Modeling variable space in assembly line feeding ⋆

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Abstract: Recently, feeding assembly stations with parts is becoming more and more difficult. This is especially true for complex products with a large variety of individual models and an increasing number of parts. The consequential lack of space at assembly stations requires not only to rethink feeding methods but also sizing assembly stations. In this paper, we show how both considerations can be taken into account within a single optimization model.

Keywords: Logistics, Optimization, Intelligent manufacturing systems, Linearizable systems, Deterministic system

1. INTRODUCTION

Multiple industries like aircraft, railway, agriculture technology or automotive are using assembly lines to finalize products by merging multiple parts. Due to technological innovation these products become more and more complex, but production numbers are decreasing due to glutted markets, and an increasing number of product variants. Therefore, a very recent trend is the assembly of multiple customized product models on a single assembly line. This increases the amount of parts that need to be handled in assembly systems.

The assembly line feeding problem was mainly introduced in the seminal paper of Bozer and McGinnis (1992). In this paper the decision between providing full pallets (called: line stocking) to an assembly line and mixed containers with different parts and their variants (called: kits) was introduced. This first descriptive model has been complemented by optimization models like those of Battini et al. (2009), Limère et al. (2012) or Sali and Sahin (2016), which do not only decide about the application of one option for an overall system, but on the application of one of these options for every single part. Furthermore, other line feeding options, next to line stocking and kitting, have been introduced, and a first approach is proposed for making an integrated decision on line feeding and line balancing (Sternatz, 2015).

Within this paper we provide a smart decision model to optimize assembly line feeding incorporating all relevant line feeding policies, extending the model of Limère et al. (2015) by kanban, sequencing and traveling kits. Additionally, we want to tackle the problem of increasing space requirements in industry by making not only a decision on the line feeding policy per part but also on the size that is available to store parts for every single station. Lastly, we include assembly of multiple products on a single assembly line as it is also done in industry. All these aspects have not been treated in the literature so far. Aiming for a cheap and feasible way to provide all parts we take all interrelated process steps from central storage to final assembly into account.

The outline of this paper is as follows: In the next section, we delineate the scope of this research. Within the two succeeding sections a MILP model is proposed. Afterwards, in section 5 some results from first experiments are included before the paper is summarized in section 6.

2. THE ASSEMBLY LINE FEEDING PROBLEM

The assembly line feeding problem (ALFP) describes an unambiguous assignment of every single part i to a line feeding option w by using a binary decision variable x_{iw} to indicate if part i is assigned to policy w. Within this paper, we distinguish five different line feeding policies, namely line stocking $w = L$, kanban $w = D$, sequencing $w = S$, stationary $w = K$ and traveling kitting $w = T$. An important difference of these line feeding policies is the way of providing parts for assembly. In line stocking, homogeneously filled pallets are provided to the assembly operator. In kanban, smaller boxes, which are also homogeneously filled, are provided on racks. Sequenced containers contain different variants of parts sorted in the order of demand. These variants belong to the same family $f \in F$. In kitting, variants of multiple families are sorted into kit boxes. Stationary kits contain only parts required by a specific single station, whereas traveling kits contain parts for multiple stations. In the latter case, kits travel along the line with the product. Kits are specified for a product $p \in P$ that has to be assembled. Figure 1 depicts the presentation of parts at the border of line (BoL) which describes the area dedicated to store parts at every station.

Line feeding policies not only determine the way how parts are provided, but also processes that are necessary to do so. We make the following common assumptions. Line stocked parts are stored on pallets in a storage and brought to

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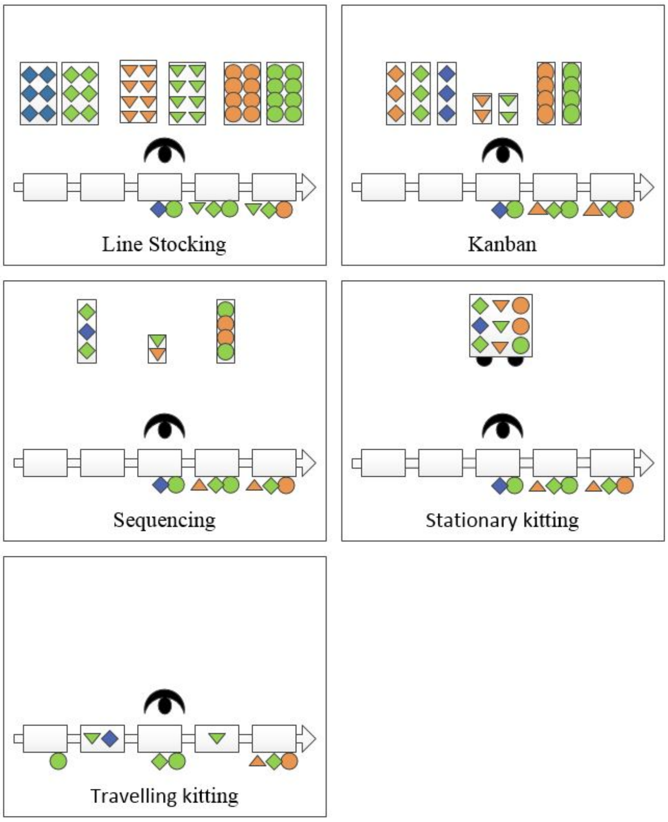

Fig. 1. Line side presentation with different line feeding policies

stations by a forklift. Kanban fed parts are prepared in an intermediate preparation area, meaning that they have to be transported from a storage to that preparation area, where some parts from a pallet are put into a smaller bin which is transported to the station to be stored in racks. For sequencing, different part variants of the same part family are sorted into a container in a preparation area and brought to the line by a tow train. A kit contains variants of multiple part families, but only for a single product. However, multiple kits can be transported in one kit container. Preparation of kits is done in a preparation area as well. Afterwards a tow train transports all containers and bins to the stations by performing a milk-run passing by all stations. In case of traveling kits, transportation is only required to the beginning of the assembly line.

For a better understanding, some important general assumptions of the model are summarized in the following.

Assumptions

(1) Demand is assumed to be deterministic.
(2) Parts can be stored either at the station where they are used or at an adjacent station. The latter is referred to as space borrowing.
(3) For every line feeding policy, a generic size for load carriers is assumed. E.g., all sequenced parts are transported in cart containers with a specific volume.
(4) At every station at most one stationary and one traveling kit can be used at the same time.

3. MODELING COSTS, TAKING INTO ACCOUNT VARIABLE SPACE

In assembly line feeding mainly five processes take place: storage of parts, preparation of parts, transportation, line side presentation and usage. All processes, except line side presentation, cause handling costs which are explained in the following. All costs are reflecting average costs over one time period.

$$TC = CS + CP + CT + CU \tag{1}$$

Equation 1 describes total costs (TC), which have to be minimized, and consist of storage costs (CS), preparation costs (CP), transportation costs (CT) and usage costs (CU). These are explained in the following in more detail.

3.1 Storage costs

After receiving parts from a supplier or a preceding production stage and ensuring quality requirements, parts are stored in an intermediate storage area. In our model it is assumed that one central storage area is solely used for storage and retrieval of full pallets which can be used to feed the line in a line stocking manner or to replenish the preparation area.

$$CS = LOC \cdot \sum_{i \in I} \sum_{w \in W \setminus \{L\}} \frac{x_{iw} \cdot \lambda_i}{n_{iL}} \cdot \frac{2 \cdot fr}{\mu_L \cdot VV_L} \tag{2}$$

Equation 2 describes storage costs for replenishing preparation areas, by summing all part demands λ_i, not being fed in a line stocking manner, divided by the amount of parts on a pallet n_{iL}, and calculating the required time for transporting these parts over the distance fr from a central storage to preparation areas by dividing through the velocity VV_L and utilization rate (see section 3.3 for further explanation) of forklifts. This is multiplied with the wage of logistical operators LOC.

3.2 Preparation costs

Preparation describes the process of changing the constellation of load carriers, used to provide parts at work stations. Operations of this process are varying with the chosen line feeding policy. Preparation costs are calculated by summing preparation times CP_w over all line feeding policies, multiplied with workers wage LOC.

$$CP = LOC \cdot \sum_{w \in W} CP_w \tag{3}$$

The major difference in part preparation for different line feeding policies is due to varying walking distances and batch sizes.

Line stocking In case of line stocking, no preparation is needed because forklifts deliver parts directly from their central storage location to the respective station.

Kanban We assume, that parts are stored in a preparation area on pallets replenished from a storage. When parts are needed at the assembly line, a logistical worker collects a batch with size bs_D of empty bins on a trolley, goes to various part locations, repacks small amounts of parts from pallets into bins and finally carries the homogeneously filled bins to the output point of the preparation area (Brynzer and Johansson, 1995). The average walking distance is around half of the aisle length AL_D but has to be taken into account twice for walking back and forth. The costs per part mostly depend on the demand λ_i and the number of parts that fit into one bin n_{iD}. It is assumed, that batches consist of parts stored quite close to each other, not affecting the average walking distance. Workers also need some time st to search for parts that are on the pick list. Finally, handling time ht_{iD} for putting a part in a bin is considered.

$$CP_D = \sum_{i \in I} x_{iD} \cdot \Big[\frac{\lambda_i}{n_{iD}} \Big[\frac{AL_D}{bs_D \cdot OV} + st\Big] + ht_{iD} \cdot \lambda_i\Big] \quad (4)$$

Sequencing For the preparation of sequenced parts, a logistical worker takes a cart container and moves it to the area, where the required part family is stored. Then parts are sorted into that container in the order of demand while walking between the storage location of different part variants. Walking distances between multiple variants of the same family are approximately estimated with an average value wf. Parts of the same family should be stored quite close to each other. Here, preparation of carts in batches is not possible due to the size of carts. Average walking distances are also assumed to be half of the aisle length AL_S times 2 for walking back and forth. For every part picked, workers require a searching time to find the correct location in the cart for placing a part. Handling times need to be taken into account for grasping and moving parts. The amount of carts that need to be prepared depends on the number of parts fitting into a cart n_{iS} and the summed demand for parts λ_i.

$$CP_S = \sum_{i \in I} x_{iS} \cdot \Big[\frac{\lambda_i}{n_{iS}} \Big[\frac{AL_S + wf}{OV}\Big] + (ht_{iS} + st) \cdot \lambda_i\Big] \quad (5)$$

Stationary kits Kit preparation differs from the previous preparation because parts of multiple families, which are stored in different locations, are included in a single kit. Therefore, the worker takes a cart container and moves along all racks in an aisle to pick parts for either a single kit or multiple kits (batch picking) (Brynzer and Johansson, 1995). In this case, the batch size of kits prepared simultaneously is equal to the number of kits, that can be transported in a single container bs_K. For preparation time calculation, the number of batches nt_K, that have to be picked, needs to be calculated by taking into account the demand of product p. For that, a binary auxiliary variables y_{ps} is used, indicating if a kit is used at station s for product p.

$$nt_K = \frac{\sum_{s \in S} \sum_{p \in P} y_{ps} \cdot \lambda_p}{bs_K} \quad (6)$$

$$CP_K = nt_K \cdot \frac{2 \cdot AL_K}{OV} + \sum_{i \in I} \lambda_i x_{iK} \cdot (ht_{iK} + st) \quad (7)$$

Traveling kits Traveling kits are prepared in the same way as stationary kits. Therefore, a similar binary auxiliary variable τ_p is used to indicate if a traveling kit is used for product p.

$$nt_T = \frac{\sum_{p \in P} \tau_p \cdot \lambda_p}{bs_T} \quad (8)$$

$$CP_T = nt_T \frac{2 \cdot AL_T}{OV} + \sum_{i \in I} \lambda_i x_{iT} \cdot (ht_{iT} + st) \quad (9)$$

3.3 Transportation costs

Irrespective of the chosen line feeding policy, parts need to be transported to the BoL. As explained before, only one kind of load carriers is assumed for every feeding policy. Therefore, costs of transportation depend on the number of parts per load carrier n_{iw} used for line feeding policy w and the demand λ_i of parts.

The overall transportation costs are describable by summing transportation times over all line feeding policies, multiplied with the costs for logistical operators:

$$CT = LOC \sum_{w \in W} CT_w \quad (10)$$

Every vehicle might not be used all the time and neither to a full extent. To guarantee a certain service level for the supply of all station with parts, it might be necessary to perform a transportation although the vehicle is not fully loaded. Therefore, an average utilization rate μ_w should be assumed for all line feeding policies. It might also account for a decrease of utilization caused by loading and unloading.

Line stocking When parts are fed via line stocking, a pallet-wise transport with forklifts is performed. Therefore, transportation time depends on vehicle velocity VV_w, distance from the central storage to the respective station of the part $di_{s_i L}$, demand λ_i, utilization rate μ_w and number of parts per pallet n_{iL}. Similar parameters are used for all transport time calculations.

$$CT_L = \sum_{i \in I} \frac{2 \cdot x_{iL} \cdot \lambda_i \cdot di_{s_i L}}{n_{iL} \cdot \mu_L \cdot VV_L} \quad (11)$$

Kanban Kanban fed parts are transported in bins, that are loaded on a tow train performing milk-runs of a certain length mr_D. Furthermore, the number of milk-runs is depending on the number of bins nbc_D that fit on one tow train.

$$CT_D = \sum_{i \in I} \frac{x_{iD} \cdot \lambda_i \cdot mr_D}{n_{iD} \cdot nbc_D \cdot \mu_D \cdot VV_D} \quad (12)$$

Sequencing Sequenced parts are packed into wheeled containers, holding up to n_{iS} parts. These containers are transported to the stations with tow trains in the same was as kanban-fed parts.

$$CT_S = \sum_{i \in I} \frac{x_{iS} \cdot \lambda_i \cdot mr_S}{n_{iS} \cdot nbc_S \cdot \mu_S \cdot VV_S} \tag{13}$$

Stationary kits Kitted parts are transported in at most nbc_K carts per two train, each cart containing a number of kits bs_K. Tow trains provide carts by performing a milk-run.

$$CT_K = \frac{nt_K \cdot mr_K}{nbc_K \cdot \mu_K \cdot VV_K} \tag{14}$$

Traveling kits Traveling kits are brought to the beginning of the line by a tow train. di_T describes the distance from the preparation area to the beginning of the line.

$$CT_T = \frac{nt_T \cdot di_T}{nbc_T \cdot \mu_T \cdot VV_T} \tag{15}$$

3.4 Usage costs

The process of part usage describes the operations performed by assembly workers consisting of multiple tasks: the actual assembly, searching and grasping parts, handling parts, walking and further small tasks like reading the assembly list. The actual assembly and handling tasks are not considered in this model since they are not affected by the selection of a certain line feeding policy (Limère et al., 2015; Sali and Sahin, 2016). However, walking and searching are and are therefore considered as usage costs.

$$CU = AOC \cdot \sum_{w \in W} CU_w \tag{16}$$

Walking times are of high relevance in this model since the length of the BoL per station is variable. Limère et al. (2015) assumed that an operator starts from the middle of a station and the average walking distance to grab one part is defined by the distance de between assembly line and BoL and a quarter of the used length of the border of line. This calculation estimates walking distances for non-moving assembly lines. However, in this model a moving assembly line is assumed, where walking distances are much shorter if parts are presented at the BoL in a logical manner (Klampfl et al., 2006).

For the present problem formulation, we distinguish between the length of a station and the length of the border of line, where parts are stored. In figure 2 it is depicted how walking distances look like if the border of line is longer than a station. Walking distances for the operator at the BoL differ with respect to the applied line feeding policy. This can easily be seen, when line stocked parts are compared with parts fed in traveling kits where no walking is necessary. Therefore, we explain the time calculation for every line feeding policy in the following.

Generally, usage costs can be calculated using the following formula, wd_{s_iw} being the walking distance for correspond-

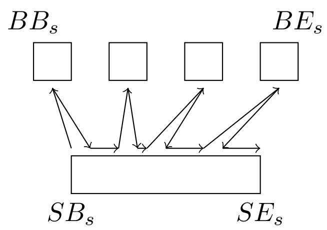

Fig. 2. Walking distances for moving assembly lines with BoL being longer than the station

ing station s of part i and line feeding policy w and OV being the operators velocity:

$$CU_w = \sum_{i \in I} \lambda_i \cdot x_{iw} \left(\frac{2 \cdot wd_{s_iw}}{OV} + st_w \right) \tag{17}$$

However, this cost formulation does not hold true for stationary kitting. Searching times, denoted by st_w, only occur in case of line stocking and kanban feeding. For the other line feeding policies, this parameter is set to 0.

Line stocking In line stocking and sequencing walking distances are assumed to be similar to the depicted walking in figure 2. In order to linearize those walking distances, they are not calculated as the second euclidean norm but as the sum of depth and average orthogonal distance. The latter depends on the length difference of the actual station and the corresponding border of line. Hence, the walking distance is depending on the beginning point BB_s and ending point BE_s of the border of line as well as the beginning point SB_s and ending point SE_s of a station:

$$wd_{sL} = de + \frac{|BE_s - SE_s| + |BB_s - SB_s|}{4} \quad \forall s \in S \tag{18}$$

Though, this formulation tries to overcome nonlinearity, the use of absolute values makes it nonlinear. Therefore, they are linearized by adding the following constraints:

$$de + \frac{p_s + q_s + m_s + n_s}{4} = wd_{sL} \qquad \forall s \in S \tag{19}$$
$$BE_s - SE_s + p_s - q_s = 0 \qquad \forall s \in S \tag{20}$$
$$BB_s - SB_s + m_s - n_s = 0 \qquad \forall s \in S \tag{21}$$
$$p_s, q_s, m_s, n_s \geq 0 \qquad \forall s \in S \tag{22}$$

Combining walking distances with the required time, a product of binary and continuous decision variables is used. In order to linearize this, a new continuous decision variable k_{iw} is used. This needs to be reformulated as follows (Glover, 1975; Torres, 1991):

$$CU_L = \sum_{i \in I} \lambda_i \cdot x_{iL} \cdot st_L + \frac{2 \cdot \lambda_i}{OV} \cdot k_{iL} \tag{23}$$
$$k_{iw} \geq 0 \ \forall i \in I, \forall w \in \{L, S\} \tag{24}$$
$$k_{iw} \geq wd_{s_iw} - \left(de + \frac{SE_{s_i} - SB_{s_i}}{2}\right) \cdot (1 - x_{iw}) \quad \forall i \in I, \forall w \in \{L, S\} \tag{25}$$

Kanban If parts are stored at the BoL in a kanban manner, it is assumed that a number of racks D_s is placed in the center of the border of line, inducing the following walking distances:

$$wd_{sD} = de + \frac{SE_s - SB_s}{4} \quad \forall s \in S \tag{26}$$

Sequencing Sequenced parts are stored in the order of use in containers. Costs can be calculated in the same way as for line stocking but neglecting searching times.

$$CU_S = \sum_{i \in I} \lambda_i \frac{2 \cdot \lambda_i}{OV} \cdot k_{iS} \tag{27}$$

Stationary kits Supply of parts within a kit seems to be similar to sequenced supply, but walking distances will differ, since parts of various assembly tasks are stored in the same container. For stationary kits we assume that the worker picks the entire kit once and positions it on the product, such that additional walking is only necessary for returning empty kits. Therefore, a logical placement of kits is the beginning (first quarter) of the station. However, it is not known, when exactly the kit is needed for the first time. This leads to an average walking distance of 1/8 to retrieve a full kit and 1/8 to return the empty kit (walking back along the station is due to comparability not included). An additional handling time ht_K to handle the kit itself is assumed.

$$CU_K = \sum_{p \in P} \sum_{s \in S} \lambda_p \cdot y_{ps} (ht_K + \frac{2 \cdot wd_{sK}}{OV}) \tag{28}$$

$$wd_{sK} = de + \frac{SE_s - SB_s}{8} \quad \forall s \in S \tag{29}$$

Traveling kits The use of traveling kits does not cause any costs since no walking or searching is necessary.

4. RESTRICTIONS IN ASSEMBLY LINE FEEDING

Within this section we introduce a list of constraints, that define in combination with the objective function and the constraints 20, 21, 22, 24, and 25, which are explained above, our assembly line feeding problem. The remaining constraints are divided into three groups: *i*) general constraints *ii*) space constraints and *iii*) auxiliary constraints, defining auxiliary variables as used in previous sections.

4.1 General constraints

$$\sum_{w \in W} x_{iw} = 1 \qquad \forall i \in I \tag{30}$$

$$\sum_{f \in F_p} \psi_{fK} \cdot v_f \leq V_K \qquad \forall p \in P \tag{31}$$

$$\sum_{f \in F_p} \psi_{fT} \cdot v_f \leq V_T \qquad \forall p \in P \tag{32}$$

Equation 32 describes the requirement of assigning every part exclusively to a line feeding policy.

Equations 30 and 31 ensure that there is enough space in a kit for every part of a family that is assigned to kitting, by summing the volumes v_f of the respective families that are used for a product p and are, hence, in the bill of material of that product denoted by set F_p.

4.2 Space constraints

Space constraints are evolving from line side presentation whereas available space at the border of line of a station is denoted by the ending point minus the starting point $BE_s - BB_s$. Note that BB_s and BE_s are continuous variables. Space requirements are described by l_w for the respective line feeding policy w. Usually, container, pallets and kanban racks are used. The following constraint ensures that all parts at a station fit into the Border of Line of that station.

$$\sum_{i \in I_s} x_{iL} \cdot l_L + D_s \cdot l_D + \sum_{f \in F_s} \psi_{fS} \cdot l_S + z_s \cdot l_K \leq BE_s - BB_s \quad \forall s \in S \tag{33}$$

The variable D_s, denoting the number of racks at station s depends on the number of parts fed in a kanban manner (see equations 34 and 35) while rn denotes the number of boxes that can be stacked in a rack. To ensure, border of lines do not overlap or exceed the total available space L, we added equations 36-38.

$$D_s \geq \frac{\sum_{i \in I_s} x_{iD}}{rn} \qquad \forall s \in S \tag{34}$$

$$D_s \leq \frac{\sum_{i \in I_s} x_{iD}}{rn} + 1 \qquad \forall s \in S \tag{35}$$

$$BE_{s-1} \leq BB_s \qquad \forall s \in S \tag{36}$$

$$BB_s \leq BE_s \qquad \forall s \in S \tag{37}$$

$$BE_s \leq L \qquad \forall s \in S \tag{38}$$

By these constraints, a random distribution of areas for all stations is allowed. E.g., one station could use the entire space and all other stations would not use any space. Generally speaking, this is a valid statement. However, we allow space borrowing only in a certain range depending on the parameter ppu, describing the percentage of the adjacent stations, that cannot be borrowed.

$$BB_s \geq SB_{s-1} + (SE_{s-1} - SB_{s-1}) \cdot ppu \quad \forall s \in S \tag{39}$$

$$BE_s \leq SE_{s+1} - (SE_{s+1} - SB_{s+1}) \cdot ppu \quad \forall s \in S \tag{40}$$

4.3 Auxiliary constraints

The following binary auxiliary constraints are used to enforce the right-hand binary variables to be one if any of the left-hand side variables is greater 0 by using a large number M. The binary variables are needed for calculations in the preceding section.

$$\sum_{i \in I_f} x_{iw} \leq \psi_{fw} \cdot M \quad \forall f \in F, \forall w \in \{S, K, T\} \tag{41}$$

$$\sum_{f \in F_p \cap F_s} \psi_{fK} \leq y_{ps} \cdot M \quad \forall p \in P, \forall s \in S \tag{42}$$

$$\sum_{p \in P} y_{ps} \leq z_s \cdot M \quad \forall s \in S \tag{43}$$

$$\sum_{f \in F_p} \psi_{fT} \leq \tau_p \cdot M \qquad \forall p \in P \tag{44}$$

5. PRELIMINARY RESULTS

The proposed model formulation allows optimizing line feeding decisions and simultaneously deciding on the available space to store corresponding parts. Using CPLEX (Version 11.7), we solved 66 datasets, with 18 experiments per dataset, all of them either to optimality or with a maximal LP-Gap of 2% within 3600 seconds.

A first conclusion of the experiments is, that all line feeding policies are used and are, therefore, beneficial under certain circumstances.

Another important insight we found is the impact of allowing variable space. Within the experiments, we tested if allowing space borrowing has an impact on line feeding policies used and on the objective function value. As space is actually borrowed when allowed, line feeding policies are changing for some parts which in turn decreases the objective value. The following table sums up these results by showing the average costs per part number and the percentage of parts fed with a line feeding policy averaged over all experiments.

Table 1. Influence of space borrowing

Space borrowing	Cost/ part	L	D	S	K	T
✗	113	10.92%	14.14%	28.83%	10.56%	35.55%
✓	106	17.25%	19.82%	22.51%	8.20%	32.22%

Moreover, in literature there are different approaches on handling costs for replenishing parts from a warehouse to the supermarket. Therefore, we conducted experiments explicitly including and excluding these costs. Obviously, the objective value was lower when no replenishment costs were assumed. But, as the percentage of parts per line feeding policy changed, it shows, that these replenishment costs are not neglectable, since they affect the actual line feeding decision as shown in the following table.

Table 2. Influence of replenishment costs

Replenishment costs	Cost/ part	L	D	S	K	T
✓	109	15.01%	17.18%	24.99%	9.14%	33.68%
✗	70	10.57%	20.27%	31.98%	11.96%	25.21%

Finally, we found that parts within one family are sometimes fed using different line feeding policies. However, this could only be observed for less than 1% of the families. Therefore, for practical easiness, it might be useful to forbid this behavior in the model by an additional constraint.

6. CONCLUSION

Within this paper we defined the assembly line feeding problem as well as relevant line feeding policies. Afterwards, we proposed an optimization model for making line feeding decisions incorporating variable space on a stationary level. Due to good solvability, the model can easily be used by practitioners. Preliminary analyses indicate that space borrowing decreases costs for line feeding by around 7% on average. In future work, we want to investigate further on line feeding policy decisions and space determination depending on characteristics, such as part volume, demand or number of parts at a station. For both decisions, we aim to reveal patterns which may be used as rules of thumb. We also aim to quantify the effect of decision making per family in comparison to a part-wise decision making. With this work we intend to support decision making for real world assembly systems.

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