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In a synchronous and fast-paced assembly line operation, it is crucial that the right parts are being supplied at the right time and at the right place. In automotive assembly, the need for efficient material handling part delivery is particularly great because of extensive product customisation and the lack of space to stock all the required parts at the assembly line. This paper introduces a mathematical cost model for evaluating the assignment of parts to one of two possible material supply systems: kitting or line stocking. Case data from an automotive company in Belgium is used to test the model. The results demonstrate that hybrid policies, where some parts will be kitted while others will be stocked in bulk at the line, are preferred to the exclusive use of either material delivery system. The factors influencing the preferred delivery method for individual parts are explored. Numerical results are presented.

Keywords: material handling; assembly lines; manufacturing management; kitting; line stocking

1. Introduction

Manufacturers of automotive vehicles face fierce competition and highly demanding customers. One way to achieve a competitive advantage is to adapt their assembly systems to mass customisation, so that they can provide the variety demanded by the customers while limiting their costs and maintaining their profitability. As a result, each vehicle coming off the line will be different from the one before and after it and will be equipped with specific options requested by a specific customer. The process is further complicated by the presence of variant parts. Variant components have multiple models of which one particular variant selected by the customer has to be on the line at the time required for the assembly of that customer's vehicle. An example of a variant part is the in-dash audio system. This leads to an increasing number of parts moving around in the assembly facility for delivery to assembly stations and to a much more complicated material supply process than in standard mass production. Mastering the new requirements for logistics and line organisation represents a valuable opportunity for companies to obtain an advantage over their competitors, and is the focus of this paper.

The planning process is further complicated by the diversity of parts being assembled at the line, ranging from small (e.g. bolts and brackets) to large and voluminous (e.g. wheel well liners and truck side mirrors). The size and weight of automotive components encourages production engineers to seek material feeding alternatives to traditional stocking at the line. Storing a full packaging unit – i.e. container or pallet or box – of each part number at the border of an assembly station would require a very large production area and line-operators would have to travel large distances to find the correct components. This is therefore not economically feasible. To address the need to reduce storage at the line and to better organise the border of the line, kitting of the assembly parts has been introduced.

Line stocking and kitting are two alternative material supply systems that are common in assembly systems. Line-stocking systems, sometimes referred to as bulk feeding, continuous replenishment or point-of-use storage systems, supply components to the assembly line in (homogeneous) individual component containers. Containers are stored close to the assembly workstations at the border of the line, and a two-bin or reorder point system is used

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to control replenishment. Kitting systems group together various components into one (heterogeneous) package according to a future assembly schedule and supply these kits to the line. The exact quantity of components required is stored in kit containers close to the assembly workstations at the border of the line, and replenishments are carried out according to the assembly schedule, which is based on the assembly cycle or takt time.

Both kitting and line stocking systems can offer operational benefits and disadvantages. However, research examining the factors that determine where each is best applied is limited. Companies lack the experience-based knowledge to guide decisions on where each type of system should be used (Hua and Johnson 2010). Hua and Johnson suggest that the product and component volume, variety and size may influence the choice. This research examines the relation between product and part characteristics and the optimal system of material supply. We develop a mathematical model that will select line stocking or kitting on an individual part basis to minimise the overall in-plant material handling costs. Based on the use of this model in an industrial case study, insight is gained in the trade-offs between kitting and line stocking and the way part characteristics and product mix influence this trade-off.

The remainder of this paper is structured as follows. Section 2 provides a brief literature review on kitting and line-stocking systems. Section 3 defines accurately the problem discussed in this paper and introduces some terminology. Section 4 presents the mathematical model. Section 5 describes a case study and Section 6 discusses the numerical results of the sensitivity analysis. Section 7 presents some conclusions and some directions for further research.

2. Literature review

A large number of studies exist that focus on the practical issues concerning the implementation of kitting as an alternative to line stocking. The problem of allocating a limited amount of available components to different kits that require the same components has been studied extensively (Chen and Wilhelm 1993, 1994, 1997, Chen 2003). The problem is extended to include additional assumptions on the substitution of parts. All models are developed to minimise total costs, including job earliness, job tardiness and in-process holding costs. De Souza *et al.* (2008) propose a model for deciding how to pack the necessary items in the available containers. The model strives to minimise holding and handling costs. The influence of uncertainty on kitting is also scrutinised. Choobineh and Mohebbi (2004) look at the positive effect of component sharing on kit availability, given variability in the procurement lead times of the components or varying demand. More theoretical derivations were shown about the work-in-process and the output of kitting operations that are subject to uncertain supply (Som *et al.* 1994, Ramachandran and Delen 2005). Kitting is also studied in relation to ergonomics. Medbo (2003) concludes that assembly work is definitively supported by the materials kit configuration. Christmansson *et al.* (2002) compare two alternative methods for materials kitting – i.e. picker-to-material and material-to-picker – with regard to muscular activity, work postures and movements. Brynzer and Johansson (1995) discuss a number of case studies yielding insight into the design of kitting systems and its influence on performance. Some issues discussed are the location of the kitting system, the work organisation behind the kitting operation, the relevance of a batching policy for picking the kits, the need for zone picking and the type of picking information used.

Other literature focuses on operationally organising and scheduling the part supply to mixed-model assembly lines (Klampfl *et al.* 2006; Boysen and Bock 2011).

Whereas the above studies concentrate on performance improvement of a kitting system that has already been implemented and on operational issues of part supply, we focus on the strategic choice to be made for each part between kitting and line stocking. Bozer and McGinnis (1992) were the first to introduce this problem. They propose a descriptive model for decision making at an early decision stage. The model facilitates a quantitative comparison between various kitting plans and line stocking, based on multiple criteria. The performance measures employed are the necessary storage and retrieval of component containers, the flow of component and kit containers, the shop floor space requirements, and the average work-in-process. The authors emphasise the preliminary nature of their model and encourage further research in the field. Carlsson and Hensvold (2008) adapt the model of Bozer and McGinnis and apply it to a real situation in vehicle manufacturing at Caterpillar. To optimise for the multiple criteria, the authors employ an analytic hierarchy process technique. Hybrid policies are examined, but no theoretical basis is provided for the selection of the delivery strategy for individual parts. Further elaborations of the model are done by Caputo and Pelagagge (2008). They distinguish between line-stocking, kitting and Kanban-based supply.

An ABC analysis is used as a basis for developing hybrid policies. No theoretical foundation for the proposed choices is provided either.

Battini *et al.* (2009) advocate an integrated approach to component management optimisation. They consider the centralisation/decentralisation decision of components and the right feeding policies in one comprehensive framework. Battini *et al.* take into consideration three assembly line feeding systems, i.e. pallet to workstation, trolley to workstation and kit to assembly line. The first system represents a line-stocking policy, where the latter two only supply the required items to the line (kitting). The model includes different costs in handling, picking and transport activities. Their focus is on multi-model assembly lines instead of high variation mixed-model lines. Part characteristics and hybrid feeding policies are not considered. Instead, a multi-factorial analysis is proposed for the determination of a single optimal feeding system for the complete line.

Hua and Johnson (2010) concede that, since the introduction of the problem of deliberately choosing between kitting and line stocking by Bozer and McGinnis, little research has addressed which system is best suited to particular environments, or what factors determine this choice. Moreover, some authors emphasise that their research shows kitting to be superior to line stocking (Ding 1992), while other research shows just the opposite (Henderson and Kiran 1993, Field 1997). Further research is therefore needed to understand the trade-offs between both systems.

3. Problem description

Consider the problem of designing a cost-effective material supply system. Without loss of generality, we consider an assembly line as the manufacturing organisation since it is the most demanding in terms of strict timing and the number and variety of parts consumed. Each individual part must be supplied to the line using one of two alternative supply systems, i.e. line stocking or kitting.

A *part* is any component or sub-assembly that will be supplied to the line for assembly. For specific parts (such as mirrors, radio systems, ...) multiple variants exist, from which the customer can select one and only one. A *part family* is the collection of all *variant parts* of a *part*, from among which the customer must select their preferred one. Each of the parts in a part family can be selected for assembly, but two different parts of the same part family will never be assembled together in one end product. For the moment we dismiss optional parts since, when not selected, often a placeholder part will have to be fitted. *Common parts* are parts that are the only element in their part family; no variants exist.

3.1 *Line stocking*

In line stocking, parts are supplied to the assembly workstations (WS) in packaging containers (often boxes, pallets or containers), which contain multiple instances of the same part. For efficiency, parts are fed to the line in the original supplier packaging. Hence full containers are stored at the *border of the line* (BoL). When the packaging container is a unit-load (i.e. a pallet or a special container), only a single unit package can be handled at a time, and forklifts are used for internal transport to the line. Unit-loads will usually be stored as a single bin at the BoL and replenishment will be controlled by a reorder-point inventory system. When the original packaging is not a unit-load but a small box, internal transport is often provided by a *tugger train* that carries out a *milk run* tour periodically. A tugger train consists of a motorised vehicle that pulls a number of un-powered trailers and drives a route with multiple stops. Boxes will typically be stored two to a part at the BoL and a two-bin inventory system controls the replenishment. Figure 1 represents the line-stocking material supply system.

3.2 *Kitting*

We build upon the definition of the kitting material supply system given by Bozer and McGinnis (1992). *Kitting* delivers specific sets of components and subassemblies to the shop floor in predetermined quantities, where each kit is collected, transported and stored in a specific container. A *kit* is a specific set of components and subassemblies that together support one or more assembly operations for one given end product. There are two types of kit: stationary kits and travelling kits. A *stationary kit* is delivered to a workstation and remains there until it is depleted. A *travelling kit* moves along with the end product and feeds several workstations before it is depleted. In this paper, we only consider stationary kits. Because each vehicle that comes off the assembly line

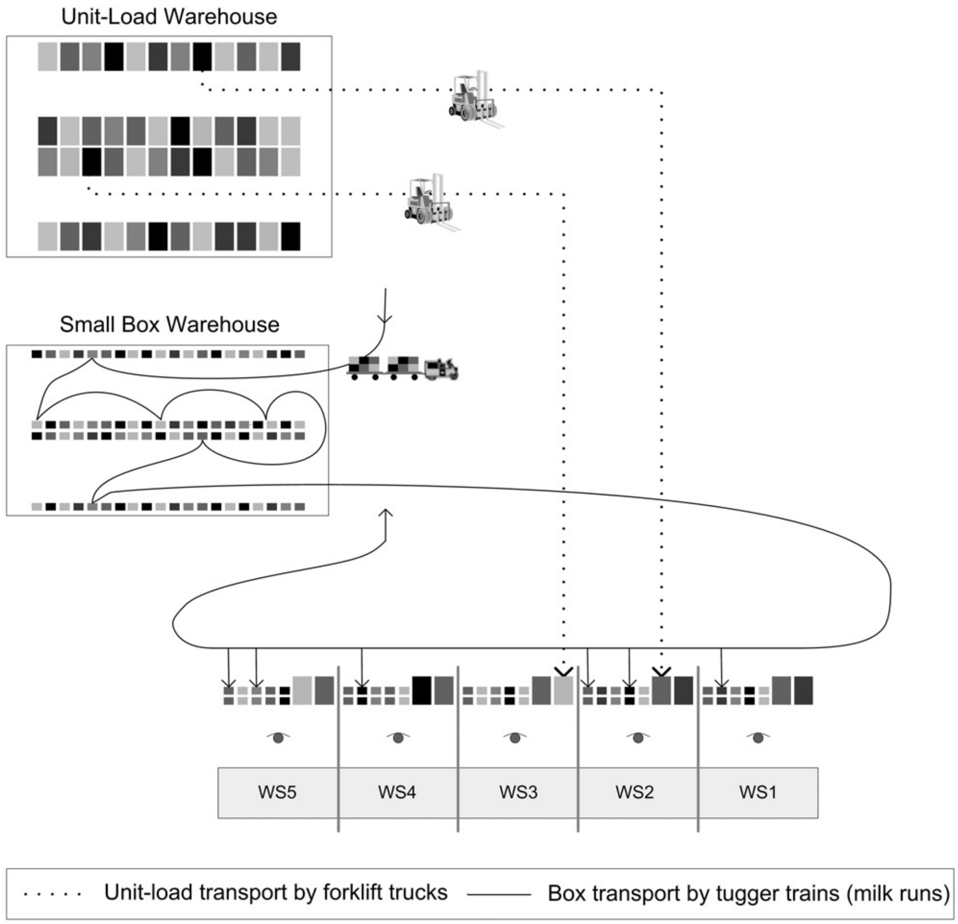

Figure 1. Line stocking.

is equipped with the particular models of the variant parts requested by the customer, each kit is different. Kits are therefore supplied to the line in sequence. Sequenced kits support the same assembly operations for consecutive vehicles, and therefore we say that they are of the same *kit type*. The content of a kit is constrained by a maximum weight and volume. *Kit containers* can contain multiple kits of the same type, and are transported to the workstations and stored at the BoL. We assume a kit container to be a rack with multiple levels, to store multiple kits in sequence. As one kit is consumed per takt time, kit container replenishments are carried out according to constant time intervals. We assume the kit containers are delivered by a tugger and internal transport is carried out as a milk run tour. Alternatively, kits could also be delivered one by one by conveyor systems.

Kit assembly is the extra material handling operation where all the parts that are required for a particular kit are physically placed in the appropriate place in the kit container. Different design options exist for a kitting system (Brynzer and Johansson 1995). The kit assembly operation can be performed in a central picking store or in decentralised areas close to the assembly stations. It can be performed by assembly operators or by special kitting operators. The parts that need to be kitted can be moved towards the operator (part-to-picker) or the operator can move to the picking locations (picker-to-part). In this paper, we assume a central picking store, called a *supermarket*, where kitting operators walk to pick the needed parts. We assume that the central picking supermarket is logically organised in picking zones, where an aisle represents a zone that contains all variant parts that can be consolidated in a kit for a certain workstation. Furthermore, we assume that multiple kits of the same type are assembled in batches. The supermarket is replenished from the unit-load warehouse and box warehouse, and stores pallets as well as boxes. This supermarket configuration has been observed in different vehicle manufacturing plants by the authors. Figure 2 illustrates the proposed kitting material supply system.

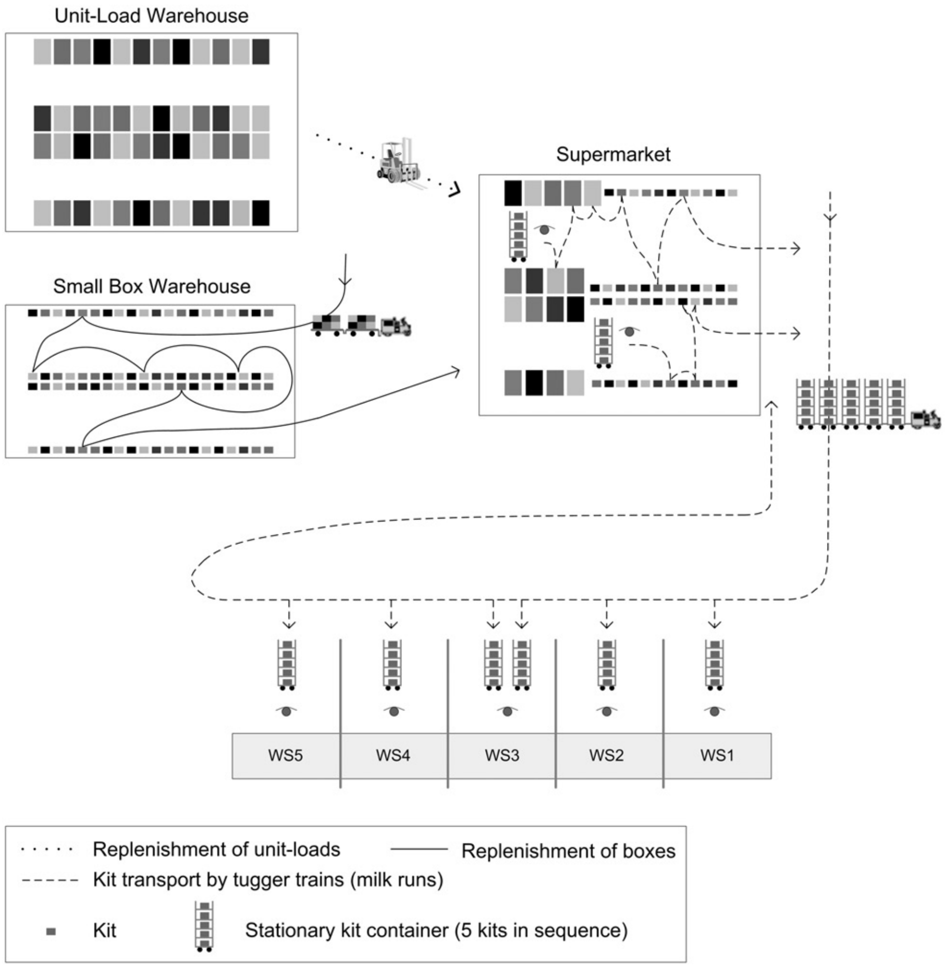

Figure 2. Kitting.

3.3 *Kitting versus line stocking*

Kitting offers some advantages over line stocking, but also involves some additional costs. Kitting advantages include:

- Reduced stock at the line means a more condensed BoL part storage and less operator travel to retrieve parts.
- Vehicle-specific kits reduce the time spent in searching for the correct part or subassembly.
- Since kits are consumed in synch with the takt time, it is easier to schedule kit replenishments than to schedule bulk replenishments, potentially improving material handling system efficiencies.
- Aside from the above, objectively quantifiable advantages, there is another advantage that is more qualitative. Kitting can improve the ergonomic conditions for the line operators. If the racks or bins for the kits are well designed, assembly workers can access parts in a more ergonomic, efficient way. Finnsgard *et al*. (2011) carried out a study to compare the ergonomic conditions for the assembly operator where components are exposed in wooden pallets versus smaller bins. The ergonomic conditions improved greatly, with a 92% reduction of potentially harmful picking activities, thereby almost eliminating potentially harmful body movements.

The disadvantage of kitting is the cost of assembling the kits, which involves an extra handling of the parts. This extra cost may be partly mitigated by the reduced handling costs within the assembly workstations. Moreover, kitting offers a decreased degree of flexibility in case of a defect or sequence change, as the sequencing point moves further away from the production line (Swaminathan and Nitsch 2007).

The improved ergonomic conditions and the decreased flexibility are factors that are qualitative and difficult to define in terms of costs. Therefore, these are left out of the model. Still, when developing a material supply strategy, these factors should be kept in mind.

4. The mathematical model

A mixed integer programming model is developed to assign individual part families to material supply system alternatives to minimise the total costs, given the average part and production mix characteristics. This is a static and deterministic optimisation problem, where the costs are the average yearly labour costs for operator picking at the line, internal transport, kit assembly operation and replenishment of the supermarket. Only operational running costs are taken into account. As no automation is considered, investment costs will be low compared to the cost of labour and are assumed to be negligible. The main decision for each part family is whether to kit or not. This decision is denoted by a binary decision variable x_{is}, which is one if a part i should be supplied to workstation s in bulk and zero if it should be kitted. Additional decision variables determine the number of kits in the system. Next, we will derive detailed expressions for the various cost components of the system. In the remainder of the section, the cost of an operator hour is denoted as OC.

4.1 *Picking at the line*

The labour cost for operator picking at the assembly line, denoted by C_{pick}, is influenced by the material supply method. On the one hand, the time to pick a unit of part i from a bulk container at station s, tp_{is}^{bulk}, is determined by the time the operator has to search for the required part in the bulk stock, τ^{bulk}, and the time to walk the distance to the container, Δ_{is}^{bulk}, back and forth at a walking velocity OV. It is defined by:

$$tp_{is}^{bulk} = \frac{2\Delta_{is}^{bulk}}{OV} + \tau^{bulk} \tag{1}$$

On the other hand, the time to pick a unit from a kit, tp^k, is determined exclusively by the time to walk the distance to the kit container, Δ^k, back and forth. The searching time is eliminated as the required parts are unmistakably presented to the operator in a kit.tp^k is represented by:

$$tp^k = \frac{2\Delta^k}{OV} \tag{2}$$

The labour cost for operator picking at the assembly line is then given by:

$$C_{pick} = OC \cdot \sum_{s \in S} \sum_{i \in I_s} q_{is}\left[x_{is} tp_{is}^{bulk} + (1 - x_{is}) tp^k\right] \tag{3}$$

Where q_{is} is the yearly usage of part i at station s.

4.2 *Transport to the line*

The internal transportation cost to the workstations, C_{tpt}, consists of the cost of transportation of unit-loads, boxes and kits to the line. Transportation of a unit-load is carried out as point-to-point transport by forklift trucks. The time to transport part i to workstation s is thus determined by the distance from the unit-load warehouse to work station s, D_s^p, back and forth, at a forklift truck velocity V^p, and by the number of unit-loads that need to be supplied to that station, i.e. the usage rate q_{is} divided by the packing quantity n_i. The cost for unit-load transport can then be defined by:

$$C_{tpt}^{pallet} = OC \cdot \sum_{s \in S} \sum_{i \in I_s \cap I_p} x_{is}\left(2 \cdot \frac{D_s^p}{V^p} \cdot \frac{q_{is}}{n_i}\right) \tag{4}$$

Transport of boxes is organised as milk run tours. Batches of boxes of different part numbers are supplied to the correct workstations on tugger trains. The mixed load is collected at the warehouse and the tugger train passes by all workstations, dropping off the parts at the correct use points. The time for one milk run is defined by the distance of the milk run tour, D^b, divided by the velocity, V^b. Furthermore, the yearly number of tours to the line depends on the number of boxes that need to be supplied to the station, i.e. q_{is}/n_i, on the capacity of the tugger train, A^b, and on the expected capacity utilisation of the tugger train, ρ^b. The cost for box transportation can then be defined by:

$$C_{tpt}^{box} = OC \cdot \frac{\sum_{s \in s} \sum_{i \in I_s \cap I_b} x_{is}(\frac{D^b}{V^b} \cdot \frac{q_{is}}{n_i})}{A^b \rho^b} \tag{5}$$

Transport of kits is organised as milk run tours as well. Batches of kits are supplied to the correct workstations on tugger trains. A tugger pulls several kit types at once and drops the kit containers/racks off at the use points at the stations. The time for one milk run is defined by the distance of the milk run tour, D^k, divided by the velocity to transport kits, V^k. Furthermore, the yearly number of kits that need to be supplied to the station is $K_s d$, where K_s is the number of kits needed at station s to assemble one vehicle, and d is the yearly demand for vehicles. The yearly number of tours to the line then depends on $K_s d$, on the capacity of the tugger train, A^k, and on the expected tugger capacity utilisation, ρ^k. The cost for kit transport finally is defined by:

$$C_{tpt}^{kit} = OC \cdot \sum_{s \in S} \sum_{i \in I_s} \frac{\frac{D^k}{V^k} K_s d}{A^k \rho^k} \tag{6}$$

It needs to be emphasised that the velocities in all three of the above transport formulas are average velocities of the material handling equipment, inclusive of stop times for loading and unloading.

The total transport cost is the sum of the costs for the three separate transportation types:

$$C_{tpt} = (C_{tpt}^{pallet} + C_{tpt}^{box} + C_{tpt}^{kit}) \tag{7}$$

4.3 *Kit assembly*

A third cost is the labour cost for the kit assembly operation, denoted by C_{kit}. The average time to pick a certain part i in the supermarket from its bulk container,tk_{is}, depends on the opportunity for picking multiple units of that part at once. We assume that multiple kits of the same type are assembled in batches. This opportunity for batch picking is constrained by the batch size in which kits are assembled, B^k, the usage frequency of part i at station s, q_{is}/d, the number of units of part i assembled at station s per vehicle, m_{is}, and physical characteristics (weight, volume) that determine the maximum number of units of a part i that can be manually picked, a_i. The opportunity for batch picking part i to assemble it in a kit for station s, θ_{is}, i.e. the number of units of part i that will on average be picked in one pick when the part is kitted, is then defined by: $\theta_{is} = \max\left\{\min\left(\frac{q_{is}}{d} B^k, a_i\right), \frac{m_{is}}{\lceil m_{is}/a_i \rceil}\right\}$. Obviously θ_{is} cannot be less than 1. The average time allocated to picking one unit from a bulk container of part i to kit for station s, tk_{is}, is then defined by the time the operator has to search for the required part in the supermarket stock, τ^k, the time to walk the distance to the container, Δ_{is}^k, back and forth at a walking velocity OV, and θ_{is}:

$$tk_{is} = \left(\frac{2\Delta_{is}^k}{OV} + \tau^k\right) / \theta_{is} \tag{8}$$

The labour cost for kit assembly is:

$$C_{kit} = OC \cdot \sum_{s \in S} \sum_{i \in I_s} [(1 - x_{is}) q_{is} tk_{is}] \tag{9}$$

4.4 *Replenishment of the supermarket*

The labour cost for the replenishment of the supermarket, C_{repl}, is determined by a constant cost for the replenishment of one box, R^b, and a constant cost for the replenishment of one pallet, R^p. The total replenishment costs can then be defined as:

$$C_{repl} = \sum_{s \in S} \sum_{i \in I_s \cap I_p} \left[(1 - x_{is}) \frac{q_{is}}{n_i} R^p\right] + \sum_{s \in S} \sum_{i \in I_s \cap I_b} \left[(1 - x_{is}) \frac{q_{is}}{n_i} R^b\right] \tag{10}$$

The complete model is given next.

$$\text{Min } C_{total} = C_{pick} + C_{tpt} + C_{kit} + C_{repl} \tag{11}$$

Subject to,

$$K_s \geq \sum_{i \in \mathrm{I}_s} \left[(1 - x_{is}) \cdot \left(\frac{m_{is} w_i}{|V_i|} \right) \Big/ w^k \right] \quad \forall s \in S \tag{12}$$

$$K_s \geq \sum_{i \in \mathrm{I}_s} \left[(1 - x_{is}) \cdot \left(\frac{m_{is}/\nu_i}{|V_i|} \right) \right] \quad \forall s \in S \tag{13}$$

$$\sum_{i \in I_s \cap I_b} \left(x_{is}/H^b \right) \leq N_s^b \quad \forall s \in S \tag{14}$$

$$N_s^b L^b + \sum_{i \in I_s \cap I_p} x_{is} L^p + K_s L^k \leq L_s \quad \forall s \in S \tag{15}$$

$$x_{is} = x_{js} \quad \forall s \in S,\ \forall i \in I_s,\ \forall j \in V_i \tag{16}$$

With,

K_s	Integer auxiliary variable Number of kits needed at station s to assemble one end product
N_s^b	Integer auxiliary variable Number of facings needed to store boxes along station s (with vertical stacking of boxes)
m_{is}	Number of units of part i assembled per vehicle at station s
w_i	Weight of part i
V_i	Set of variant parts of $i \in I$; the family of part i
w^k	Weight constraint on one kit unit; maximum weight per kit
ν_i	Number of units of part i that a kit can maximally hold; this categorical parameter represents the volume (small, medium, large, extra-large) of a part i {100, 20, 5, 1}
L^b	Length of a box along the line
H^b	Vertical stacking height of boxes (units) at the BoL
L^p	Length of a pallet along the line (we assume no stacking of pallets at the line)
L^k	Length of a kit container/rack along the line (we assume no stacking of kits containers at the line)
L_s	Available length along workstation s

Constraints (12) and (13) are, respectively, the weight and volume constraint for kits. More than one kit is needed at a station $s(K_s > 1)$ if the total weight of all parts kitted at station s exceeds the limit w^k (12). More than one kit is needed at a station $s(K_s > 1)$ if the total volume occupation (%) of all parts kitted at station s exceeds 100% (13). Division by the cardinality $|V_i|$ ensures that if a part family consists of multiple variant parts only one free space needs to be provided in the kit, as only one of the variant parts will be required per end product. Equation (14) calculates the required length along workstation s to store the boxes supplied in bulk at the BoL, given that they can be stacked vertically. Constraint (15) represents the space constraint at the line. We assume that picking at the line is done from one facing, i.e. the space constraint at the line is one-dimensional. The space required for boxes, pallets and kits is limited to L_s, the available length along workstation s. Constraint (16) ensures that, if one part in a family is assigned to a certain supply system, all variant parts are assigned to the same system. This assumption is made as the result of practical implementation considerations.

4.5 *Possible extensions of the model*

Note that at the moment walking distances are provided in the model as averages. In the future, the model can be refined with more realistic walking distances, taking into account that the operator has to walk in a triangular manner because of the steadily moving conveyor belt, and including walking distances that depend on the required storage space at the BoL. This will, however, turn the model into a non-linear formulation. More research is needed to determine the different impacts on operator walking distances.

Moreover, one constant operator cost per hour is used in the model. Often, wages of assembly workers are much higher than those of logistics workers, who can be subcontracted. A single parameter OC for both kinds of worker influences the results in favour of line stocking. The model can be easily adjusted to include two separate parameters, OCP for production operators, and OCL for logistics operators.

Finally, distances are provided for the milk run tours of boxes and kits. These are the distances of routings passing at all pick-up and drop-off stations. The milk runs and the according distances obviously can change depending on the number and types of part selected for this kind of part delivery. In our model we choose to model constant distances because we tactically approach the problem, and we do not focus on operational issues. For instance, we note that the two milk run tours in reality can be a single tour transporting both kits and boxes at once. To obtain the desired result, multiple iterations can be done with the model, changing the milk run distances at every iteration.

5. Case study

Data was obtained from a truck manufacturing company. The assembly line produces medium duty trucks in a one shift operation. The line consists of 94 stations. Parts that are currently supplied to the line in-sequence from suppliers are out of scope of the study. Small parts that are supplied in small cardboard boxes are also omitted from consideration. We assume a kit container to be a rack with multiple levels, to store multiple kits in sequence. Parts that do not fit in a kit either because of the weight constraint or because of the volume constraint are filtered out of the database. These parts will be supplied to the line in bulk. The remaining 1773 parts are assigned either to line stock or kitting, using the proposed optimisation model.

Figure 3 shows the structure of the input data. In the first place, each part i is characterised by a number of parameters. Figure 3 represents all the parameters, and also shows connections between parameters that are related in some way. Parts are delivered in boxes or in pallets and this original packaging entity is represented by $packing_i$. In the case data set, 72% of the parts are delivered in boxes, and the remaining 28% are delivered on pallets. The number of units of a part in its packaging unit n_i ranges from one to 6050 for boxes and from 13 to 1800 for pallets. The weight of one unit of a part is between five grams and 45.5 kilograms. For parts that are supplied in boxes, the weight is lower and varies between five grams and 4.25 kilograms. Parts supplied on pallets are generally heavier; the weights vary between five grams and 45.5 kilograms. For volume, we can see the same relationship with the original packing. For parts in boxes, between one and 6050 units fit in one kit. For parts on pallets, this is less, and only one to 112 units fit in one kit. The maximum number of units of a part i that can be manually picked, a_i, is determined by the physical characteristics (weight, volume) of a part. Either one, two, five or ten parts can be manually picked in one pick. The bill of material sets m_{is}, and it ranges from one to 34 units of part i assembled per vehicle at station s. Parts with a high m_{is} are often smaller parts. The frequency of trucks in which part i is assembled at station s is f_{is} and it varies between 5 and 100%. The yearly usage rate q_{is}, set by m_{is} and f_{is}, goes from 175 units for slow movers to 89,250 for very popular parts. Table 1 summarises the part parameters.

Aside from individual part parameters, every part i also belongs to a part family V_i. If a part family is assigned to the kitting system, space to store the multiple variants at the line in bulk will be freed up. The number of variant parts a customer can choose from is referred to as the cardinality of the part family. In the case data set, the cardinality of the part families, $|V_i|$, ranges from one to 16.

Finally, parts have to be supplied to a workstation s at the line. If a station receives many parts, the opportunities for kitting increase, as will the tendency for larger and denser kits. If this happens, the transport cost of the kit can be spread over more parts and kitting will become more attractive. In the case data set, the stations receive between one and 74 parts. The weight and volume constraints determine how many kits will be needed at the station for the assembly of one end product.

Additional case features are specified in Table 2. We assume that storage areas are organised in an intelligent and efficient way. Therefore, the average operator walking distances at the line and in the supermarket are longer for slow-movers and shorter for high-usage parts.

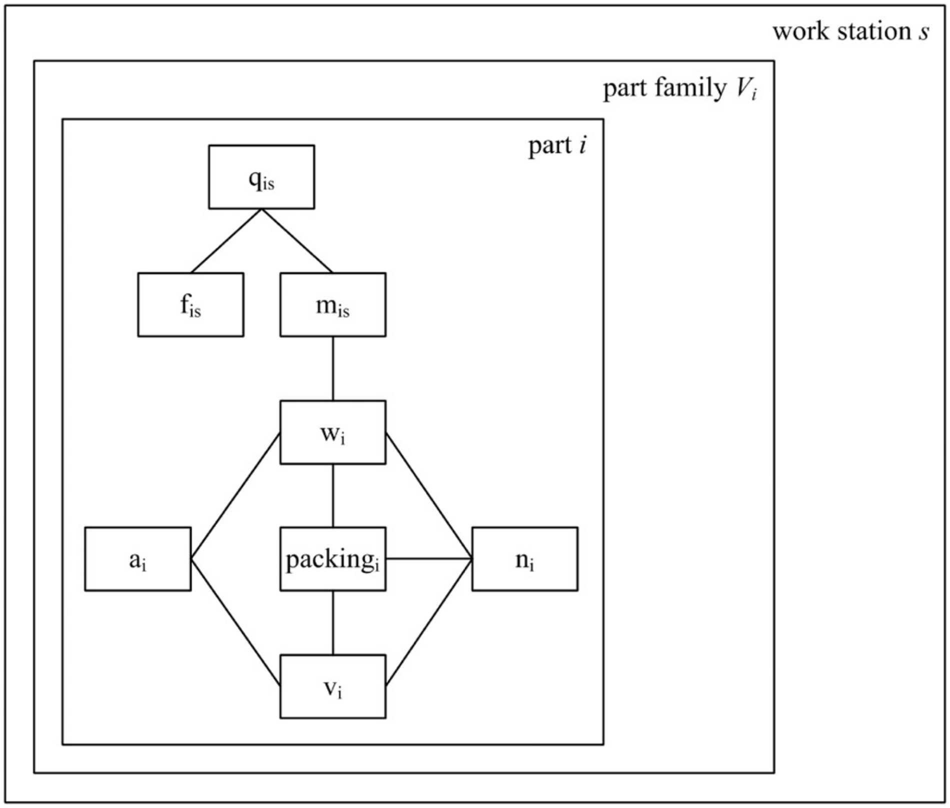

Figure 3. Structure of the input data.

Table 1. Part parameters.

Parameter	Value
Number of stations	94
Number of parts to a station	[1–74]
Number of parts in a part family	[1–16]
Packing	72%box– 28%pallet
n_i, of a box (units)	[1–6050]
n_i of a pallet (units)	[13–1800]
w_i of a part (kg) in a box	[0.005–4.25]
v_i, of a part (units kit) in a box	[1–6050]
w_i of a part (kg) in a pallet	[0.005–45.5]
v_i of a part (units/kit) in a pallet	[1–112]
m_{is}	[1–34]
f_{is}	[0.05–1]
a_i	{l;2;5;10}
q_{is}	[175–89,250]

6. Computational results and discussion

The mathematical model is implemented using the modelling language AMPL 11.2, and solved with CPLEX 11.2 on an Intel Centrino Duo 1.67 GHz with 2 GB RAM memory. Table 3 presents the main results for the problem instance described in the previous section. The total cost of the optimal assignment is €371,862 per year. In this optimal allocation, 1027 parts will be supplied to the line in bulk and 746 parts, or 42% of the parts, will be supplied to the line in kits in sequence. These parts constitute a total of 50 kits delivered to 37 of the 94 stations.

Table 2. Case parameters.

Parameter	Value
OV (m/h)	3600
OC (€h)	30
Δ_{is}^{bulk} (m)	
$q_{is} > 2500$	2
$2500 > q_{is} > 800$	2.5
$q_{is} < 800$	3
τ^{bulk} (h)	0.0003
Δ^k (m)	1.5
Δ_{is}^k (m)	
$q_{is} > 2500$	2
$2500 > q_{is} > 800$	2.5
$q_{is} < 800$	3
τ^k (h)	0.0003
B^k (number of kits)	5
D_s^p (m)	[54–302]
V^p (m/h)	2880
D^b (m)	1640
V^b (m/h)	2412
A^b (number of boxes)	60
ρ^b	0.5
D^k (m)	1640
V^k (m/h)	2412
A^k (number of kits)	70
ρ^k	0.8
R^b (€)	0.2
R^p (€)	1.2
w^k (kg)	50
L^b (m)	0.8
H^b (number of boxes)	4
L^p (m)	1
L^k (m)	0.8
L_s	8

Table 3. Main results of the case study.

	Total cost (€ year)	# of parts kitted	# of kits
Optimum	371,862	746 (42%)	50
All bulk	325,834	0 (0%)	0
All kitting	600.688	1773 (100%)	253

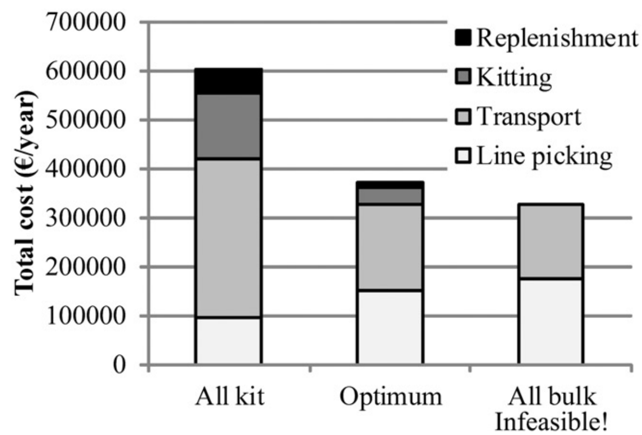

Figure 4. Detail of the cost subdivision.

We also calculated the total costs for the same industrial problem instance if all items would be supplied to the line in bulk, and if all items would be kitted. If the problem instance is solved to optimality without space constraints, all parts will be assigned to bulk feeding (line stocking). We notice that the 'all bulk' scenario at €325,834 per year is cheaper than the optimum. The reason for a higher cost optimum is the available space at the BoL, which is constrained to eight metres per station. The 'all bulk' scenario is therefore in reality not a feasible solution. In contrast, the 'all kit' scenario at €600,688 per year is much more expensive than the optimum. Although 42% of the parts are kitted in the optimal case, the 50 kits only constitute 20% of the kits in the 'all kit' scenario and the total cost does not increase proportionally with the number of parts kitted.

Figure 4 shows the cost details. The 'all kit' scenario leads to increased internal transportation costs. Kits are composed per station and the density of this composition cannot be ensured. Even with the expected filling degree of milk run tours for kits being higher, transportation will be less efficient. Meanwhile, the line picking costs have decreased. However, additional material handling operations are required for the kit assembly and the replenishment of the supermarket, through which the decrease in line picking costs is offset. Looking at the optimal costs, it can be seen that the change in costs with regard to the 'all bulk' scenario is limited. Kits will be composed in such a way that transport efficiency is not significantly reduced and additional material handling costs are limited. Figure 5 shows the space that is used along the BoL of each of the stations. For the 'all bulk' scenario, this amounts to 25.6 metres. For the optimal assignment, the space along the border is bounded to eight metres. For stations where this can be achieved by supplying everything in bulk, no changes are made. For the other stations, parts are kitted until the space needed at the BoL goes below eight metres. If at this time the kits are not full, additional parts for which the total cost will decrease can be fitted. These parts will be 'free riders' because the transportation cost for the kit is already charged to the solution and does not need to be increased any more.

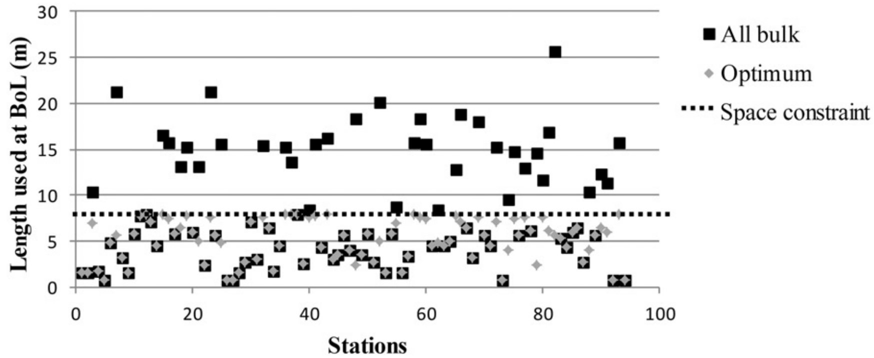

Figure 5. Length used at the border of line of the station.

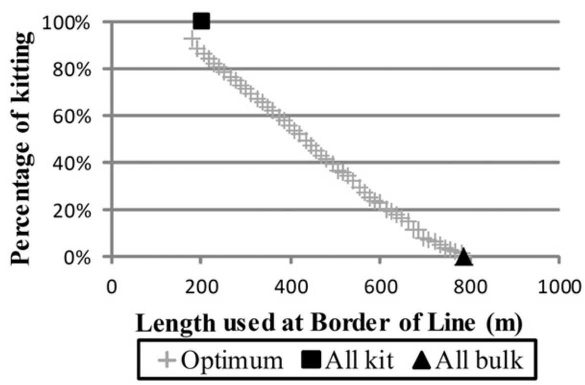

Figure 6. Length used at the border of line as the percentage of kitting changes.

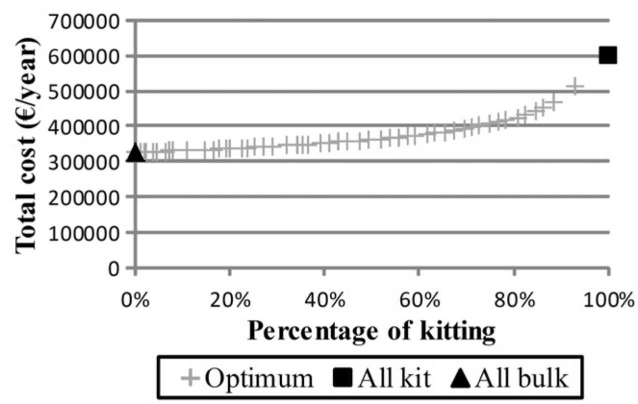

Figure 7. Total cost as the percentage of kitting changes.

In Figure 5 it can be seen that there is much 'free riding' when the space used at the BoL goes from above eight metres in the 'all bulk' scenario to way below eight metres in the optimal assignment policy.

Noticing the lower cost for the 'all bulk' scenario, but realising at the same time the infeasibility of this solution because of the space constraint, we were interested in seeing the evolution of the costs when stations become smaller and space becomes increasingly constrained. Decreasing the space along the BoL of the stations below eight metres soon led to infeasibility because some stations will still need a lot of space even if parts are kitted. This is the case if parts are voluminous. Therefore, in a slightly adjusted model we did not allocate space to stations, but to the complete BoL. The constraints (4) are replaced by one global constraint:

$$\sum_{s \in S} \left(N_s^b L^b + \sum_{i \in I_S \cap I_p} x_{is} L^p + K_S L^k \right) \leq LL \tag{17}$$

When the adjusted model is solved to optimality, the allocation of the border of the line space to the stations will be generated and for each individual part the most cost-effective material supply method is selected. Figures 6 and 7 illustrate what happens if the total space allocated to the line is changed. The 'all bulk' scenario and the 'all kit' scenario are also marked on the graph. When space becomes more constrained, a linear increase in the percentage of kitting leads to a more than linear increase in total costs. Above 50 to 60% of kitting, the costs increase considerably. It needs to be remarked that, to allocate space to stations, this adjusted model does not take into account work content. The focus is instead on the constraint on line storage space.

To validate the model further, additional part datasets were created through Monte Carlo simulation, based on the characteristic distributions of the original data. In Table 4 some information about the datasets and runtimes is summarised. Table 5 presents the results.

Table 4. Test datasets.

	# of parts	# of part families	# of stations	CPU time (s)
Input 1	1815	692	104	1.625
Input 2	1826	756	95	1.234
Input 3	1755	707	92	1.250
Input 4	1768	703	93	1.063
Input 5	1741	735	96	1.781

Table 5. Results from test datasets.

	All bulk	All kitting		Without space constraint			With space constraint		
	Total cost	Total cost	# kits	Total cost	% kitting	# kits	Total cost	%kitting	# kits
Input 1	328,116	588,469	233	326,749	1.7%	3	377,504	42.8%	54
Input 2	425,269	721,287	296	425,269	0.0%	0	477,786	43.5%	53
Input 3	330,577	573,396	217	329,421	2.5%	3	367,545	36.3%	42
Input 4	342,657	594,748	225	342,340	0.9%	1	391,379	40.6%	**53**
Input 5	393,741	693,333	264	391,876	3.4%	6	444,344	39.1%	55

We notice that, contrary to the original dataset, in four of the five datasets some kitting is proposed even without imposing a space constraint at the line. This means that some parts exist for which the overall cost for bringing these parts to the line in kits is lower than the cost to feed them to the line in bulk. Either the double-handling of the parts, when kitting them first and later picking them from kits, is cheaper than the single handling of picking from bulk at the line, or the transport in kits is more efficient than the transport in bulk. As can be seen from the results, these kinds of part are rather limited.

The results show that in all datasets parts exist that are 'free riding'. Indeed, the percentage of kitting is not spread over the same percentage of kits but there is a clustering effect. Once a station receives a kit, additional parts at the station can benefit freely from this kit transport, i.e. if the weight and volume constraint of the kit allows it. Moreover, the more than linear increase in costs with an increasing portion of kitting can also be validated for all datasets.

Finally, we were interested in identifying general characteristics that make a part and its part family a desirable candidate for kitting. The parts that are kitted to satisfy the space constraints are characterised by the following:

- *Parts that free up a lot of space at the BoL but do not incur a lot of extra costs*. Variant parts belonging to part families with a high cardinality need only one space in the kit, whereas much space is freed up at the line by removing multiple part containers.
- *Parts that can be kitted efficiently*. If a large advantage can be gained from batch picking in the kitting area, the double-handling resulting from kitting does not have to be much more expensive than picking parts from bulk. If such parts can be 'free riding' in a kit, the extra cost of double-handling might be offset by economising on the bulk transportation cost.
- *Smaller parts have an advantage over large parts*. The reason for this is that smaller parts have a higher chance of fitting in an existing kit, and will thus rather benefit from 'free' transport.
- *Parts in pallets free up more space at the line*. If a part is supplied on a pallet it will rather be kitted than another part that is supplied in a box given that both parts occupy the same space in a kit. The reason for this is the elimination of abundant stock at the line.

7. Conclusions and directions for future research

To guarantee efficient operation, an assembly line needs to be fed by the right materials at the right time and at the right place. Kitting and line stocking are two different line-feeding methods that are both widely found in industry.

Each method has its advantages and disadvantages and both methods have proponents and opponents. The lack of knowledge about the trade-offs involved for each method and the lack of a mathematical model to guide the selection process has led to intuitive decision making and even controversy. This research addresses both of these gaps, and provides a new methodology to investigate the trade-offs between kitting and line stocking.

The key contribution is a mathematical cost model for the selection of the appropriate material supply method. This model offers the opportunity to select for each individual part the material supply method that is most cost-effective for the overall material delivery system.

The model is applied to case study data from the automotive industry. The numerical results show that kitting all parts is not a cost-efficient way to mitigate the shortage of space at the line. To avoid a steep increase in costs, which would result from kitting all parts, a fraction of the parts is identified for kitting by the model that minimises the total cost while satisfying the space constraint. The kitted parts are further analysed and guidelines are presented for their selection.

The proposed model is a first attempt to fill a gap in the international scientific literature related to kitting. The model takes into account the part characteristics and practical constraints impacting the development of hybrid feeding policies. The case study demonstrates its potential value to industrial decision makers since cost savings of 38.1% were achieved compared to the 'all kitting' solution.

Further research is needed, and should address in more detail the design of kitting systems. Also, the model should be tested on additional case studies to establish the validity of the results across a wide variety of applications. Moreover, it would be interesting to compare results of this static and deterministic model with results from a dynamic simulation study. This will give an additional understanding of the impact of production variations and other dynamic effects.

Acknowledgement

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