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Planning and dimensioning of a milk-run transportation system considering the actual line consumption

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Abstract: the appeal of a forklift-free shop floor is pushing enterprises towards lean logistic systems and tugger trains are becoming popular means of supply in intensive material handling production systems. Planning a tugger train system is a complex task influenced by a large set of interrelated parameters. The only standard available to help the planner in designing the tugger train logistic system is the draft norm VDI 5586 (April 2016). However this norm is only applicable under a set of restricting assumptions. In this paper a methodology to complement the approach proposed by the VDI is introduced and then applied to a numerical example. The results are briefly presented and discussed before suggesting forthcoming research.

Keywords: Milk-run, planning, tugger train, lean logistics, buffer dimension, reordering method

1. INTRODUCTION

Safety enhancement, traffic reduction and efficiency improvement are the expected benefits of supplying the assembly line with tugger trains, in place of forklifts. For these reasons, tugger trains are becoming popular means of supply in intensive material handling production systems (Schmidt, Meinhardt and Schulze, 2016). However, introducing this material handling system, based on the "pull" principle of Kanban and the milk-run approach, is more complex than the mere replacement of one means of transport by another. A complex planning influenced by a set of interrelated parameters is essential and an impact on the dispatching strategies, layout and current processes is often inevitable. Recently the Association of German Engineers (VDI– Verein Deutscher Ingenieure) has developed and published a standardized approach (VDI 5586, April 2016, still a draft version) to tackle the problem of planning in-plant milk-run systems. The planning method proposed mainly focuses the material-flow and it is bounded to a set of strong assumptions. These assumptions limit the applicability of the methodology only to specific scenarios, where production and logistic systems are designed at the same time and can influence each other during the planning process. Moreover, in the planning method introduced by the VDI, the information flow is only partially considered and the whole tugger train system is dimensioned according to a pure schedule-driven, therefore "push" approach. Dimensioning a logistic system following a schedule-driven approach means: (1) to estimate the items consumption independently from the actual production and (2) to dimension the buffers at the points of use as if production and logistics would be perfectly synchronous (material delivery is synchronous with the material consumption dictated by the production line speed). Any deviation from the plan (either wanted or unwanted) could cause total loss of control on the actual material flow, with problems such as: (1) redundant line-side material, (2) a new material flow of not-entirely-empty containers or (3) starvation of items at the point of use with causing slowdown or stop of the production.

How could the planning method be complemented in order to consider a demand-driven "pull" approach for material supply, hence the actual material consumption on the line? How could uncertainty be included in the planning so that lineside activities (e.g. assembly) are never stopped because of stock out or material shortage?

In this paper, a new planning method will be presented and explained focusing not only the material flow, but also taking into account the current processes of the company and the related information flow. The method proposed will allow the planner to correctly dimension the buffer at the points of use considering existing processes and evaluating the impact of adopting different replenishment methods, such as Kanban cards, e-Kanban or direct order through buttons or sensors.

2. STATE OF THE ART

In this section, first a brief overview on tugger train systems is given, then the planning method proposed by the VDI is summarized and analyzed. Lastly, the VDI method for buffer dimensioning is explained in detail, laying the foundation for its further development, object of the next section.

2.1 Tugger train system

A typical tugger train system is a transport concept based on the milk-run principle, where material is transported from a centralized warehouse, also called supermarket (Fig. 1, Warehouse SM), to a defined number of stops (Fig. 1, S1 to S5), along a fixed defined route. Generally, these systems are operating on a fixed schedule (Klenk, Galka, Günthner, 2012). The means of transport is the tugger train, which consists of a

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tugger and a set of trailers. On each trailer are loaded one or more standard Unit Load (UL). Often, in order to couple the Unit Load with the trailer, a mechanical interface, called trolley, is needed. The number of trailers usually varies from 2 to 5. Key components of a tugger train systems are shown in the following Fig. 1.

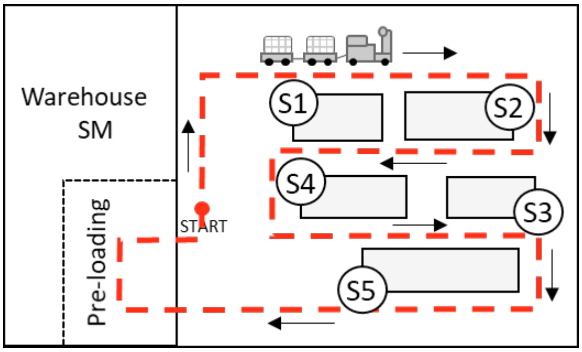

Fig. 1 Tugger train system layout (example)

When looking at Fig. **1**, boundaries of the system could be identified together with interfaces with uphill and downhill processes. The tugger train system is interfaced uphill with the warehouse (SM), for instance, through a pre-loading area and downhill with the production line through buffers at each stop. As explained by Harris H. et al. (2003) the process of supplying material along the route could be (1) coupled or (2) decoupled with the uphill commissioning process at the supermarket: (1) coupled means that the commissioning process is performed by the tugger train driver and a path through the shelves of the supermarket is included in the route, (2) decoupled means that material supply and commissioning processes are clearly separated: the tugger train driver enters the supermarket and stops at a specific point (pre loading area Fig. **1**) to unload the empty unit loads and load the full ones. The commissioning process at the SM is accomplished by another operator or automated system. Especially in this case, the role played by the information gathering and the commissioning process itself is extremely important when dimensioning the logistic system and the necessary buffers at the point of use (Droste, Deuse, 2011).

2.2 VDI 5586

The VDI 5586 consists of two parts. The first, “Blatt 1”, concerns an overview on tugger train systems. It lays the foundation for understanding both technical aspects and alternative concepts of system development. Here examples of different system configurations are explained according to two possible paradigms to deliver material to the line: (1) the push paradigm, based on the perfect synchronism between theoretical consumption and real need of material, and (2) the pull principle, which uses techniques like the Kanban to ensure that the only material that is moved to the lines, it is the one that is really needed. In the second part, “Blatt 2”, a method to plan and dimension a tugger train systems is introduced, based however only on the push paradigm. Given that all the parameters characterizing the route such as route length, stops along the route and stops sequence are a priori defined, the method introduced by the VDI could be applied performing the following 8 steps calculation: (1) Throughput (UL/h), (2) Route frequency (lap/h), (3) Route period (h), (4) Route capacity Utilization, (5) Cycle time (t_{cyc}) (h), (6) Number of trains necessary, (7) Route time Utilization and (8) Buffer dimensions. The method can be applied to one single route at a time. Neither procedures for automatic route determination, nor for optimization fall within the scope of the norm. Key design figure of the tugger train route is the desired average throughput, where average means not only average in quantity, but also average in unit load type. The consumption rate of the items (UL/h) is considered to be constant and not subjected to any kind of variability and it is therefore unmistakably predictable, hence the possibility of using the push paradigm for moving to the line material that is theoretically needed according to the master production schedule. As a result, if the process runs smoothly, the tugger train system will be able to supply what is needed, where is needed and exactly when is needed.

2.3 The role of information

In the previous sections an overview on tugger train systems and the planning method introduced by the VDI has been given. In this section the role of information in decoupled systems is clarified. As already mentioned in a decoupled system supply and commissioning processes are neatly separated. This neat separation, however, is only possible if the actual material demand is deterministic and used to calculate the optimal delivery times (Klenk, Galka, Günthner, 2012). In other words, the whole planning relies on steady and frozen master production schedules with no margin for last minute adjustments or flexibility for human or system mistakes, sentence material shortage. In order to avoid this risk and supply what is actually needed to the line, a consumption oriented system should be adopted. Items are reordered according to the actual material consumption following the pull principle. Thanks to this information it is possible to synchronize production and logistics. The most common reorder techniques for detecting and communicating the actual need of the line are (1) the Kanban card, (2) the e-Kanban and (3) the direct order through a button or sensor placed lineside. The planning method must consider the whole replenishment process, which starts exactly when the need for a certain item is generated by its actual consumption. In the case of a tugger train system this means that the transportation of a certain item (Unit Load) is authorized only after the transportation order for the specific item has arrived at the supermarket (SM). In other words it is the need that triggers the transport, or, better put, the *information* of the need triggers the commissioning process. The commissioning process ends when the required unit loads are ready in the pre-loading area of the SM. For this reason the time that the information takes to be communicated to the SM is a key factor for the planning of the system and the dimensioning of the buffers. The planning method introduced by the VDI 5586, however, does not consider the information flow. It is explicitly explained how the whole tugger train logistic system is dimensioned according to a deterministic approach. The commissioning process at the SM starts independently from the production and it is based on the expected consumption rate at the points of use (hence on the frozen master production schedule). Any deviation from the plan (either wanted or unwanted) could cause total loss of control on the actual material flow, with problems such as: redundant material at the delivery side, a new material flow of not-entirely-empty containers or starvation of items at the point of use causing slowdown or stop of the production. This is evident especially in the last step of the planning method “buffer dimensions”.

2.4 Buffer Dimensioning

- Following the VDI approach

According to the VDI the buffer dimensions should be calculated for each item separately adding one extra position in order to make it possible to exchange the empty unit load with the full one, as shown in the following formulas.

$$q_{A,H} = 1 + \lceil n_{LT,A,H} \rceil \tag{1}$$

$$n_{LT,A,H} = \frac{\lambda_{A,H}}{f_r} \tag{2}$$

$$Q_R = \sum_{n_A} q_{A,H} \tag{3}$$

Where $q_{A,H}$ is the buffer dimension in number of unit load per item (A) at the stop (H), $n_{LT,A,H}$ the average consumption in UL of the item A at the stop H in the span of time between two visits to the same stop H (called hereafter “takt”), $\lambda_{A,H}$ the average consumption of unit load per hour of item A at the stop H and f_r is the hourly route frequency. Q_R represents the total number of buffer positions needed considering the requirements of every stop belonging to the route (R).

- Complementing the guideline approach

This formula for the calculation of the buffer dimension for each item suits only when material is pushed to the line following the master production schedule and independently on the actual consumption. In the case the system is designed to answer to last-minute fluctuations and unforeseeable events, the actual consumption of items must be considered and therefore the replenishment of the buffers must be triggered through a reordering method (Kanban card, e-Kanban, etc.) rather than pushed according to the master production schedule. In this case the buffer at the stops represents the decoupling point between logistics and production and its dimensioning must be consistent with the pull principle and reordering method upon which the system will work. Dimensioning the buffer without considering the information flow, which is different according to different reordering methods, would lead to its underestimation. In order for the logistic system to work properly and react to disturbances the calculation of the buffer must consider both the gathering of information and the process of commissioning at the SM.

3. METHOD

The method proposed in this section aims at dimensioning the buffer of a tugger train system, considering the ability of the system of answering to last-minute fluctuations and unforeseeable events; the material is therefore replenished to the lines following the pull paradigm and using different reordering systems. The approach is based on the formula proposed by the VDI 5586; the calculation still considers an extra place at the buffer for the UL exchange, but the average consumption of UL of the item A at the stop H in a takt is weighted by a factor k.

$$q_{A,H} = 1 + \lceil k * n_{LT,A,H} \rceil \tag{4}$$

The factor k is affected by the reordering method and the information gathering process and estimates the maximum number of takt needed in order to accomplish the replenishment activities. The idea that led the authors to introduce this factor is absolute stock-out avoidance, which brings to the necessity of considering a replenishment worst-case scenario that could be caused by: traffic delays, changes in the production schedule, production yield variance, etc. For this reason also the cycle time, needed in order to calculate the factor k, should be calculated following the worst case approach.

The method hereafter presented is applicable to three different scenarios, which differ in the reordering process and, consequently, in the calculation of the factor k.

3.1 Scenario 1

Reordering method: Kanban card (attached to the unit load)

Information gathering process description: The driver of the tugger train stops at a stop H along the route, unloads the full unit loads and loads the empty ones on the train. The driver

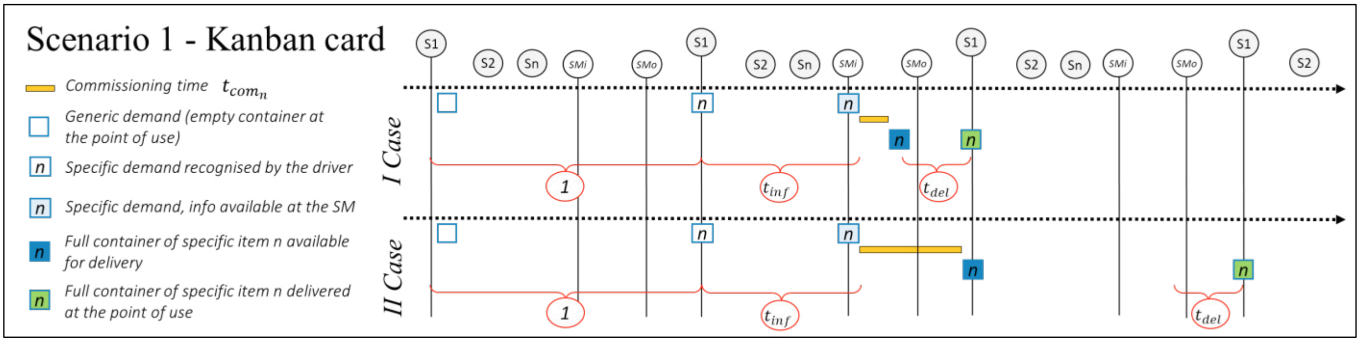

Fig. 2 Scenario 1 - Reordering process Kanban card

drives back to the supermarket and unloads the empty containers. Only then, the information about what is needed at the points of use it is available at the supermarket and the commissioning process can start. After the commissioning process has finished, the unit loads are in the pre-loading area, ready to be loaded on the first available tugger train. Considering the information gathering process, the worst case occurs when the demand, represented by the empty blue square in Fig. 2 and by an empty container in reality, appears right after a tugger train has left the stop H (S1 in Fig. 2). The demand can only be detected next time a tugger train stops at the same stop, which happens after one takt. Once the demand has been recognized and the empty container loaded on the trailer, the train continues its tour until he drives back to the SM: this is the time the information takes to be communicated to the SM (t_{inf}). Only after the acknowledgment of the demand the commissioning process can start and will last, for the item A, a specific commissioning time t_{com_A}.

$$k_{A,H} = 1 + \left\lceil \frac{t_{inf} + t_{com_A} + t_{del}}{t_{TA}} \right\rceil, k \in N \qquad (5)$$

$$t_{inf} + t_{del} = t_{cwc} \qquad (6)$$

After the unit load has been commissioned it can be loaded on the tugger train. The unit load will then be delivered to the point of use: this is called “delivery time” (t_{del}). As shown in (6), in this case (t_{inf}) and (t_{del}) are always complementary and, put together, equivalent to the cycle time in the worst case (t_{cwc}), hence the longest time a cycle can last, due to the fact that the train visits the maximum possible amount of stops (loads and unloads UL not in the same, but in different stops of the route). A fundamental role is played by the commissioning time. In fact, if the commissioning is fast enough to make the requested UL available before the tugger train loading process starts (Fig. 2, *I Case*), the unit load could be delivered within the next tour. Otherwise the ceiling-up function prevents the buffer from being under dimensioned allowing the delivery of the unit load within the tour after the next (Fig. 2, *II Case*).

3.2 Scenario 2

Reordering method: e-Kanban (Barcode)

Information gathering process description: The driver of the tugger train stops at a stop H, unloads the full unit loads, scans the barcode of the empty ones and load them on the tugger train. The information is immediately available to the SM and the commissioning process can start immediately after $(t_{inf} = 0)$. The driver continues his tour until he drives back to the supermarket and unloads the empty containers. When calculating the delivery time t_{del}, the worst case is considered, meaning that the tugger train will visit the maximum amount of stops between the stop *H* and the Supermarket, hence $t_{del_{A,H,wc}}$.

$$k_{A,H} = 1 + \left\lceil \frac{t_{com_A} + t_{del_{A,H,wc}}}{t_{TA}} \right\rceil, \ k \in N \qquad (7)$$

Considering the information gathering process the worst case occurs again when the demand appears right after a tugger train has left the stop (Fig. 3). If the commissioning process finishes before the train is loaded at the supermarket, the unit load could be delivered within the next tour (Fig. 3, *I Case*), otherwise the ceiling-up function prevents the buffer from being under dimensioned allowing the delivery of the unit load within the tour after the next (Fig. 3, II Case).

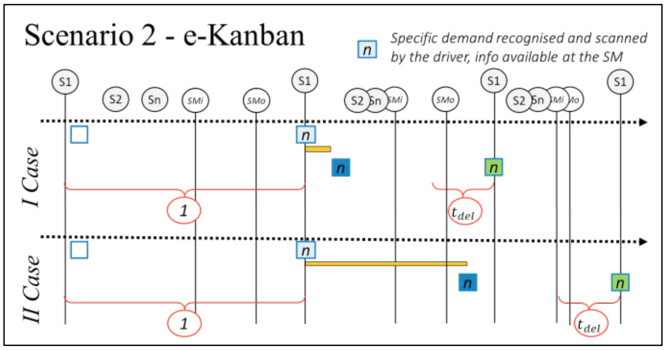

Fig. 3 Scenario 2 - Reordering process e-Kanban

3.3 Scenario 3

Reordering method: direct order line side (button or sensor)

Information gathering process description: The reordering process is independent of the tugger train driver. The operator who is working on the assembly or production line (line side) is responsible for pressing the proper button as soon as a unit load is empty (alternatively the presence of an empty container can be detected by a sensor that triggers the demand). The information is immediately transmitted to the supermarket and the commissioning process could start right away $(t_{inf} = 0)$. The driver drives along the route exchanging full unit loads with empty ones and loading at the supermarket what is ready to be loaded.

$$k_{A,H} = 1 + \left\lceil \frac{t_{com_A} + t_{del_{A,H,wc}}}{t_{TA}} \right\rceil, \ k \in R \qquad (8)$$

In order to understand the worst case, the concept of break-even time needs to be explained first. Fig. 4, *I Case,* shows the best case scenario which defines the break-even time. In this case the signal for the demand arrives in the exact same moment the commissioning process should start in order for the UL to be loaded on the tugger train right before its departure from the SM. As a result the UL will be delivered within the next tour. Theoretically, if the demand arrives even one second after the break-even time, the commissioning process will not be finished before the train has departed from the SM. In this case (the worst case indeed), the item will not be delivered in the next tour, but in the one after the next and the buffer available at the stop should be large enough to cover not only the commissioning time and the time of delivery for the train to arrive at the stop, but also one additional takt time as shown in (8) and Fig. 4, *II Case*. If the demand arrives before the break-even time the item will be delivered within the next departure and so the buffer estimated in (8) will be large enough. For the sake of completeness Fig. 4, *III Case* shows what would happen with a longer commissioning time,

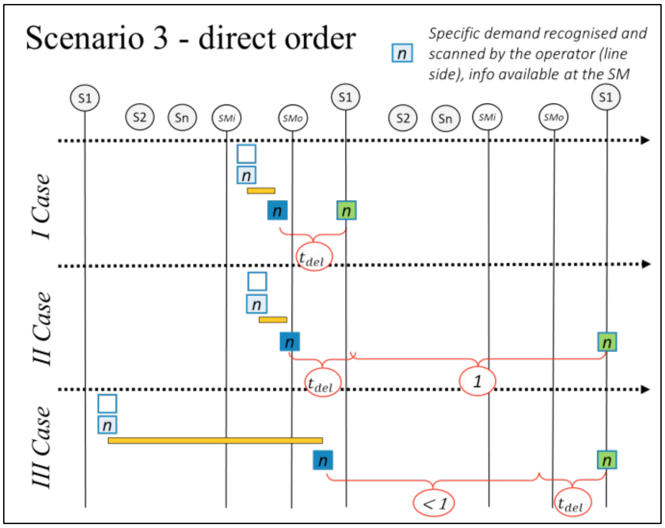

Fig. 4 Scenario 3 - Reordering process direct order

proving that the formula applies even to this case and that the time between the end of the commissioning and the beginning of the delivery process is always smaller than one takt time. For these reasons the ceiling up function it is no longer necessary and k belongs to the set R and not N, which is the only difference between formula (7) and (8).

4. RESULTS

In this section a numerical example will be introduced and both the method proposed by the VDI and the one presented in this paper applied, in order to estimate the buffer dimensions according to different reordering processes and compare the results. As already mentioned in the introduction planning and dimensioning a tugger train system is a complex topic influenced by a set of interrelated parameters. In order to help the reader focusing the buffer dimensioning problem, the following example is based on few simplifications and assumptions: the variety of articles delivered is limited in number and type, the delivery route is unique and delivery and commissioning process at the supermarket are decoupled.

A tugger train supplies an assembly line with different parts (9 items) homogeneously stored in a unique type of unit load (UL). The ULs are delivered along one single route made of a set of 5 stops (S1-S5, see layout in Fig. 1) equally distributed along the route. The route is 124 meters long and the tugger train speed is assumed to be, for the sake of simplicity, 1 (m/s). Also to simplify calculation, instead of considering the true acceleration and deceleration ramps of the vehicle, a 10 seconds delay is considered for each stop; following the same approach, an extra delay of 20 seconds (for the whole route) is considered in order to take into account accelerations and decelerations due to corridor, junctions and turns. Exchange time (full UL with empty UL at the stop as well as empty UL with full UL at the SM) for each UL is considered to be 30 seconds. The tugger train tows three (3) trailers and each trailer is able to carry one (1) unit load at a time. The UL could be loaded or unloaded on both side of the trailer. The commissioning time at the supermarket is 2 min for each UL, but it is possible to commission up to three (3) unit loads simultaneously, so that the whole train can be commissioned within 2 minutes. Every hour the line generates an output of 5 finished products. The following Table 1 summarizes the consumption rates according to each item and stop along the route considering the line throughput variation. These data have been the input for the system dimensioning.

Table 1 Consumption rates according to different line throughputs

			Line Troughput 5 Products		Line Troughput 10 Products		Line Troughput 12 Products	
Item #	Stop (S)	Unit Load Type	Consumption [UL/h]	Consumption at the Stop [UL/h]	Consumption [UL/h]	Consumption at the Stop [UL/h]	Consumption [UL/h]	Consumption at the Stop [UL/h]
001	S1	GLT	2	3,00	4	6,00	4,8	7,20
006		GLT	1		2		2,4	
004	S2	GLT	3	5,00	6	10,00	7,2	12,00
005		GLT	2		4		4,8	
002	S4	GLT	1	6,00	2	12,00	2,4	14,40
007		GLT	3		6		7,2	
008		GLT	2		4		4,8	
009	S3	GLT	1	1,00	2	2,00	2,4	2,40
003	S5	GLT	1	1,00	2	2,00	2,4	2,40

In order to find a numerical evidence of the impact of the proposed method, the tugger train system has been planned according to different line throughputs, keeping other parameters unchanged. The line throughput has been increased first by 100% to 10 product/hour and then by an additional 20% to 12 finished product every hour (see Table 2 , forecast-driven column). First, the planning has been conducted according to a forecast-driven reordering process, hence following the 8-steps planning method described in the VDI norm, then, with exactly the same data in input, the planning has been repeated applying the method proposed in this paper for three different reordering methods: Kanban card, e-Kanban and direct order.

Results are shown in Table 2 and represented in the following Fig. 5. It is clear that applying the method proposed by the VDI a variation in the line throughput does not affect the buffer dimensioning. In fact, a higher route frequency ensures that the needed material is always fed to the line in the right amount.

Table 2 Tugger train system dimensioning according to different throughputs and reordering methods

	Reordering process	Forecast-driven (push)			Kanban Card (pull)			e- Kanban (pull)			Direct Order (pull)		
0	Line Througput [products/h]	5	10	12	5	10	12	5	10	12	5	10	12
1	Througput [UL/h]	16	32	38,4	16	32	38,4	16	32	38,4	16	32	38,4
2	Route frequency [lap/h]	6	12	15	6	12	15	6	12	15	6	12	15
3	Takt time [min]	10	5	4	10	5	4	10	5	4	10	5	4
4	Route Utilization (Capacity)	0,89	0,89	0,853	0,89	0,89	0,853	0,89	0,89	0,853	0,89	0,89	0,853
5	Cycle time [min]	5,75	5,75	5,65	5,75	5,75	5,65	5,75	5,75	5,65	5,75	5,75	5,65
6	Number of trains necessary	1	2	2	1	2	2	1	2	2	1	2	2
7	Route Utilization (Time)	0,575	0,575	0,706	0,575	0,575	0,706	0,575	0,575	0,706	0,575	0,575	0,706
8	Buffer dimensions (Q_R)	18	18	18	18	20	23	18	19	20	18	19	19

On the other hand the increased frequency leads to an increase in necessary buffer places when the push paradigm is abandoned and different reordering processes are considered. When this is the case, the buffer dimension tends to grow together with the frequency increase. It is also noticeable how different reordering methods are more or less sensitive to an increase in line throughput, main reason being the different reaction time to disturbances characterizing the logistic system.

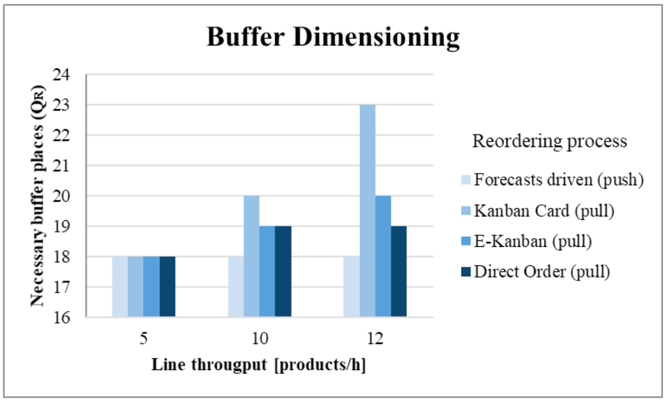

Fig. 5 Buffer dimensioning according to different line throughput and reordering processes

As expected a pull logistic system where the reordering process is triggered by a direct order (button or sensor) is much more reactive in comparison to a logistic system based on the Kanban card method. As already explained the tugger train planning is a multidimensional problem and the reordering method is only one of the many aspects one could have influence on in order to increase the reliability of the logistic system. In the specific example, for instance when the line throughput is set to 10 (product/h), replacing the e-Kanban with the direct order brings no benefits in terms of buffer reduction. If reducing the buffer places is the goal and framework conditions cannot be changed other aspects such as the possibility of varying the stops order along the route, the number of items in each container or the commissioning process should be investigated.

5. DISCUSSION AND CONCLUSION

Built on the strong statement that production should never stop or slow down because of logistics, the introduced method is based on a worst-case approach. Whether considering the worst-case approach is better than considering a probabilistic one does not fall within the scope of this section. However, given that monitoring and improving are inevitable steps for the successful adoption of a lean system, starting from a system which is correctly dimensioned is far better than starting from an under dimensioned one. Following the method proposed in this paper, it is possible to design a tugger train system from scratch, as long as the designer is able to steer and freeze, at each step of the method, several technical aspects such as layout configuration, technical equipment selection, takt time of deliveries, etc.. Consequences of these choices are not only affecting the logistic system itself. As a result the method proposed is useful especially when the design of the logistic system is taken into consideration at an early stage of the factory or line design. For this reason this method applies mainly to recent facilities or production lines of intensive production system, where the simultaneous planning of production and logistic systems is supported (Schmidt, Meinhardt and Schulze, 2016). As a matter of fact the expected benefits of safety enhancement, traffic reduction and efficiency improvement drew small and medium sized enterprises (SME) attention. Especially in this kind of industrial realities it is not always trivial to redesign the production line, modify the layout or change well established existing processes. Exactly under these circumstances, where the freedom of the designer is limited, the buffer dimensioning method plays a fundamental role. Given that the buffer dimension is more a constraint then the goal of the planning process, only through a specific and precise buffer dimensioning method, it is possible to evaluate different design alternatives, to define a threshold in the performance level of up-hill and down-hill processes and to lay the foundation to overturn the methodology proposed by the VDI adapting it to highly constrained scenarios. Further research on this topic is foreseeable: first validating the method results through a simulation model, than developing a new extensive planning methodology in order to help SMEs evaluating the opportunities and risks of investing in a lean logistic system based on tugger trains.

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