Acta logistica - International Scientific Journal about Logistics
Volume: 6 2019 Issue: 3 Pages: 85-91 ISSN 1339-5629

doi:10.22306/al.v6i3.125

Received: 27 June 2019
Accepted: 15 July 2019

THE OVERLOOKED DEPENDENCIES OF MATERIAL FLOWS ON QUALITY AND QUALITY ASSURANCE

Moshe Eben-Chaime
Department of Industrial Engineering & Management, Ben Gurion University of the Negev,
P.O. Box 653, 8410501 Be'er Sheva, Israel, even@bgu.ac.il

Keywords: material flow, material handling, quality, inspection errors, yield rates

Abstract: The flow of materials is a major constituent of in-plant logistics and similar factors govern resource requirements and material flows. In particular, quality factors and the configuration of the quality assurance – the inspections' system. Nonetheless, no study considers the association between and the dependencies of material flows on quality levels and the configuration of the inspections' system. The configuration of the inspections' system affect the structure of the material flow network by adding nodes – inspection stations, to it and changing the paths, accordingly. In addition, the quality levels, the configuration of the inspections' system, and inspection error rates significantly affect the volumes of material flows. These effects are quantified, demonstrated and discussed in this study.

1 Introduction

"Material handling is of extreme importance to logistics and manufacturing industries as it accounts for a large percentage of the operation."[1] This work is concerned with the flow of materials in manufacturing processes which can be conducted either inside a single facility or be distributed between several links of a supply chain. Material flows are a primary input to facilities' design and to the design of the material handling (MH) system, and the flows, the layout and the MH system significantly affect the performance of the entire system – production or service system [1-7].

Even larger attention has been drawn to quality issues, but the vast majority of the quality and operations systems research, naturally focuses on operations management. Still, the dependency of the volumes processed in production/manufacturing facilities and consequently, of capacity and resource requirements on quality has been noticed in the facilities' design literature. However, while similar factors govern resource requirements and material flows, no study associated quality and the configuration of the quality assurance system with material flows and the design of the MH system. This is the aim of this work: to study, and characterize the association between and the dependencies of material flows on quality and on the configuration of the quality assurance – the inspections' system.

2 Literature survey

To locate this study within the existing body of literature, it is best to refer to the description in [2], where two approaches for facility design are discussed. Both approaches involve complex processes, but in both there is a single origin, which provides the necessary input information for the whole design process. In the first approach, it is termed 'material flow calculations', while in the second this initial phase is decomposed into two steps: 'input: production data' and 'handling relations'. Similarly, in the well-known systematic layout planning (SLP) methodology [4,5,7], the design begins with input data collection from which material flows and resource requirements are derived. This study is concerned with these initial steps, more accurately, with the translation of the production data into both material flow calculations and handling relations and, in particular, with the dependencies of material flows on quality issues.

Quality issues have drawn large attention, but the vast majority of the quality and operations systems research, naturally focuses on operations management. Operations are managed in an existing system where the capabilities and capacities of the resources are given, at least for the near future. Resource availability constrains and often limits system's operation. The question is, then, what is the best that can be done with, or how to best utilize, the available resources. This is often termed throughput analysis (e.g., [8]). However, there are other, no less important questions, including the question of what are the appropriate resources? What are the required capabilities and capacities? What amount of each resource will best satisfy the requirements? These issues are usually of concern with respect to production resources but are of no less significance with respect to MH resources (e.g., [9,10], which are 'throughput analysis' studies).

Resource requirements, quality and flows are central issues in the facilities design literature, which tells us (e.g., [3-6]) that extra capacity is required to compensate for yield losses due to imperfect quality. Yet again, the results are rather limited. First, "very limited work exists in analyzing assembly system quality when multiple products are produced in the same system" [11]. Quality issues, including inspection errors, like other components of manufacturing/production systems, are stochastic in nature. Stochastic models of production systems (e.g., [12,13]) are usually based on queuing theory and hence, consider processing and productive times, while here the production quantities are of concern. Some (e.g., [6,13]) translate the changes in quantities to time by inflating processing times, but this approach is limited in its ability to cope with assembly systems of multiple products, which are of major concern in this study.

The work of Eben-Chaime [14] is, perhaps the first step in this direction (and note the difference between the analysis in [14] and the incomplete/imperfect analysis in Appendix A of [6]), but even in this work inspections and inspection errors are disregarded. A common method for coping with defective items is to make inspections (e.g., [15-19]). Nevertheless, focusing on quality, most studies on inspections (e.g., [17-19]) concentrate on error type II – missed defective units, while taking no notice of the waste which is associated with type I errors – false rejections. Very few studies, if any, consider assembly system quality with inspections and inspection errors of both types. Furthermore, while similar factors govern resource requirements and material flows, no study considers the association between and the dependencies of material flows on quality and the configuration of the quality assurance – inspections', system. The configuration of the inspections' system affect the structure of the material flow network by adding nodes – inspection stations, to it and changing the paths, accordingly. In addition, the quality level, the configuration of the inspections' system, and inspection error rates significantly influence the volumes of material flows. These effects are discussed quantified and demonstrated in the sequel.

3 Method

Without loss of generality, the dependencies of the material flows on the quality level and the configuration of the inspection system are demonstrated by several numerical examples. Basically, the method follows the principles in [14], yield rates are calculated in an opposite direction to material requirements (required quantities), the inversion of the input-output relationships, the actual yield (defect) rates of assemblies, etc. However, inspections are not considered in [14] and their inclusion require some modifications. First, the *product structure* does not include inspections and hence, should be replaced by another model. Besides, inspections are activities not components. Hence, to includes inspections, the description should be of the manufacturing/production process. Then, calculations of conforming rates and required inputs, similar to the calculations of material requirements and actual yield rates of assemblies, should be developed for inspections.

3.1 Process description

An excellent process description is the *operations process chart* (OPC), which is discussed briefly towards the end of [14]. “The operations process chart is one of the most useful techniques in manufacturing planning. ***Actually, it is a ‘diagram’ of the manufacturing process***. It has been used in many ways as a planning and control device. With the addition of other data, it can be extremely useful in manufacturing management” [3]. Moreover, the manufacturing/production process of each product can be described completely by a single OPC, even when the process is decomposed into sub-processes' which can be performed at different locations and/or by different organizations. The OPC of the product used in this study is portrayed in Figure 1 and includes the three most common activities: operations, which are represented by circles, inspections, which are represented by rectangular boxes, and material flows to which the arrows correspond. The arrows describe the flow of materials between subsequent activities and are directed according to the flow of the process. It should be noted that each branch – a series of operations, in an OPC correspond to a component of the product while operations with more than a single entry depict assemblies where the entering arrows correspond to the components. The activities are numbered to facilitate communication. These are the top numbers in the circles and boxes: 0 and 3 are assembly operations, 1, 2, 5 and 6 are inspections and the rest are regular (non-assembly) operation.

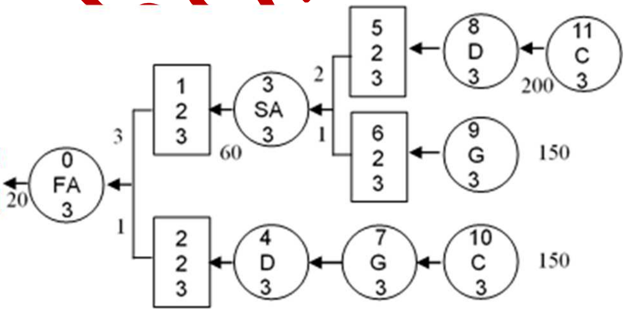


Figure 1 An extended operations process chart

The OPC in Figure 1 is an extended version, which contains additional information as suggested by Apple. The letter in the middle of each circle is the station type which has been chosen to do the operation, while the number on the circle's bottom is the mean defect rate, d_i, in percents, 3 = 3%. There is some freedom to choose the station type for each operation, which is highly significant, but the calculations need to be done for each combination of choices because the defect rate (and the processing time) depends on both the operation and the station where it is performed. In the sequel, let $d_{i,j} > 0$ only for the chosen station type. The numbers in the boxes, below the activity number, are the error rates: type I, α_i, in the middle and type II, β_i on the bottom. The single digit numbers by the arrows are the assembly ratios, which are specified in the bill of material of each product (e.g., [6,20], while the larger numbers are the number of units per material handling trip. Namely, in operation 3, two unit of the component which arrives from inspection 5 are assembled with a single unit of the other component and in operation 0, a single unit of the component on the lower branch is added to three sub-assemblies. Likewise, the assembled units moved from operation 0 onward in lots of 20 units, while the units on the lower branch are moved in lots of

150 units all the way from the raw material storge up to operation 0. Like the defect rates which depend on the choice of station, the number of units per trip depend on the choice of MH equipment. Thus, the configuration of the MH system has a significant influence on system's performance, but again, the calculations need to be done for each configuration.

3.2 Assumptions

The calculations in the next sub-section are based on certain assumptions, which are listed below. Of course, these assumptions do not hold completely, but even so, the results provide very good approximations.

1. The workstation has already been specified for each operation.
2. The operations are independent of each other.
3. The inspections are independent of each other.
4. The operations and the inspections are independent of each other.
5. All processes are statistically in control.
6. Defective units are detected only by inspections.
7. Each defective unit is removed as soon as it is detected.

As noted, there is some freedom to choose the station type for each operation, but the calculations need to be done for each combination of choices. Assumptions 2–4 are used in the calculations of the yield of serial processes and in the calculations below. These assumptions are quite reasonable, as different operations/ inspections are performed at different stations. Assumption 5 implies that items turn defective due to random causes only, in an independent manner (e.g., [16]). Some defective units might be rejected not by inspections, but the numbers are small and assumption 6 greatly simplify the presentation. The calculations can be modified to handle cases where assumptions 6 and 7 do not hold. Finally, mean defect rates and mean error rates are used, since long-term performance of repeated processes are considered.

3.3 Calculations

First, recall the basic principle noted in [14]. Production planners know how many end items are needed and from these figures, order quantities are calculated backward – opposite to the direction of the OPC's arrows, as in material requirements planning [20]. Further, defective units cannot be used as intended. Hence, more units should be produce to replace any defective unit. Consequently, the simple input-output relationships, with imperfect quality: $Q^{out} = (1\text{-}d)\cdot Q^{in}$, where d is the mean defect rate, should be inverted:

$$Q^{in} = Q^{out}/(1\text{-}d). \tag{1}$$

In the sequel, the conforming or yield rate: $y = 1\text{-}d$, is used for convenience.

Recall also the actual yield rate, $y_A{}^a$, of assembly operations, which, for an assembly operation with K component types, assembly ratio $m(k)$, component conforming rates y_k and self defect rate d_A, is:

$$y_A^a = (1 - d_A)\prod_{k=1}^{K} y_k^{m(k)}, \tag{2}$$

where the self defect rate d_A in the portion of the units that turn defective during the assembly. Eq. (2) can be generalized to include non-assembly operation, too, by letting K be 1; i.e., a single component type, whose assembly ratio $m(1) = 1$, too. Accordingly, $m(k) = 1$ anywhere in Figure 1, unless a larger value is specified explicitly. Due to the use of the conforming rates of the components, these yield rates should be calculated first. Hence, yield rates are calculated forward – along the direction of the OPC's arrows.

An addition of this study, is the inclusion of inspections and inspection errors. By assumptions 6 and 7, above, units are removed from the process by inspections. Hence, inspections' output is smaller than the input. Assemblies' output is also smaller than the input but for a different reason – the join of several components to form a single (sub)assembly, and by assumption 6, the output of a regular operations equals its input. The units removed are of one of two types: defective units and falsely rejected units, due to type I errors. With the 'contribution' of type two errors, the approved units are also of one of two types: conforming units and missed defective units. Let d be the defect rate upon arrival to an inspection, α the type I error rate and β the type II error rate. Then, the portion of units that continues after the inspection is: $\beta\cdot d + (1-\alpha)\cdot(1-d)$ and the conforming rate upon leaving the inspection is:

$$(1-\alpha)\cdot(1-d)/[\beta d + (1-\alpha)\cdot(1-d)]. \tag{3}$$

However, inspections fix nothing. It is the removal of the defective units detected by the inspections that improves the outgoing quality. Further, usually one cannot tell whether a rejected unit is defective or a false rejection, whenever units are rejected more units must be produced to replace them – any rejected unit requires compensation. Hence, the required input of an inspection is:

$$Q/(1-\alpha)\cdot(1-d). \tag{4}$$

Following the description above, each OPC is traversed twice. First, with the direction of the arrows, conforming rates are calculated using the generalized Eq. (2) for operations and Eq. (3) for inspections. Upon arrival to the last activity, the overall yield rate of the whole process is obtained. Then, a backward traverse is conducted. The process yield rate is substituted in Eq. (1) to derive the required input to the last activity for the desired input. Then, going back on each arrow the required input for the activity in the arrow's head is multiplied by the assembly ratio on the arrow, $m(k) = 1$ if not specified otherwise, to determine the required output from the activity on the arrow's tail, and Eq. 4 is employed whenever an inspection is encountered.

4 Results

Key factors, as noted in the introduction, are the volumes of material flows, which are derived from the volumes of material requirements. Consequently, material requirements are considered first.

4.1 Yield rates and material requirements

Material requirements, as also noted, depend on the yield rates. Hence, the calculations begin with these rates. The calculations are demonstrated on a couple of simple cases – no inspection and a single, final, inspection after operation 0. No inspection means that the inspections in activities 1, 2, 5 and 6 are inactive. That is: $\alpha = 0$ and $\beta = 1$ for all four inspections. Assuming, for convenience only, that the arriving materials to operations 9, 10 and 11 are of perfect quality, the yield rate of each is 97%. Substituting this value in Eq. (2) for operations 7 and 8 result in 94.09% yield rate for both. Continuing from operation 7 to operation 4, the yield rate of the latter is about 91.27%. Passing over the inactive inspections 5 and 6, the yield rate of the assembly operation 3 is: $0.97 \cdot 0.9409^2 \cdot 0.97 \approx 83.3\%$, where the first 0.97 is the self defect rate of the assembly, while the 0.97 at the end corresponds to the component which arrives from operation 9. The term is the middle corresponds to the component that arrives from operation 8 and is squared because its assembly ratio is 2. Passing, again, over the inactive inspections 1 and 2, the yield rate of the assembly activity 0 can be calculated: $0.97 \cdot 0.9127 \cdot 0.8333 \approx 51.17\%$. Noteworthy are the assemblies' mutual effects – the dramatic drop of the yield rates in operations 3 and 0. In this example, the last value: 51.17% is the process yield rate, too – the outgoing quality. This implies that just a little less than half of the assembled units are defective. Consequently, in order to produce say, 1,000 conforming units, $1{,}000/0.5117 \approx 1{,}954.4$ units should be assembled, on average, knowing that on average, 954.4 of them will be waste.

Traversing back on the OPC, no assembly is conducted on the lower branch of the chart and hence, the same number: 1,954.4 units are required in operations 4, 7 and 10. Since 3 units of the sub-assembly, which are assembled in operation 3 are assembled in each unit in operation 0, about 5,863.3 sub-assemblies are required. The assembly ratio of the components which arrive through operation 9 is 1, 5,863.3 units are required of this component, while some 11,727 units are required of the other component, whose assembly ratio is 2. Note again the assemblies' mutual effects. Of the 1,954.4 units which arrive to operation 0 from operation 4, only about 8.7% or 170.6 units are defective, on average. Another 1,954.4 - 1,000 - 170.6 = **783.8** units, are conforming units which will either be assembled with defective sub-assemblies or the assembly will turn defective in operation 0. The same hold for the sub-assembly: 979.3 defective sub-assemblies arrive to operation 0, out of 5,863.3 and only 3,000 are required to assemble 1,000 units in operation 0. This leaves **1,884** conforming sub-assemblies, on average, which will either be assembled with defective mates (sub-assemblies) or defective unit of the other component, or the assembly turn defective in operation 0.

A simple, perhaps the simplest, way to improve the outgoing quality is to inspect the assembled units when leaving operation 0. Assuming that $\alpha = 2\%$ and $\beta = 3\%$, as specify for all the inspections in Figure 1, another 2% of the conforming assemblies will be falsely rejected. Thus, only $0.98 \cdot 0.5117 \approx 50.14\%$ of the assembled units will pass the inspections. In parallel, 3% of the defective assemblies, a bit less than 1.5% of the assembled units will be missed by the inspection. The resultant outgoing quality is, thus, 97.16% (roughly 0.5014/(0.5014+0.015), up to the rounding of the numbers). While this is a significant quality improvement, the required input has grown, according to Eq. (4), to 1994.3 units, on average, adding yet more waste.

Three more cases, where some in-process inspections are active, have been analyzed: inspection 1 and 2 are active; inspections 5 and 6 replace inspection 1, that is 2, 5 and 6 are active; and all four inspections are active. The results are summarized in Table 1. In the left column in the table, A#, the activity numbers are listed. In the next column, S#, the successor of each activity, the activity at the head of the arrow pointing out from the activity in A#, is shown. These activity-successor pairs play important role in analyzing material flows. In the column headed 'type', the station type chosen for each activity – the letter in its circle in the OPC, is shown. "I" in this column indicates inspection. In the column headed '$m(i)$', the assembly ratios are listed while In the column headed 'u/t', the numbers of units per MH trip are listed. The remaining columns are paired – a pair for each case. In the left column in each pair, which is headed 'volume' the material requirements are listed. The numbers calculated above appear in the two pairs on the left: no inspection and final inspection. In the right column of each pair the number of MH trips are listed. These numbers are obtained by dividing the corresponding volume by the corresponding number of units per trip. The number of trips on the row of operation 0, for example, are the corresponding volumes divided by 20.

Table 1 Material requirements and material flows

A	S				No inspection		Final inspect.		Inspect. 1+2		Inspect.2+5+6		Ins. 1+2+5+6	
#	#	type	$m(i)$	u/t	volume	trips	volume	trips	volume	trips	volume	trips	volume	Trips
0			1	20	1954.4	97.7	1994.3	99.7	1053.1	52.7	1149.3	57.5	1037.4	51.9
1	0	I	3	60					3870.2	64.5			3289.5	54.8
2	0	I	1	150					1177.4	7.85	1284.9	8.57	1159.8	7.73
3	1	SA	1	60	5863.3	97.7	5983	99.7	3870.2	64.5	3447.8	57.5	3289.5	54.8
4	2	D	1	150	1954.4	13	1994.3	13.3	1177.4	7.85	1284.9	8.57	1159.8	7.73
5	3	I	2	200							7478.3	37.4	7135	35.7
6	3	I	1	150							3627	24.2	3460.5	23.1
7	4	G	1	150	1954.4	13	1994.3	13.3	1177.4	7.85	1284.9	8.57	1159.8	7.73
8	5	D	1	200	11727	58.6	11966	59.8	7740.5	38.7	7478.3	37.4	7135	35.7
9	6	G	1	150	5863.3	39.1	5983	39.9	3870.2	25.8	3627	24.2	3460.5	23.1
10	7	C	1	150	1954.4	13	1994.3	13.3	1177.4	7.85	1284.9	8.57	1159.8	7.73
11	8	C	1	200	11727	58.6	11966	59.8	7740.5	38.7	7478.3	37.4	7135	35.7

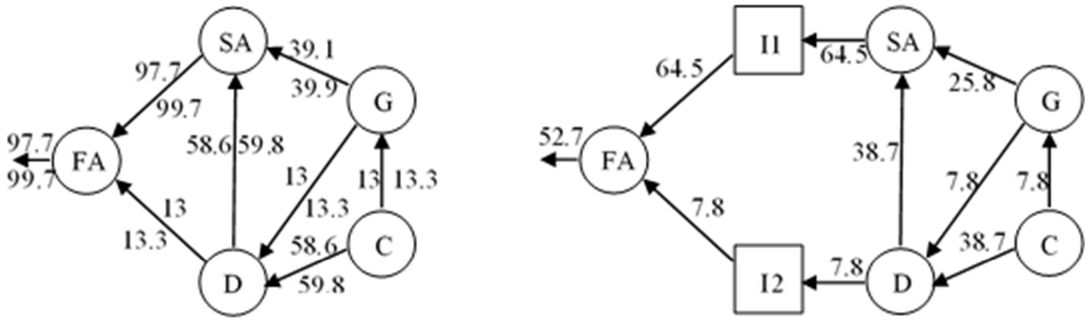
The yield rates of the three cases on the right side of Table 1 – with in-process inspections, are: 94.96%, 87.01% and 96.4%, respectively. These values are less than the 97.16% of the final inspection but much higher than 51.17% with no inspection. Further, the corresponding scenarios involve much less waste as indicated by both the volumes – the material requirements, and the numbers of MH trips in the corresponding columns. In this example, the replacement of inspection 1 with 5 and 6 appears to be inferior – lower yield rate and higher waste, while the addition of 5 and 6 to 1 and 2 requires deeper examination since two more inspections are required to obtain rather small improvements. Cost factors might be incorporated in the analysis to facilitate resolution.

Another phenomenon in Table 1 are the empty cells. These cells correspond to inactive inspections and are associated with the structure of the material flow network, as discussed next.

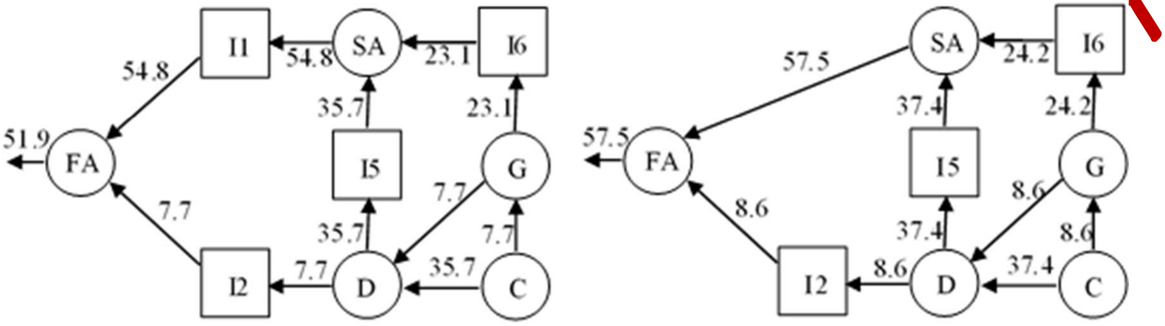
4.2 *Quality, inspections and material flows*

In this section the goal of this study is arrived at: the association between and the dependencies of material flows on quality and the configuration of the quality assurance – inspections', system. Observe that, while few arrows can point into an activity, only a single arrow points out of each activity in Figure 1. This is a general observation, any OPC can have this attribute and if not, it can easily be decomposed into several OPCs, each of which has this attribute. As a consequence, the activity-successor association can be used and the relevant information to each arrow can be presented next to the activity on its tail, as in the columns headed $m(i)$ and 'u/t' in Table 1. An assembly ratio $m(i)$ associates each activity to its successor and the 'u/t' entry is the number of units per MH trip from the activity to its successor. However, several operations can be conducted in the same station type and materials flow between stations. For example, the arrow between operations 11 and 8 represents flows from station type C to station type D. Similarly, the arrow between operations 10 and 7 represents flows from C to G. This information can also be found in Table 1. Not in the example in Figure 1, but in general, there might be many arrows between the same station types, either in the same OPC or in different OPCs of other products which are produced in the same multi-product system. The MH system should handle total flows: the sums of the flows – of the numbers of material handling trips, on all the arrows between the same station types and in the same direction. This information and this discussion lay the foundations for material flow analyses.

Figure 2 is the core of this study. It portrays the material flow networks: structure and volumes, for the cases in Table 1; but while there are five cases in Table 1 there are only four networks in Figure 2, because in the network (a) both first cases of Table 1: no inspection and final inspection, are presented. This is done by displaying two volumes on each arrow: the smaller volumes correspond to the 'no inspection' case, while the larger volumes correspond to the 'final inspection' case. Since the 'final inspection' follows operation 0, it is not shown in the network (a) but the arrow pointing out of operation 0 either leads to the inspection or elsewhere – storage, etc.



(a) No/Final inspection (b) Inspections 1 and 2 are active



(d) Inspections 1, 2, 5 and 6 are active (c) Inspections 2, 5 and 6 are active

Figure 2 An extended operations process chart

A quick glimpse at Figure 2 tells the whole story. First, the structures of the four networks are different and second, the flow volumes are different. All these differences are ramifications of imperfect quality. Changes in quality levels – the yield rates, will result in different volumes. Moreover, imperfect quality forces the use of inspections and Figure 2 clearly demonstrates how the design of the inspection system affects both the structure of the material flow network and the volumes of the flows.

5 Conclusions

Comparing the numbers in Table 1 and the networks in Figure 2 reveals the complexity of the inspection system's design problem. To illustrate, consider the arrow from D to FA in the network (a). Inspection 2 splits the MH trips on this arrow – each trip is divided into two legs, but while the volumes on each leg is smaller than both values in the network (a), their sum is larger. The distances are out of the scope of this study but additional stations require additional space thereby lengthening the distances. In addition, each MH trip involves a load and an unload of the cargo, adding more work to the MH equipment. Consequently, the selection of the desired solution: where to improve the quality, where to place inspections etc., is a complex problem, and material flow is just one of its many facet.

While a single and very small example is used in the presentation above, the generality of the conclusions is easy to imagine. No system is perfect. In the quality literature, in particular, there is a distinction between 'in' and 'out' of control', where even when a process is 'in control' the quality is not perfect, but within acceptable level; e.g., [15,16]. Hence, the questions at the end of the previous section always exist, including the implications on material flows and the MH system and its design. Surfacing these facets, which have been ignored thus far despite their significance, is a significant contribution of this study. In addition, the tools used above are generally applicable to analyze and design manufacturing/production systems of multiple products with assembly operations.

References

[1] LEUNG, C.S., LAU, H.Y.K.: *Simulation-based optimization for material handling systems in manufacturing and distribution industries*, Wireless Networks, pp. 1-22, Nov. 2018.

[2] TELEK, P.: *Process-based planning of material handling in manufacturing systems*, XXIII International Conference on Manufacturing (Manufacturing 2018), IOP Conference Series: Materials Science and Engineering, Vol. 448, pp.1-17, 2018. doi:10.1088/1757-899X/448/1/012018

[3] APPLE, J.M.: *Plant layout and material handling* (2nd Edition), The Ronald Press Company, New York, USA, 1963.

[4] FRANCIS, R.L., MCGINNIS, L.F., WHITE, J.A.: *Facility Layout and Location: An Analytical Approach*, 2nd ed., Englewood Cliffs, N.J. USA, Prentice-Hall Inc., 1992.

[5] TOMPKINS, J.A., WHITE, J.A., BOZER, Y.A., TANCHOCO, J.M.A.: *Facilities Planning*, 4th ed., New York, USA, Wiley, 2010.

[6] STEPHENS, M.P.: *Manufacturing Facilities Design & material handling*, 6th ed., West Lafayette, Indiana, USA, Purdue University Press, 2019.

[7] KLAUSNITZER, A., LASCH, R.: Optimal facility layout and material handling network design. *Computers and Operations Research*, Vol. 103, pp. 237-251, 2019. doi:10.1016/j.cor.2018.11.002

[8] LI, J., BLUMENFELD, D. E., HUANG, N., ALDEN, J. M.: Throughput analysis of production systems: recent advances and future topics, *International Journal of Production Research*, Vol. 47, No. 14, pp. 3823-3851, 2009.

[9] CHAWLA, V.K., CHANDA, A.K., ANGAR, S.: Material handling robots fleet size optimiztion by a heuristic, *Journal of Project Management*, Vol. A, No. 3, pp. 11-188, 2019. doi: 10.5267/j.jpm.2019.4.002

[10] TU, Ying-Mei, LU, Chun-Wei, LEE, Amy H.I.: AMHS capacity determination model for wafer fabrication based on production performance optimization, *International Journal of Production Research*, Vol. 51, No. 18, pp: 5520-5535, 2013. doi: 10.1080/00207543.2013.784416

[11] HU S.J., KO, J., WEYAND, L., ELMARAGHY, H.A., LIEN, T.K., KOREN, Y., BLEY, H., CHRYSSOLOURI, G., NASR, N., SHPITALNI., M.: Assembly system design and operations for product variety, *CIRP Annals-Manufacturing Technology*, Vol. 60, No 2, pp. 715-733, 2011.

[12] BUZACOTT, J.A., SHANTHIKUMAR, J.G.: *Stochastic Models of Manufacturing Systems*, Englewood Cliffs, N.J., USA, Prentice-Hall Inc., 1993.

[13] HOPP, W.J., SPEARMAN, M.L.: *Factory Physics*, 3rd ed., New York, USA, McGraw-Hill, 2011.

[14] EBEN-CHAIME, M.: Mutual Effects of Defective Components in Assemblies, *Journal of Manufacturing System*, Vol. 36, No. 1, pp. 1-6, 2015. doi: 10.1016/j.jmsy.2015.02.008

[15] MANDROLI, S.S., SHRIVASTAVA, A.K., DING, Y.: A survey of inspection strategy and sensor distribution studies in discrete-part manufacturing processes, *IIE Transactions*, Vol. 38, No. 4, pp. 309-328, 2006.

[16] SHI, J., SHIYU, Z.: Quality control and improvement for multistage systems: A survey, *IIE Transactions*, Vol. 41, No. 9, pp. 744-753, 2009.

[17] CHEIKHROUHOU, N., SARKAR, B., GANGULY, B., MALIK, A.I., BATISTA, R., LEE, Y.H.: Optimization of sample size and order size in an inventory model with quality inspection and return of defective items, *Annals of Operations Research*, Vol. 271, No. 2, pp. 445-467, 2018.

[18] LOPES R.: Integrated model of quality inspection, preventive maintenance and buffer stock in an imperfect production system, *Computers & Industrial Engineering*, Vol. 126, pp. 650-656, 2018. doi:10.1016/j.cie.2018.10.019

[19] TEKIN, S., ANDRADÓTTIR, S.: Inspection location in capacity constrained lines, *Central European Journal of Operations Research*, Vol. 14, No. 1, pp. 1-33, 2019.

[20] ORLICKY, J.: *Material requirements planning: the new way of life in production and inventory management*, NY, USA, McGraw Hill, 1975.

Review process

Single-blind peer review process.