parameters variations.

In order to assess how components attributes might affect the policy assignment, an analyis of policy allocation frequency according to component weight and volume is depicted in Figures 12 and 13, respectively. The effect of component unit cost is not shown as it is quite similar to that of component weight. This happens because in the

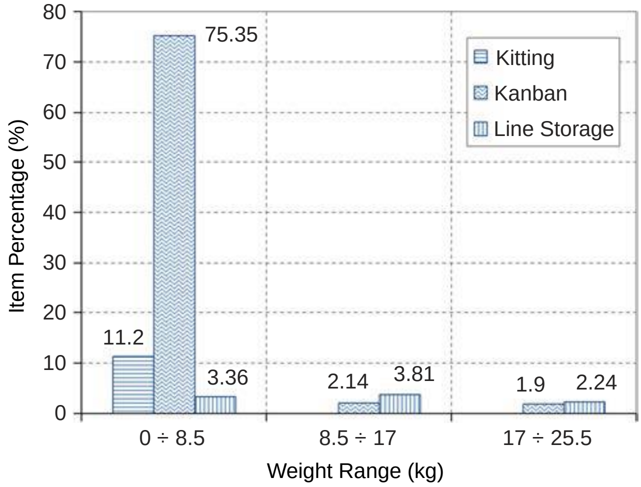

Figure 12.
Influence of component weight on policy selection

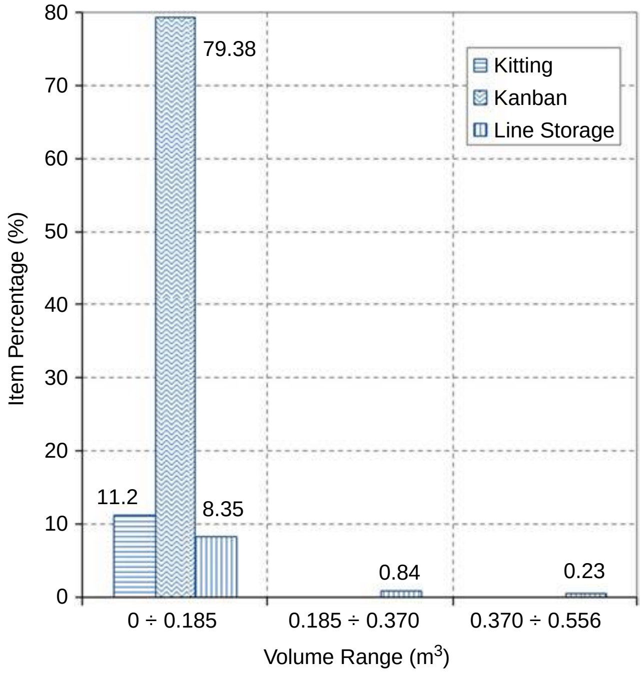

Figure 13.
Influence of component volume on policy selection

present case study the item unit cost was found to be roughly proportional to its weight, thus suggesting a collinearity effect. Moreover, holding cost, which is proportional to components unit cost, was found in this case to be much less relevant than labor cost which, in turn, is more affected by components size and volume. The choice of a kitting policy resulted limited to lower weight and smaller volume components only, which can be kitted more easily. Again results confirm that kitting is penalized by high labor cost, especially when inventory holding cost is not a driving factor, and is applied preferably to small-sized components owing to limitation in kit containers size. Nevertheless, JIT delivery was the most frequently chosen solution for small-sized components. Probably this is a result of the combined effect of low impact of holding cost, allowing storage of moderate inventories at workstations, and savings derived from reducing kitting labor. For small-sized and lighter components LS is a marginal choice. In intermediate and high-weight classes items are quite evenly distributed between JIT and LS, but passing to middle and high-volume classes only LS is used. Possibly this derives from the constraint imposed by JIT bin dimensions. Summarizing the above results one observes that JIT is the preferred policy as it strikes a compromise between opposite advantages and drawbacks of LS and kitting policies. Kitting proves to be unsuitable to medium- and large-sized items, while containers size forces large-sized items to be fed with LS policy. When containers size and components dimensions allow both JIT and LS, then the two policies are distributed quite evenly among components. This suggest that kitting may be a viable option especially for mixed model assembly lines in high-mix and low-volume application, not studied in this work, or when high-value and small-sized components are needed to configure specific end-item variants. However, general conclusions leading to simple rules-of-thumbs allowing assignment of feeding policies on the basis of parts attributes must not be inferred from this specific case study. Moreover, the above results are strongly influenced by the frequency distribution of components number in each size class. In fact, as shown in Figure 4, in this case study the overwhelming majority of components is included in the smaller size classes.

6. Discussion of model limitation and managerial implications

This work presented a decision support system helping plant designers and production managers in the selection of parts feeding policies for assembly systems, which is a relevant strategic problem when designing assembly systems. The proposed model can be used to plan a material feeding system in new facilities or to redesign an existing one in case of changes to system layout or when production mix and volumes change. This allows to explore trade-offs between alternatives in order to deploy customized feeding policies differentiated on components basis to better fit specific company requirements, simultaneously carrying out sizing of required resources (containers, storage equipment, workforce and vehicles). The methodology has general applicability to any manufacturing context and the model formulation is flexible enough to accomodate changes useful to better represent specific manufacturing systems. At present the model has been developed for the single-line, single-model application. This can be considered a limitation to be overcome by future research extending the model scope. However, the model can be extended to multi-product and multiple-lines cases. The extension of the model to a multiple-lines system is straightforward as the procedure is repeated for each line independently, and results are then aggregated. In case of a multi-model line the components requirements for the average production mix could be used. Nevertheless, this simplified approach would neglect issues related to variability of parts consumption at workstation. In this case a variable number of parts types should be fed to workstation according the production schedule, and safety stocks should be included to accomodate changes to parts consumption rates. Safety stock, used to hedge against demand variability is another factor neglected in this model which assumes a deterministic and constant demand.

The case study in the automotive sector demonstrated that policy selection can not be carried out resorting to simple guidelines and rules-of-thumbs, but requires careful analysis because counterintuitive results can be obtained. Nevertheless, the cost saving potential resulting from adopting multiple feeding policies is significant. A general conclusion is that, given the different characteristics and economic value of components feeding an assembly system, to adopt the same feeding policy to all components may not be the most cost-effective solution. However, no further generalizable conclusion can be obtained about the application of this tool, given that the choice of material handling solution depends from the specific context and from the priorities set by plant managers. Therefore, the same method can lead to different conclusions when changing scenarios.

To better appreciate the innovative contribution of this work, it has to be considered that most previous models were descriptive, discussing advantages and drawbacks of available policies and providing planning models for a single given policy, but did not provide a means to choose the right policy in a specific context. Moreover, this paper is based on expanded and novel formulations of costs and resource requirements for all of the three considered policies. Furthermore, earlier papers on the subject usually focus on kitting vs LS decisions only, and do not include JIT approaches in the comparison. Recently some papers dealt with design of JIT systems but, once again, not in comparison with other policies. Here all three policies are compared in an integrated manner within a prescriptive model, seeking a dedicated policy assignment to each part type based on a cost minimization approach. While this model includes a much higher number of cost items respect other models available in the literature, its main limitation lies in the fact that not all context-related decision factors are included yet, especially non-quantitative ones (such as obsolescence or quality-related issues, system flexibility and reconfigurability, implementation difficulty). In case of new system design some of the model parameters are likely to be unknown, but using average values from experience is generally enough to perform a preliminary planning of the material feeding system. In this case the capability of quickly performing sensitivity analyses by changing the parameters values proves to be a useful tool. It can be objected that optimization models are meaningful only if the input data can be anticipated with sufficient precision, since the solver will opportunistically exploit all aspects of the solution space. The model assumes that information about product structure and part requirements are known and that a preliminary design of the assembly system (i.e. line balancing) has been carried out. In the authors' opinion this is a reasonable set of input data, likely to be anticipated with enough precision even when the model is used at a "strategic" level, i.e. during the preliminary design of both the product and assembly system. In fact, the model does not require more detailed data than any other similar model existing in the literature.

As always happens the quality of the model's output strongly depends on the quality of input data. Responsibility for this is left to the user. As pointed out above, the kind of cost information requested to the user is usually well known to a plant manager. In case a cost data is not available an educated guess can be easily provided based on common industry values. Moreover, experience with practical application of the model in industrial firms showed no particular problem in this respect, and sensitivity analysis should always be carried out to verify the stability of the obtained solution. Finally, as happens in all additive models when random errors occur, it is credible that possible overestimation errors in one cost item can be compensated in the overall sum by an underestimation of other cost items. so that the overall results is suitably accurate. Furthermore, the case study showed that policy allocation is quite robust respect variation in parameters values, as it is more influenced by the product and assembly system structure.

7. Conclusions

In this paper an integer linear programming model has been developed to find the optimal feeding policy for each component to be delivered to an assembly line. Results show that the selection of items feeding modes is not a trivial matter and that given the different characteristics and value of components, to adopt the same feeding policy for all items can be a poor solution. Intuition-based approaches, qualitative assessments, or rules-of-thumbs can lead to unsatisfactory results as well, while the optimal choice resulting from item-by-item analysis allows significant savings provided that the organizational burden to arrange different concurrent feeding systems on the shop floor can be tolerated. Given that an optimal feeding policy allocation can not be obtained following predefined rules, and that optimal allocation usually prescribes different feeding policies to be assigned to items of the same size and value range, then the effectiveness of the suggestes approach respect an arbitrary policy selection is evidenced. It is expected that the proposed approach can represent a powerful and general purpose decision tool for production managers to assist in the selection of proper policies for components delivery to assembly systems at an early decision stage. Further research is needed to further extend the model application scope and capabilities. At first new descriptive models will be developed to account for other material delivery options (i.e. centralized/decentralized kitting or kitting at the supplier or at a third party logistic provider) and to increase their level of detail, also accounting for multiple products and multiple lines with partially common components.

Extension to multi-model lines with variable production mix seems to be especially relevant. This will allow to assess the influence of variable parts consumption rates at the workstation, a case where kitting would be favoured as it increases the WIP requirements at workstations. Layout imposed constraints or different architectures of the assembly systems should be also taken into account. A parametric scenario analysis is also needed to assess whether changes in product and assembly system structure as well as different degrees of product mix variability affect feeding policy selection. The role played by product attributes in the selection of parts feeding policies needs an in-depth evaluation. This could also help in devising possible rules for assigning parts feeding policies as a function of production scenario and product attributes. Another issue to be explored is the impact of container size on material flow and related cost. The model could even be extended to include delivery lot sizes as an optimization variable. An extension to the stochastic environment will also allow to factor in the product mix and demand variability issues as far as line-side safety stock requirements are concerned. Another issue to be investigated is the synergy or interaction between concurrent material feeding systems operating on the shop floor, as it can increase the management complexity. Finally, the impact of feeding policy on quality issues and on assembly line design and balancing deserves a specific attention being a field totally neglected by earlier reseach. However, the resulting increase in the level of detail would reduce the usefulness of the model in preliminary system design.

References

Battini, A., Faccio, M., Persona, A. and Sgarbossa, F. (2009), "Design of the optimal feeding policy in an assembly system", *International Journal of Production Economics*, Vol. 121 No. 1, pp. 233-254.

Boysen, N., Emde, S., Hoeck, M. and Kauderer, M. (2015), "Parts logistics in the automotive industry: decision problems, literature review and research agenda", *European Journal of Operational Research*, Vol. 242 No. 1, pp. 107-120.

Bozer, Y.A. and McGinnis, L.F. (1992), "Kitting versus line stocking: a conceptual framework and a descriptive model", *International Journal of Production Economics*, Vol. 28 No. 1, pp. 1-19.

Brynzér, H. (1995), "Evaluation of kitting systems: implications for kitting systems design", licentiate thesis, Dept. of Transportation and Logistics, Chalmers University of Technology, Göteborg.

Brynzér, H. and Johansson, M.I. (1995), "Design and performance of kitting and order picking systems", *International Journal of Production Economics*, Vol. 41 Nos 1-3, pp. 115-125.

Caputo, A.C. and Pelagagge, P.M. (2008), "Analysis and optimization of assembly lines feeding policies", *Proc. MITIP Conference, November 12-14, Prague*.

Caputo, A.C. and Pelagagge, P.M. (2011), "A methodology for selecting assembly systems feeding policy", *Industrial Management and Data Systems*, Vol. 111 No. 1, pp. 84-112.

Caputo, A.C., Pelagagge, P.M. and Salini, P. (2010), "Genetic algorithm for optimal selection of feeding policies in assembly systems", *Proc. 8th International Conference on Manufacturing Research ICMR10, September 14-16, Durham University, Durham*.

Caputo, A.C., Pelagagge, P.M. and Salini, P. (2012), "A linear programming approach for optimal selection of feeding policies in assembly systems", *Proc. EUROMA 4th Production & Operations Management World Conference, July 1-5, Amsterdam*.

Caputo, A.C., Pelagagge, P.M. and Salini, P. (2013), "Analysis and optimization of assembly lines feeding policies", *XVIII Summer School "Francesco Turco", September 11-13, Senigallia*.

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

Caputo, A.C., Pelagagge, P.M. and Salini, P. (2015b), "Planning models for continuous supply of parts in assembly systems", *Assembly Automation*, Vol. 35 No. 1, pp. 35-46.

Carlsson, O. and Hensvold, B. (2008), "Kitting in a high variation assembly line. A case study at Caterpillar BCP-E", master thesis, Lulea University of Technology, Lulea.

Cottyn, J., Govaert, T. and Van Landeghem, H. (2008), "Alternative line delivery strategies support a forklift free transition in a high product variety environment", *Proc. HMS 2008: 11th International Workshop on Harbor Maritime Multimodal Logistics Modeling and Simulation*, pp. 55-60.

Ding, F.Y. (1992), "Kitting in JIT production: a kitting project at a tractor plant", *IE Solutions*, Vol. 24 No. 9, pp. 42-44.

Faccio, M. (2014), "The impact of production mix variations and models varieties on the parts-feeding policy selection in a JIT assembly system", *International Journal of Advanced Manufacturing Technology*, Vol. 72 Nos 1-4, pp. 543-560.

Field, K.A. (1997), "Point-of use storage saves TI millions", *Modern Materials Handling*, Vol. 52 No. 7, pp. 42-44.

Fredriksson, P. (2006), "Operations and logistics issues in modular assembly processes: cases from the automotive sector", *Journal of Manufacturing Technology Management*, Vol. 17 No. 2, pp. 168-186.

Govaert, T., Bauters, K., Limère, V. and Van Landeghem, H. (2011), "Forklift free factory : a case study of different transportation systems in the automotive industry", *Proc. 9th Annual International Industrial Simulation Conference ISC2011, Centro Culturale Don Orione, Venice, Italy, June 6-8*.

Hanson, R. (2009), "On the options available in the design of in-plant materials supply systems", Licentiate Thesis Report No. L2009:031, Department of Technology Management and Economics Division of Logistics and Transportation, Chalmers University of Technology, Göteborg.

Hanson, R. (2012), "In-plant materials supply: supporting the choice between kitting and continuous supply", PhD thesis, Department of Technology Management and Economics Division of Logistics and Transportation, Chalmers University of Technology, Göteborg.

Hanson, R. and Brolin, A. (2012), "A comparison of kitting and continuous supply in in-plant materials supply", *International Journal of Production Research*, Vol. 51 No. 4, pp. 979-992.

Hanson, R. and Finnsgård, C. (2014), "Impact of unit load size on in-plant material supply efficiency", *International Journal of Production Economics*, Vol. 147, Part A, pp. 46-52.

Henderson, R. and Kiran, A.S. (1993), "Kitting elimination supports just-in-time principles", *Industrial Engineering*, Vol. 25 No. 3, pp. 46-48.

Hua, S.Y. and Johnson, D.J. (2010), "Research issues on factors influencing the choice of kitting versus line stocking", *International Journal of Production Research*, Vol. 48 No. 3, pp. 779-800.

Jainury, S.M., Ramli, R., Ab Rahman, M. N. and Omar, A. (2014), "Integrated set parts supply system in a mixed-model assembly line", *Computers & Industrial Engineering*, Vol. 75, September, pp. 266-273.

Johansson, E. (2009), "Information management for materials supply systems design", *International Journal of Production Research*, Vol. 47 No. 8, pp. 2217-2229.

Johansson, E. and Johansson, M.I. (2006), "Materials supply systems in product development projects", *International Journal of Operation and Production Management*, Vol. 26 No. 4, pp. 371-393.

Johansson, E., Bellgran, M. and Johansson, M.I. (2006), "Evaluation of materials supply systems during product development projects", *International Journal of Production Research*, Vol. 44 No. 5, pp. 903-917.

Kilic, H.S. and Durmusoglu, M.B. (2012), "Design of kitting system in lean-based assembly lines", *Assembly Automation*, Vol. 32 No. 3, pp. 226-234.

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

Limère, V. and Van Landeghem, H. (2008), "A decision model for line feeding", *Proc. 22nd National Conference of the Belgian Operations Research Society*, *January 16-18*, *Brussels*.

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

Limère, V., De Cock, K. and Aghezzaf, E.-H. (2013), "Generic simulation model for assembly line supply", *Proc. 11th Annual Industrial Simulation Conference*, pp. 192-197.

Limère, V., Van Landeghem, H. and Goetschalckx, M. (2015), "A decision model for kitting and line stocking with variable operator walking distances", *Assembly Automation*, Vol. 35 No. 1, pp. 47-56.

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

Medbo, L. (1999), "Material kitting system design", working paper, Department of Transportation and Logistics, Chalmers University of Technology, Goteborg.

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

Sohal, A.S. (1997), "Manufacturing reorganization at Varian Australia: a case study on value-added management", *Technovation*, Vol. 17 No. 6, pp. 329-339.

Vijaya Ramnath, B. (2010), "Development of lean kitting model for automotive industry", PhD thesis, Anna University, Chennai.

Vijaya Ramnath, B., Elanchezhian, C. and Kesavan, R. (2010), "Suitability assessment of lean kitting assembly through fuzzy based simulation model", *International Journal of Computer Applications*, Vol. 4 No. 1, pp. 25-31.

Wänström, C. and Medbo, L. (2008), "The impact of materials feeding design on assembly process performance", *Journal of Manufacturing Technology Management*, Vol. 20 No. 1, pp. 30-51.

About the authors

Professor Antonio C. Caputo was born in Genova, Italy on June 22, 1966. He received his Master's Degree in Mechanical Engineering from the University of Roma, La Sapienza, in 1991. In 1995 he obtained a PhD Degree in Mechanical Engineering and joined the Faculty of Engineering at the University of L'Aquila, Italy, where he was appointed Full Professor in Industrial and Plant Engineering. From 2010 he moved to the University of Roma Tre. In 1991-1992 he served as a volunteer in the Italian National Corps of Firefighters. His primary research interests include design of manufacturing systems, industrial logistics, production planning and control, industrial safety. Professor Antonio C. Caputo is the corresponding author and can be contacted at: acaputo@uniroma3.it

Professor Pacifico M. Pelagagge was born in Palermo, Italy on June 21, 1956. He received his Master's Degree in Chemical Engineering from the University of L'Aquila in 1979. In 1980 he joined the Faculty at the University of L'Aquila as an Assistant Professor, to become Associate Professor in 1987. He is currently a Full Professor in Industrial Plants at the same university. He served two years as an officer in the Italian Navy and then worked for the Italsiel Software Co. as a Consultant Engineer. His current research interests include design and simulation of manufacturing systems, production and operations management and plant utilities.

Dr Paolo Salini was born in L'Aquila, Italy, on February 8, 1980. He received his Master's Degree in Mechanical Engineering from the University of L'Aquila in 2005. After working in the field of thermomechanical integration of electronic components for Selex – Marconi Company, he earned a PhD Degree in Industrial and Plant Engineering at the University of L'Aquila. He is now a Research Assistant at the same university. His primary research interests include design of manufacturing systems, material handling and design of heat recovery systems.

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