Modified work rule for Y-shaped self-balancing line with walk-back and travel time

Daisuke Hirotani†
Faculty of Management and Information Systems
Prefectural University of Hiroshima, Hiroshima, Japan
Tel: (+81) 82-251-9737, Email: dhiro@pu-hiroshima.ac.jp

Katsumi Morikawa
Faculty of Engineering
Hiroshima University, Higashi-Hiroshima, Japan
Tel: (+81) 82-424-7704, Email: mkatsumi@hiroshima-u.ac.jp

Katsuhiko Takahashi
Faculty of Engineering
Hiroshima University, Higashi-Hiroshima, Japan
Tel: (+81) 82-424-7705, Email: takahasi@hiroshima-u.ac.jp

Keisuke Nagasawa
Faculty of Engineering
Hiroshima University, Higashi-Hiroshima, Japan
Tel: (+81) 82-424-7703, Email: nagasa-kei@hiroshima-u.ac.jp

Abstract. In the traditional lines such as assembly lines, usually each worker is assigned to a particular fixed work. However, when the imbalance between workers' speeds exists, if any worker will delay the overall work in the line, the production rate of the particular line will also decrease. For avoiding this problem, "Self-Balancing Line" was introduced. In this type of line, each worker is assigned work dynamically, thus they can keep the balanced production under satisfying the specific conditions, and line is assumed to be serial. Recently, papers that assume Y-shaped type have been published. In this type of line, line has two sub-lines and then combines two sub-lines. In the previous paper of Hirotani *et al.* (2015), condition for achieving the maximum production rate can be derived. However, any worker takes more time to walk-back or travel according to the worker position. Therefore, to modify rule that introduce waiting for any worker according to the workers position, walk-back and travel time decreases comparing waiting time, and then production rate increases. In this paper, work rule that modify the self-balancing line is proposed and compared with the traditional work rule such as traditional self-balancing line and fix work assignment rule.

Keywords: Self-Balancing Line, Walk-Back time, Travel Time, Y-shaped, Work Rule

1. INTRODUCTION

In the traditional assembly line, each worker is usually assigned to a fixed work, and each worker iterates the assigned work continuously as assembly line balancing. For this line, assigning workers to the balanced work is studied in the previous research, (for example, Scholl (1995)). When imbalance of speed of workers exists in this kind of line, the slowest worker will delay the overall work. As a result, the production rate of the production line will also decrease. For solving this problem, "Self-Balancing Production Line" was introduced. The utilization of the mentioned method is reported in at least two commercial environments: apparel manufacturing and distribution warehousing (Bartholdi *et al.* (1999)). In this type of production line, each worker is assigned to work dynamically, and when the last worker completes an item, he/she walks back and takes over the next item from his/her predecessor. Then, the predecessor walks back, takes over the next item from his/her predecessor, and so on until the first worker walks back and starts a new item. Since faster workers are assigned more work in processing an item, and slower workers are less, they can keep the balance. For this line with constant working speed, it has been found that the maximum production rate can be achieved if the workers are sequenced from slowest to fastest (Bartholdi and Eisenstein (1996)). Also, the other conditions for three workers have been found numerically by simulation (Bartholdi *et al.* (1999)), and the performance of production line with n workers have been analyzed analytically (Hirotani *et al.* (2006)) .

Recently, other types of production line have been analyzed. Lim (2011) analyzed the cellular production line. This line divide into two lines and each worker has different speed for two lines. Based on the paper, Lim and Wu (2014) analyzed cellular U-line with discrete work stations. Xu *et al.* (2014) analyzed tree-shaped production line. In this line, shape looks like "Y". Therefore, line has two sub-lines and then combines two sub-lines. In this type of line, it can utilize to order picking. There are three end points and these are located according to "Y" shape, and each truck picks an item according to the Y's route. For production, there are two parts and make one item with two parts, this situation can be considered. In the previous research of Bartholdi *et al.* (2006), if walk-back and travel times are ignored, result of traditional serial line can be applied. Xu *et al.* (2014) considers walk-back and travel time for only two workers. Hirotani *et al.* (2015) analyzed this kind of line for n workers. They find that if only one worker processes at specific place, the maximum production rate can be achieved. However, this condition is a strict condition, and any worker takes more time to walk-back or travel according to the worker position. Therefore, to modify rule that introduce waiting for any worker according to the workers position, walk-back and travel time decreases comparing waiting time, and then production rate increases. In this paper, work rule that modify the self-balancing line is proposed and compared with the traditional work rule such as traditional self-balancing line and fix work assignment rule.

This paper is organized as follows: In section 2, assumptions, and characteristics of this self-balancing production line with walk-back and travel time are explained. In section 3, we propose modified work rule for Y-shaped line. In section 4, we compare with the work rule of previous papers by production rate. Finally, concluding and remarks are described in section 5.

2. THE PRODUCTION LINE

2.1 Assumption

In this paper, the production line with the following assumptions is considered. These assumptions are the same as the previous paper (Hirotani *et al.* (2015)).

1. Each worker processes only one identical item sequentially.
2. Line shape looks like "Y" (see Figure 1). There are three end points (L, R, E) and one point (D) in this line. There are three sub-lines (LD, RD, DE). Length of each line is l, r, d, respectively. Note that $l<r$ and $l+r+d=1$. For each sub-lines, we call these L section, R section, D section, respectively.
3. Workers are sequenced from one to n on production line under the condition that these sub-lines combine to one line from point L to point E. Each worker processes according to the line from point L to point E. If any worker arrives at point D, he/she has to travel to point R, and then he/she processes again from point R. Process flow is also shown in Figure 1. Each worker cannot pass over the upstream and downstream workers.
4. Worker i processes with constant working speed $v_i(>0)$ regardless the line. Also, each worker has the same constant walk-back and travel speed $v_r(>0)$ for all workers.
5. When the last worker finishes processing an item, worker n walks back to the direction of worker n-1 and takes over the next item from worker n-1. Then, worker n-1 walks back to worker n-2 and takes over the next item from worker n-2. Similarly, all workers walk back to their preceding worker and take over the next item from the preceding worker, and worker 1 introduces a new item into the system from point L. Time for taking over an item is ignored.
6. The position of worker i when he/she starts to process is given by x_i under the condition that these sub-line combine to one line and length of virtually combined line is 1. Then, the position at iteration t is defined as $x_i^{(t)}$. Note that $x_1^{(t)}=0$ for any iteration t. This is because the first worker always starts to process a new item.

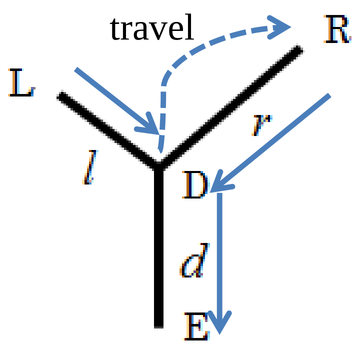

Figure 1: The Y-shaped production line and process flow for each worker

2.2 Behavior of workers for Y-shaped line

In this line, difference with traditional serial line with walk-back time is travel time. Figure 2 shows the time chart for three workers. In figure 2, dashed line represents instantaneous move at point D. This is because point D has two different points (i.e., 0.2 and 0.5 in figure 2). That is why this phenomenon occurs. If worker 1 arrives point D, he/she have to move to point R. During the travel, it takes time of $r*v_r$. In addition, in circle area, worker 1 takes over an item to worker 2 when worker 1 is traveling. If this phenomenon occurs, both worker have to travel or walk-back more.

Figure 2: Time chart for three workers

2.3 Previous result for related research

At first, we show the result of the serial line with walk-back time. This is because if travel time is ignored, the line is the same as the serial line with walk-back time (Bartholdi *et al.* (2006)). Condition of convergence that line can balance for n workers for all i (i=2,3,…,n) has been found in previous paper (Hirotani *et al.* (2005)) as follows:

$$\left(\sum_{k=1}^{i-1}(-1)^{i+k-1}\frac{v_k v_r}{v_k+v_r}\right)\left(\frac{1}{v_n}+\frac{1}{v_r}\right)<1 \tag{1}$$

If convergence, above mentioned fixed point that worker i (i=2,3,…,n) starts to process can be defined as follows (Hirotani *et al.* (2005)):

$$x_i^* = \frac{\sum_{k=1}^{n} C_{i-1}V_{n,k}v_r^{n-k}}{\sum_{k=1}^{n} kV_{n,k}v_r^{n-k}} \tag{2}$$

where $V_{n,k}$ is a product-sum of all combinations of the velocities of k workers chosen from v_1 to v_n, and C_i is the coefficient in $V_{n,k}$, which is the number which contains v_1 to v_i in $V_{n,k}$. For instance, $C_2V_{3,1}=1*v_1+1*v_2+0*v_3=v_1+v_2$. Note that $V_{n,0}=1$ and $C_0V_{n,k}=0$ for all n and k. Note that $x_1^*=0$ since worker 1 always start to process a new item.

In the previous paper of Xu *et al.* (2014), there are two workers and they assume $v_1<v_2<v_r$. Under these assumptions, they analyze according to the s:

$$s=\frac{1/v_2+1/v_r}{1/v_1+1/v_2+1/v_r} \tag{3}$$

This is a relative processing time and special case of equation (2) under n=2. Using this, they divide four areas: (a) $s<l$, (b) $l<s<r$, (c) $r<s<l+r$, (d) $s>l+r$.

Based on the previous paper of Xu *et al.* (2014), Hirotani *et al.* (2015) analyzed this kind of line for more than three workers. In that paper, they find that if only one worker processes in R section, the maximum production rate can be achieved since travel time can be substituted to walk-back time. Based on this result, they proposed the algorithm that higher production rate can be achieved for n workers.

3. MODIFIED WORK RULE FOR Y-SHAPEDLINE

In the work rule for traditional self-balancing production line as shown in section 2.1, worker has to process until taking over an item from his/her predecessor. However, as shown in Figure 3, when taking over occurs until traveling or walking-back time, it takes more traveling or walk-back time, and then, production rate decreases.

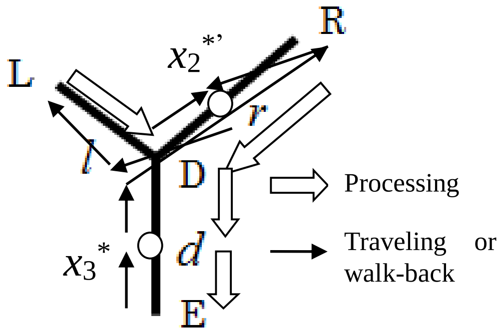

Figure 3: Example the case of increasing traveling and walk-back time for three workers

In this paper, we introduce the concept of waiting to decrease traveling and walk-back time and propose modified worker rule as follows:

Modified work rule for Y-shaped line

- Identify worker j^* that processes at point R deriving by equation (2) under the condition of $l < x_j^* < l + r$. If $j^*=2$, worker 1 processes only L section and when he/she arrive at point D, he/she has to wait until taking over an item to worker that processes at point D. If $j^* \neq 2$, worker j^*-1 processes only R section and when any worker arrives at point D, he/she has to wait until taking over an item to worker j^*. Other worker follows the work rule for traditional self-balancing line as shown in section 2.1.

We show an example under three workers. If $j^*=2$, worker 1 processes only L section, and arrives at point D earlier. Therefore, worker 1 has to wait. If new starting point for worker 2 is in R section, worker 3 takes over an item from worker 1 and exchanges an item with worker 2 when worker 3 walks-back and meets with worker 2. If new starting point for worker 2 is in D section, worker 2 takes over an item and worker 2 walks back to point R. If $j^*=3$ and new starting point for worker 3 is in R section, worker 3 has to wait at point D until taking over an item from worker 1, and then worker 3 walks-back to worker 2. If $j^*=3$ and new starting point for worker 3 is in D section, worker 2 has to wait at point D until taking over an item from worker 1, and then worker 2 walks-back to point R with an item. Other workers that not mention above follows rule of traditional self-balancing line.

4. COMPARISON WITH TRADITIONAL WORK RULE

In this section, to show effectiveness of proposed work rule, we compare with traditional work rules for three workers. The number of traditional work rule we consider is two. First is fixed work rule. In this rule, one worker processes only L section, one worker processes only R section, and the other worker only processes E section. In this case, production rate PR_{fix} can be calculated as follows:

$$PR_{fix} = 1/\max\left(\left(\frac{1}{v_1}+\frac{1}{v_r}\right)l, \left(\frac{1}{v_2}+\frac{1}{v_r}\right)r, \left(\frac{1}{v_3}+\frac{1}{v_r}\right)d\right)$$

Each term means spending time of processing and walking back for each worker. In that case, travel time cannot be considered and any worker may wait since an item has to be taken over, and production rate can be calculated as reciprocal of spending time. Therefore, above equation can be derived.

Second is traditional work rule without waiting. This rule is the same as Xu *et al.* (2014). In this comparison, we consider six cases that are the same as Hirotani *et al.* (2015) to derive x_2^* and x_3^* by equation (2) as follows:

$$x_2^* = \frac{v_1v_2v_3 + (v_1v_2 + v_1v_3)v_r + v_1v_r^2}{3v_1v_2v_3 + 2(v_1v_2 + v_1v_3 + v_2v_3)v_r + (v_1+v_2+v_3)v_r^2}$$

$$x_3^* = \frac{2v_1v_2v_3 + (2v_1v_2 + v_1v_3 + v_2v_3)v_r + (v_1+v_2)v_r^2}{3v_1v_2v_3 + 2(v_1v_2 + v_1v_3 + v_2v_3)v_r + (v_1+v_2+v_3)v_r^2}$$

4.1 Case of $x_2^* < x_3^* \leq l$

In this case, worker 1 processes only L section, also worker 2, and worker 3 processes all sections (L, R, D) (see Figure 4). Therefore, worker 3 has to travel when moving from point D to R with time r^*v_r. Considering the condition of $l < x_j^* < l + r$, no j^* exists. Therefore, production rate of proposed work rule PR_{pro} and traditional work rule PR_{tra} is the same as follows:

$$PR_{pre} = PR_{pro} = \frac{3v_1v_2v_3v_r + 2(v_1v_2 + v_1v_3 + v_2v_3)v_r^2 + (v_1+v_2+v_3)v_r^3}{(v_1+v_r)(v_2+v_r)(v_3+v_r)}$$

Above production rate is the same as the previous paper of Hirotani *et al.* (2005). Because only one worker processes in R section, and then, travel time can be substituted to walk-back time.

Comparing PR_{fix}, production rate PR_{pro} is higher than PR_{fix} unless the following condition satisfies.

$$\left(\frac{1}{v_1}+\frac{1}{v_r}\right)l = \left(\frac{1}{v_2}+\frac{1}{v_r}\right)r = \left(\frac{1}{v_3}+\frac{1}{v_r}\right)d$$

If above conditions satisfies, all workers can take over an item without waiting time. Therefore, maximum production rate (PR_{pre} and PR_{pro}) can be achieved.

We show a numerical example under l=0.2, r=0.3, d=0.5, v_1=1, v_2=0.5, v_3=8 and v_r=100. Calculating x_2^* and x_3^*, x_2^* is 0.1113 and x_3^* is 0.1672. Therefore, this example can be applied in this section. In this case, PR_{fix}, PR_{pro} and PR_{tra} are 1.658, 8.895, and 8.895, respectively.

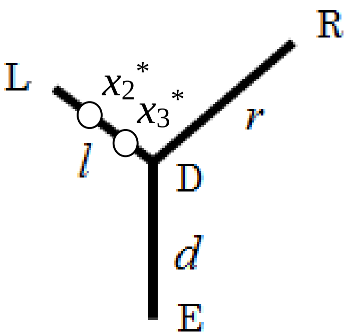

Figure 4: Case of $x_2^* < x_3^* \leq l$

4.2 Case of $x_2^* \leq l < x_3^* \leq l + r$

In this case, worker 1 processes L section, worker 2 processes L and R section, and worker 3 processes R and D section (see Figure 5). Therefore, worker 2 has to travel when moving from point D to R with time r^*v_r. Considering the condition of $l < x_j^* < l + r$, it satisfies $j^*=3$. Also, the worker who processes at point R is worker 2. As shown in section 3, worker 2 or 3 has to wait until taking over on item to worker 1 when worker 2 or 3 arrives at point D. Considering this case, worker 1 takes more time for processing and walk-back comparing traditional work rule in proposed work rule. That is, only worker 1 affects the production rate. Under this condition, time spending of processing and walking-back for worker 1 is as follows:

$$\frac{l}{v_1} + \frac{l}{v_r}$$

In traditional work rule, following formula can be made:

$$\frac{x_2^*}{v_1} + \frac{x_2^*}{v_r} = \frac{x_3^* - x_2^*}{v_2} + \frac{(r + l - x_3^*) + (l - x_2^*)}{v_r} + \frac{r}{v_r}$$
$$= \frac{1 - x_3^*}{v_3} + \frac{1 - x_3^*}{v_r}$$

After solving above simultaneous equations, worker's starting points x_2* and x_3* can be derived, and time spending of processing, walking-back and traveling can be also derived. Finally, production rate can be derived based on spending time.

Therefore, production rate of proposed work rule PR_{pro} and traditional work rule PR_{tra} are as follows:

$$PR_{pro} = \frac{v_1 v_r}{l(v_1 + v_r)}$$

$$PR_{tra} = \frac{v_r(v_1 v_2 v_3 + 2(v_1 v_2 + v_1 v_3)v_r + (v_1 + v_2 + v_3)v_r^2)}{(v_1 + v_r)((1 - 2d)v_2 + v_r)(v_3 + v_r)}$$

Comparing these results, PR_{pro} is higher than other two rules under some condition. Especially, when x_2* is a value close to l or l is smaller than d, PR_{pro} is higher than PR_{tra}. However, condition is very limited. PR_{pro} is less than PR_{tra} for all condition of worker speed according to the line lengths of l, r, and d. PR_{pro} affects only worker 1. The production rate cannot increase even if speed of workers 2 or 3 increase. Also, PR_{fix} is not more than PR_{pro} and PR_{tra} for all speed and length.

We show a numerical example under l=0.2, r=0.3, d=0.5, v_1=2.01, v_2=0.5, v_3=8 and v_r=100. Calculating x_2^* and x_3^*, x_2^* is 0.1995 and x_3^* is 0.2499. Therefore, this example can be applied in this section. In this case, PR_{fix}, PR_{pro} and PR_{tra} are 1.658, 9.852, and 9.851, respectively. Comparing PR_{pro} and PR_{tra}, difference is too small. That is why condition is very limited.

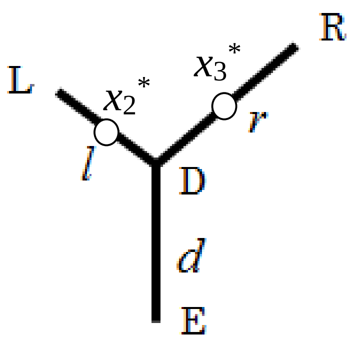

Figure 5: Case of $x_2^* \leq l < x_3^* \leq l + r$

4.3 Case of $x_2^* \leq l$, $l + r \leq x_3^*$

In this case, worker 1 processes only L section, worker 2 processes all sections, and worker 3 processes only D section (see Figure 6). Therefore, worker 2 has to travel when moving from point D to R with time r^*v_r. Considering the condition of $l < x_j^* < l + r$, no j* exists. Therefore, production rate is the same as section 4.1.

We show a numerical example under l=0.2, r=0.3, d=0.5, v_1=3, v_2=9, v_3=8 and v_r=100. Calculating x_2^* and x_3^*, x_2^* is 0.1568 and x_3^* is 0.6013. Therefore, this example can be applied in this section. In this case, PR_{fix}, PR_{pro} and PR_{tra} are 14.56, 18.58, and 18.58, respectively.

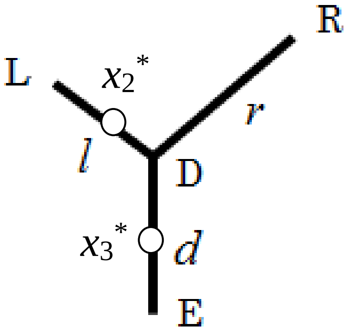

Figure 6: Case of $x_2^* \leq l$, $l+r \leq x_3^*$

4.4 Case of $l < x_2^* < x_3^* \leq l+r$

In this case, worker 1 processes L and R section, worker 2 processes only R section, and worker 3 processes R and D section (see Figure 7). Therefore, worker 1 has to travel when moving from point D to R with time $r*v_r$. Considering the condition of $l < x_j^* < l+r$, it satisfies $j*=2$. Also, the worker who processes at point R is worker 1. As shown in section 3, worker 1 has to wait until taking over on item to worker 2 when worker 1 arrives at point D. Considering this case, workers 2 and 3 takes more time for processing and walk-back comparing traditional work rule in proposed work rule. That is, workers 2 and 3 affect the production rate. Under this condition, following formula can be made:

$$\frac{x_3^{**}}{v_2} + \frac{x_3^{**}}{v_r} = \frac{(1-l) - x_3^*}{v_3} + \frac{(1-l) - x_3^*}{v_r}$$

Note that x_3** is a new starting point under the condition that worker 2 starts to at point R. That is, this is different from x_3*.

In traditional work rule, following formula can be made:

$$\frac{x_2^*}{v_1} + \frac{r + l - x_2^* + l}{v_r} + \frac{r}{v_r} = \frac{x_3^* - x_2^*}{v_2} + \frac{x_3^* - x_2^*}{v_r}$$
$$= \frac{1 - x_3^*}{v_3} + \frac{1 - x_3^*}{v_r}$$

As explained in section 4.2, after solving above simultaneous equations, worker's starting points x_2* and x_3* or x_3** can be derived, and time spending of processing, walking-back and traveling can be also derived. Finally, production rate can be derived based on spending time.

Therefore, production rate of proposed work rule PR_{pro} and traditional work rule PR_{tra} are as follows:

$$PR_{pro} = \frac{v_r(2v_2v_3 + (v_2 + v_3)v_r)}{(1-l)(v_2 + v_r)(v_3 + v_r)}$$

$$PR_{tra} = \frac{v_r(-v_1v_2v_3 + 2v_2v_3v_r + (v_1 + v_2 + v_3)v_r^2)}{((1-2d)v_1 + v_r)(v_2 + v_r)(v_3 + v_r)}$$

Comparing these results, PR_{pro} is higher than other two rules under some condition. Especially, when x_2* is a value close to l, PR_{pro} is higher than PR_{tra}. Also, PR_{fix} is not more than PR_{pro} and PR_{tra} for all speed and length.

We show a numerical example under l=0.2, r=0.3, d=0.5, v_1=2.4, v_2=2, v_3=8 and v_r=100. Calculating x_2^* and x_3^*, x_2^* is 0.2001 and x_3^* is 0.3675. Therefore, this example can be applied in this section. In this case, PR_{fix}, PR_{pro} and PR_{tra} are 6.536, 11.71, and 11.54, respectively. That is why PR_{pro} is higher than PR_{tra}.

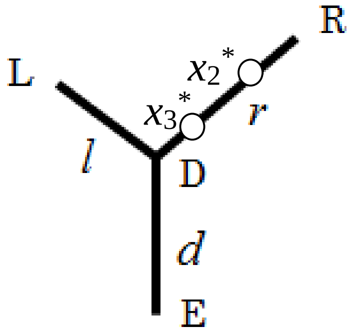

Figure 7: Case of $l < x_2^* < x_3^* \leq l+r$

4.5 Case of $l < x_2^* < l+r \leq x_3^*$

In this case, worker 1 processes L and R section, worker 2 processes R and D section, and worker 3 processes only D section (see Figure 8). Therefore, worker 1 has to travel when moving from point D to R with time $r*v_r$. Considering the condition of $l < x_j^* < l+r$, it satisfies $j*=2$. Also, the worker who processes at point R is worker 1. This is the same as the previous subsection. Therefore, production rate is the same as the previous subsection.

We show a numerical example under l=0.2, r=0.3, d=0.5, v_1=4, v_2=8.5, v_3=8 and v_r=100. Calculating x_2^* and x_3^*, x_2^* is 0.2015 and x_3^* is 0.6119. Therefore, this example can be applied in this section. In this case, PR_{fix}, PR_{pro} and PR_{tra} are 14.81, 19.05, and 18.63, respectively. That is why PR_{pro} is higher than PR_{tra}.

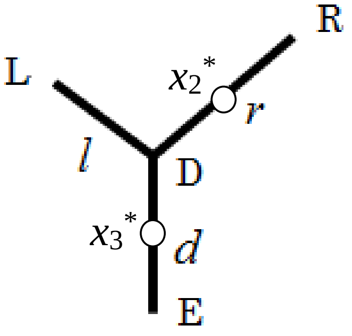

Figure 8: Case of $l<x_2^*<l+r\leq x_3^*$

4.6 Case of $l+r\leq x_2^*<x_3^*$

In this case, worker 1 processes all sections, worker 2 processes only D section, and also worker 3 (see Figure 9). Therefore, worker 1 has to travel when moving from point D to R with time $r*v_r$. Considering the condition of $l < x_j^* < l + r$, no $j*$ exists. Therefore, production rate is the same as section 4.1.

We show a numerical example under l=0.1, r=0.2, d=0.7, v_1=4, v_2=1, v_3=8 and v_r=100. Calculating x_2^* and x_3^*, x_2^* is 0.3141 and x_3^* is 0.3950. Therefore, this example can be applied in this section. In this case, PR_{fix}, PR_{pro} and PR_{tra} are 4.950, 12.24, and 12.24, respectively.

Note that this case can be applied at least the condition of $l+r<d$. This is because necessity condition for balancing the line with walk-back time by expanding equation (1) is as follows:

$$\left(\frac{v_1 v_r}{v_1 + v_r}\right)\left(\frac{1}{v_n} + \frac{1}{v_r}\right) < 1$$

It means that v_1 should be smaller than v_n for many cases. Therefore, worker 1 should process less comparing worker 3. That is why condition of $l+r<d$ should be hold in this case.

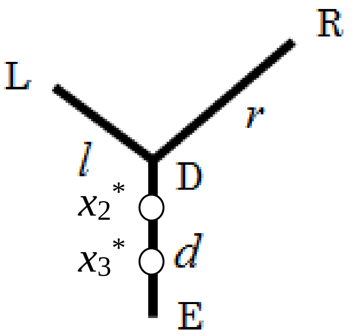

Figure 9: Case of $l+r\leq x_2^*<x_3^*$

5. CONCLUDING AND REMARKS

In this paper, we consider Y-shaped self-balancing production line and propose modified work rule that any worker has to wait at point D. By comparison with traditional serial production line with walk-back time, we can find that production rate of proposed work rule is higher than work rule of previous papers under any starting point is a value close to l in R section.

However, we only focus only one worker. Modifying the work rule that consider more than two workers to increase production rate is a future research work.

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