World Academy of Science, Engineering and Technology
International Journal of Industrial and Manufacturing Engineering
Vol:4, No:5, 2010

Analysis of Production Loss on a Linear Walking Worker Line

Qian Wang, Sylvain Lassalle, Antony R. Mileham, and Geraint W. Owen

***Abstract*—**This paper mathematically analyses the varying magnitude of production loss, which may occur due to idle time (in-process waiting time and traveling time) on a linear walking worker assembly line. Within this flexible and reconfigurable assembly system, each worker travels down the line carrying out each assembly task at each station; and each worker accomplishes the assembly of a unit from start to finish and then travels back to the first station to start the assembly of a new product. This strategy of system design attempts to combine the flexibility of the U-shaped moving worker assembly cell with the efficiency of the conventional fixed worker assembly line. The paper aims to evaluate the effect of idle time that may offset the labor efficiency of each walking worker providing an insight into the mechanism of such a flexible and reconfigurable assembly system.

***Keywords*—**Production lines, manufacturing systems, assembly systems, walking workers.

I. Introduction

MANY manufacturing companies are increasingly moving towards highly flexible production facilities making use of flexible machinery and highly skilled workers [1]. For example, approximately one third of all German companies that have invested in highly advanced automaton have recognized that these solutions are not flexible enough and have reduced again their level of automation; 38% of these companies have reduced automation by taking advantage of a more efficient use of their qualified workforce [2]. These workers are normally trained to perform multiple or all the required tasks in a production area leading to significant improvements in terms of cost, time, quality and variety over a traditional static allocation of workers to stations in which each worker only performs a single and repetitive task.

In this paper, the authors present a study of a so-called linear walking worker assembly line which has been implemented into a local medium-sized manufacturing company. The company produces medium to large pipeline actuators with a range of eight basic models and a high level of customization for each product. The assembly system is illustrated in Fig. 1; each worker travels with a partially assembled product downstream and stops at each station carrying out the essential assembly work as scheduled. Each worker is previously trained to be capable of building a product completely from start (the first station) to end (the last station) along the line. Under such a 'pull' system, a new item of assembled products enters the line whenever a walking worker is available after a product assembly is completed by this walking worker at the end of the line and this worker then releases the assembled product and moves back to the first station ready to start a new item. Because each item can only travel with one walking worker who works on it by visiting all stations along the line, the number of items in the system is therefore deterministic and theoretically it cannot be greater than the total number of workers employed on the line. Thus, this type of system inherently prevents unnecessary in-process inventory thereby decreasing the buffer requirement. Moreover, each walking worker on the line cannot be starved because each worker is attached to one item all the time and it is their responsibility for completely assembling a product within an expected cycle time through training, this decreases the loss of labor efficiency and maximizes individual labor utilization in practice. Nevertheless, the loss of labor efficiency can be made by the idle time, which includes the combination of possible in-process waiting time and traveling time incurring from each walking worker.

The authors only found one similar study of a linear type of the walking worker line on which walking workers follow an operational rule called 'bucket brigade'. Within this 'bucket brigade' system, each worker carries work forward from station to station until someone takes over her/his work; then this worker goes back to take the work from her/his predecessor. A comprehensive survey of the 'bucket brigade' method was summarized by Bratcu and Dolgui [3, 4]. The main benefit reported by Bartholdi *et al* [5] is that this simple functioning protocol yields a spontaneous line balancing. Zavadlav *et al* [6] argued that this rather stressful baton-relay-like production manner may exhibit chaotic in practice. Apparently, the linear walking worker assembly line described from this paper is operated differently as one described in the 'bucket brigade' walking worker line. The focus of the work presented in the paper is to investigate the varying magnitude of idle time (i.e. in-process waiting time and traveling time) that may affect the system performance providing an aid in determining and optimizing the design of such a dynamic,

Q. Wang (corresponding author), Department of Mechanical Engineering, University of Bath, Bath, UK (tel: +44 (0) 1225 385138; fax: +44 (0) 1225 386928; e-mail: Q.Wang@bath.ac.uk).
S. Lassalle, IFMA, Campus Des Cezeaux, France (e-mail: Sylvain.Lassalle@ifma.fr).
A. R. Mileham, Department of Mechanical Engineering, University of Bath, Bath, UK (e-mail: A.R.Mileham@bath.ac.uk).
G. W. Owen, Department of Mechanical Engineering, University of Bath, Bath, UK (e-mail: G.W.Owen@bath.ac.uk).

flexible and reconfigurable assembly system using walking workers.

II. Analysis of the Linear Walking Worker Assembly Line

Fig. 1 illustrates the linear walking worker assembly line, where a walking worker j completes a product at the last machine Mm; this worker then moves back to the first machine M1 to begin the assembly of a new product.

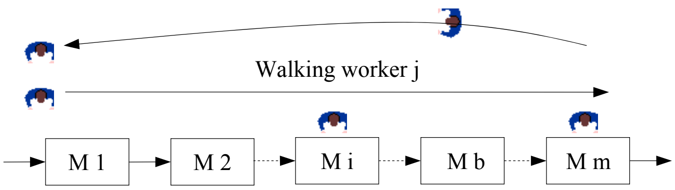

Fig. 1 The linear walking worker assembly line

The following assumptions and constraints are used in this study:

1. To avoid collision, a faster worker will not overtake a slower worker, i.e., FIFO (first in first out).
2. Breakdown, setup or changeover times are not considered in this case study.

The following notations are used:

- *m*: the total number of stations (or machines) on the line.
-*N*: the total number of walking workers in operating the system.
- PTi : the processing time (fixed) at machine i .
- PTi, j : the processing time at machine i for walking worker j (1 ≤ j ≤ N).
- *IPWTj*: the in-process waiting time for worker j (1 ≤ j ≤ N).
- *TTj*: the average traveling time for walking worker j (1 ≤ j ≤ N), who travels from the first station to the last station down the line.
- *ITj:* the total idle time for walking worker j (1 ≤ j ≤ N) during a completion of a product.

A. Workers with Equal Performance

In the first case study, we assume that each walking worker has equal efficiency; this is an ideal situation. Shown in Fig. 1, we note that machine b (Mb), where b refers to the bottleneck, has the longest processing time. After a period of system warm-up to reach a steady state, from the moment that a walking worker j leaves the bottleneck Mb to the moment that this worker is about moving into the bottleneck Mb again (but not in Mb yet), a total amount of processing (operation) time this walking worker spends in a circuit is given by:

$$\sum_{\substack{i=1 \\ i \neq b}}^{m} (PTi) = \sum_{i=1}^{m} (PTi) - PTb \qquad (1)$$

Meanwhile, a total amount of time that other walking workers (except walking worker j) spend in terms of processing (operation) times at Mb is given by:

$$(N-1) \times PTb \qquad (2)$$

If (1) ≥ (2): there is no in-process waiting time. If (1) < (2): the in-process waiting time for this walking worker j is given by:

$$IPWTj = (2) - (1) = [(N-1) \times PTb] - [\sum_{i=1}^{m} (PTi) - PTb],$$

i.e.,

$$IPWTj = N \times PTb - \sum_{i=1}^{m} PTi \qquad (3)$$

Thus, the total idle time for this worker j during the completion of a product is given by:

$$ITj = IPWTj + 2TTj = N \times PTb - \sum_{i=1}^{m} PTi + 2TTj, \text{ i.e.,}$$

$$ITj = N \times PTb - \sum_{i=1}^{m} PTi + 2TTj \qquad (4)$$

Therefore, the amount of time this walking worker needs for producing a unit in a circuit is given below:

$$ITj + \sum_{i=1}^{m} (PTi) \text{, or,}$$

$$N \times PTb + 2TTj \qquad (5)$$

Based on this, the output worker j produces after a period of run Tp is given by:

$$Tp \,/\, [\, N \times PTb + 2TTj \,] \qquad (6)$$

Because we assume that each walking worker has equal efficiency in this case; for a system with N walking workers, the overall output after a period of run Tp is given by:

$$N \times \{\, Tp \,/\, [\, N \times PTb + 2TTj \,] \,\} \qquad (7)$$

B. Workers with Unequal Performance

In practice, it is impossible that each walking worker has equal efficiency. In this case, the slowest worker may determine the overall output of the line. After a warm-up period, the slowest worker will only possibly encounter the in-process waiting time in front of the bottleneck machine Mb. From the moment that the slowest worker s leaves the bottleneck, this worker needs the following amount of time to arrive to it again in a circuit:

$$\sum_{\substack{i=1 \\ i \neq b}}^{m} (PTi, s) = \sum_{i=1}^{m} (PTi, s) - PTb, s \qquad (8)$$

Meanwhile, a total amount of time that other walking workers spend at Mb is given by:

$$\sum_{\substack{j=1 \\ j\neq s}}^{N}(PTb,\, j) \tag{9}$$

If (8) ≥ (9): there is no in-process waiting time. If (8) < (9): the in-process waiting time for the slowest walking worker s is given by:

$$IPWTs = (9) - (8) = [\sum_{\substack{j=1 \\ j\neq s}}^{N} PTb,\, j] - [\sum_{i=1}^{m}(PTi, s) - PTb, s],$$

or

$$IPWTs = [\sum_{j=1}^{N} PTb,\, j] - [\sum_{i=1}^{m}(PTi, s)] \tag{10}$$

Thus, the total idle time for this slowest worker s during the completion of a product is given by: *ITs* = *IPWTs* + *2TTs*, i.e.,

$$ITs = [\sum_{j=1}^{N} PTb,\, j] - [\sum_{i=1}^{m}(PTi, s)] + 2\text{TTs} \tag{11}$$

Knowing that a faster worker cannot overtake the slowest worker, therefore, each walking worker will have the same output as the slowest worker can produce. We define T to be the amount of time each walking worker needs for producing a unit, two cases are possible:

If the slowest walking worker does not encounter any in-process waiting time:

$$T = \sum_{i=1}^{m} PTi, s\ + 2\text{TTs} \tag{12}$$

Because IPWTs is 0, based on equation 10, T can also be given by:

$$T = \sum_{j=1}^{N} PTb,\, j\ + 2\text{TTs} \tag{13}$$

If the slowest worker encounters an in-process waiting time before moving into the machine b:

$$T = IPWTs + \sum_{i=1}^{m} PTi, s + 2\text{TTs} \tag{14}$$

or,

$$T = \sum_{\substack{j=1 \\ j\neq s}}^{N} PTb,\, j\ + 2\text{TTj} \tag{15}$$

Finally, a total amount of in-process waiting time a walking worker j spends for producing one unit is given by:

$$IPWTj = T - \sum_{i=1}^{m} PTi,\, j\ - 2\text{TTj}$$

or

$$IPWTj = \sum_{\substack{j=1 \\ j\neq s}}^{N} PTb,\, j - \sum_{i=1}^{m} PTi,\, j \tag{16}$$

III. Case Studies

Let us consider a simplified case based on the linear walking worker assembly line with system parameters shown in Table 1. It indicates varying cycle times (mean) at different stations on the 8-station (M1-8) line and the reconfigured 9-station (M1-9) line respectively. Both lines, however, have the same work content. Apparently, station M7 has the longest processing time in each case and it is considered as a major bottleneck station along the line. We also describe a qualified walking worker who is able to complete a unit within an expected cycle time from the first station (M1) to the last station (M8 or M9) as a fully efficient worker (let us say 100% efficiency); and describe a slower walking worker who has, for example, 95% efficiency of qualified walking workers.

We assume that an average traveling time between two adjacent stations for each worker is 5 seconds. Thus, with 8 walking workers (2 slower walking workers at 95% efficiency) operating on the 8-station line, the total idle time for the slower worker s to produce a unit in a circus is given below:

TABLE I
The Cycle Times in Seconds at Different Stations

Stations	Original Cycles Times	Rebalanced Cycle Times
M1	105	89
M2	69	83
M3	100	88
M4	82	92
M5	115	95
M6	121	89
M7	123	106
M8	102	93
M9	n/a	82
Total Cycle Time	817	817

$$ITs = IPWTs + 2TTs =$$

$$[\sum_{j=1}^{8} PTb,\, j] - [\sum_{i=1}^{8}(PTi, s)] + 2\times 35 \approx 207s.$$

Therefore, the total loss of labor efficiency for each walking worker to produce a unit accounts for about 20.2 % of the full capacity, in which about 13.4 % of the full capacity is lost due to the total in-process waiting time (137s) and about 6.8 % of the full capacity is lost due to the total traveling time (70s).

By reducing the number of walking workers on the line to be 7 (2 slower walking workers at 95% efficiency) operating on the same line, the total idle time can be significantly reduced to be 84s, in which about 1.6 % of the full capacity is lost due to the total in-process waiting time (14s) for each walking worker as shown below:

$$ITs = IPWTs + 2TTs =$$

$$[\sum_{j=1}^{7} PTb, j] - [\sum_{i=1}^{8} (PTi, s)] + 2 \times 35 \approx 84s.$$

By contrast, the total loss of labor efficiency is mainly caused by the total travelling time for each walking worker, which accounts for about 7.8 % loss of the full capacity in this case. The above results demonstrate that the in-process waiting time can be altered or decreased by simply adjusting the number of walking workers on the line. This can not be done from the conventional line using fixed workers as the line needs to be fully manned at all stations during a period of production.

Alternatively, the in-process waiting time can also be reduced by having one more station than the number of walking workers on the line. For instance, with 8 walking workers (2 slower walking workers at 95% efficiency) and the same work content on the reconfigured 9-station line, the in-process waiting time for the slower walking worker s is given below:

$$IPWTs = [\sum_{j=1}^{8} PTb, j] - [\sum_{i=1}^{9} (PTi, s)] \approx 0s.$$

With this approach, the in-process waiting time can be significantly decreased whilst the loss of labor efficiency is purely caused by the total traveling time (80s), which accounts for about 8.9 % loss of the full capacity in this case. Nevertheless, this result is obtained based on one assumption that the work content at stations is divisible.

We can also use the developed equations to calculate the minimal number of walking workers required to match a target of a demand rate on a daily or weekly basis. For example, within the 8-station line, assuming that each walking worker has equal performance (i.e., 100% efficiency) apart from one slowest walking worker who has an average 95% efficiency of other walking workers, it can be computed that the line is capable of producing 1 unit every 130 seconds as the longest processing time (123s) and the slowest walking worker (at 95 % efficiency) determine the overall output rate in this case) or 222 units per day (8 hours per shift),

i.e., $\frac{3600 \times 8}{130} = 222$ units per day.

If a daily demand of 150 units is planned, it can be computed that the line is required to produce 1 unit every 192 seconds; we then have

$$[\sum_{i=1}^{8} (PTi, s)] + 2 \times 35 \leq 192 \times N \text{ or}$$

$$N \geq \{\sum_{i=1}^{8} (PTi, s)] + 2 \times 35\} / 192,$$

we get N ≥ 4.84. In theory, with a minimum number of 5 walking workers (including one slowest walking worker at 95% efficiency), the line can achieve the daily demand of 150 units as requested.

IV. Conclusion

This paper presents a mathematical analysis of a so-called linear walking worker assembly line based on a real production line in a local manufacturing plant. The overall research work aims to provide the better understanding of such a dynamic, flexible and reconfigurable assembly system. The focus of this paper is to investigate the idle time, which includes the in-progress waiting time and the traveling time, each walking worker may encounter due to bottlenecks and traveling distances along the line. These bottlenecks can be a machine with the longest processing time or a walking worker with variable performance. The determination of this idle time is one key factor in the system design as it affects the overall cycle time for each walking worker to produce a unit in its entirety from start to finish. The research concludes that the effect of bottlenecks, which may lead to the in-progress waiting time, can be simply reduced using the walking worker method. It is also of note that optimizing the number of walking workers (or stations) on the line can alter and decrease the in-process waiting time thereby increasing the worker utilization (e.g., in terms of the output per worker per hour).

Acknowledgment

The authors wish to acknowledge Paul Kimmins, Graeme Oliver and Tim Eggington, Rotork Controls Ltd., for their cooperation in providing data, in-house training and measurement on site in the factory. The work has been carried out at the EPSRC E-IdMRC at the University of Bath (RC-ME0096H), Bath, UK.

References

[1] W. J. Hopp, M. R. Iravani, and B. Shou, "Serial agile production systems with automation," Operations Research, vol. 52, pp. 852–866, 2005.

[2] H. Bley, G. Reninhart, G. Seliger, M. Bernardi, and T. Korne, "Appropriate human involvement in assembly and disassembly," CIRP Annals, vol. 53, pp. 487–509, 2004.

[3] A. I. Bractu, and A. Dolgui, "A survey of the self-balancing production lines ("bucket brigades")," Journal of Intelligent Manufacturing, vol. 16, pp. 139–158, 2005.

[4] A. I. Bratcu, and A. Dolgui, "Some new results on the analysis and simulation of bucket brigades (self-balancing production lines)," International Journal of Production Research, vol. 47, pp. 369–387, 2009.

[5] J. J. Bartholdi, D. Leonid, and D. D. Eisenstein, "Dynamics of two- and three-worker "bucket brigade" production lines," Operations Research, vol. 47, pp. 488–491, 1999.

[6] E. Zavadlav, J. O. McClain, and L. J. Thomas, "Self-buffering, self-balancing, self-flushing production lines," Management Science, vol. 42, pp. 1151–1164, 1996.

Qian Wang is a senior researcher of the Innovative Design and Manufacturing Research Centre (IdMRC) in the Department of Mechanical Engineering at the University of Bath, UK. He had experience of both industry and academia in diverse projects. He received his PhD in Industrial and Manufacturing Systems from the University of Sussex, UK. His current research interest involves the design and optimization of flexible and reconfigurable assembly systems and warehousing systems.

Sylvain Lassalle was a research engineer based in IFMA, France. He received his MSc degree after he successfully completed his MSc project in Walking Worker Assembly Lines in 2006.

Antony R. Mileham is a Professor and was Head of the Department of Mechanical Engineering at the University of Bath, UK. His research interest covers a broad area of manufacturing with particular reference to the modeling and optimization of manufacturing processes and systems.

Geraint W. Owen is a Lecturer in Design and Manufacturing in the Department of Mechanical Engineering at the University of Bath, UK. His research activities are focused on reduction of changeover times, flexible assembly system design, reverse engineering and rapid sheet metal prototyping.