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The effect of worker fatigue on the performance of a bucket brigade order picking system

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Abstract: Order picking (OP) remains a very costly process with a high amount of manual human work. Different management policies have been developed in the past to improve the performance of order picking systems. Among these is the Bucket Brigade (BB), which is a self-organizing concept for manual OP systems with promising impact on the throughput rate. One general problem of manual OP systems is that worker fatigue can become an issue leading to decreased worker performance and an increased risk of injuries. This is one of the reasons why some researchers highlighted the importance of considering human factors in the design and operations of manual OP systems. This paper develops a mathematical model for managing a Bucket Brigade order picking (BBOP) system subject to worker fatigue. Numerical experiments illustrate the behavior of the model and how worker fatigue affects the performance of a BBOP system.

Keywords: Warehousing, Order picking, Bucket brigade, Ergonomics, Human Factors, Fatigue.

1. INTRODUCTION

Manual picker-to-parts order picking (OP) is the most labor-intensive activity in warehouses (Bartholdi and Hackman 2017), and it usually accounts for up to 55% of the total warehouse operating costs (Tompkins et al. 2010). Travelling is the dominant order picking activity, and it is responsible for about 50% of the total OP time (de Koster et al. 2007). In light of the impact of OP on the efficiency of the supply chain, OP has frequently been studied in the past (van Gils et al. 2018). A strong focus of prior research on OP was on mathematical models that support companies in reducing OP times, improving OP quality, and increasing service levels.

A self-organizing concept for OP is the Bucket Brigade (BB). This concept emerged in the late 1990s when it was transferred from assembly lines to OP (Bartholdi and Eisenstein 1996a, 1996b). A Bucket Brigade order picking (BBOP) system is defined as a *"new style of order picking in which the work is reallocated by the independent movements of the workers. If the bucket brigade is configured properly, the order pickers will balance the work amongst themselves and so eliminate bottlenecks. Moreover, this happens spontaneously, without intention or awareness of the workers. This means that order picking can be more effective than if planned by a careful engineer or manager"* (Bartholdi and Hackman, 2017).

According to Bukchin et al. (2016), in a BBOP system, each worker travels through the warehouse to complete his/her picking list. When the last worker completes his/her list, reaching the end of the picking route, he/she returns back to take over the list from the previous upstream worker (this event is referred to as a hand-off), who does the same, until the first worker takes a new list from the starting point of the picking route. The time required to return upstream to the hand-off point is assumed negligible compared to the time required to work downstream. Few authors studied how BB can improve OP performance (see Section 2 for an overview of the literature). These works, however, considered "machine-like" characteristics of the human workers in the BB ignoring the effect of fatigue, which led to only partially realistic results. In practice, human factors can have a great impact on the performance of the OP system (Grosse et al. 2015). Thus, researchers have recently started to consider human factors in the planning of OP processes to obtain results that are closer to reality and to manage OP systems in a way that better satisfies the requirements imposed on the system by its workers (Grosse et al. 2017). To the best of the authors' knowledge, however, the influence of fatigue on the performance of a BBOP system has not been investigated so far.

The aim of this paper therefore is to integrate worker fatigue, as a physical human factor, into a mathematical model of a BBOP system. The model is tested in numerical experiments to analyse the effect of worker fatigue on the performance of the BBOP system. The results are used to derive managerial recommendations on the use and improvement of BBOP systems. The remainder of this paper is structured as follows. The next section reviews relevant literature on BB in both

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assembly and OP planning. We also shortly discuss the literature on fatigue models. Section 3 introduces the mathematical model. Numerical studies are performed in Section 4 and results are discussed. The paper concludes in Section 5.

2. LITERATURE REVIEW

2.1 Bucket brigades

BBs have been studied both for assembly lines as well as for OP systems. For assembly lines, Bartholdi and Eisenstein (1996a) were the first to propose a basic mathematical formulation for a BB system and to investigate the system's performance. They demonstrated that ordering the workers from the slowest to the fastest along the production line leads to higher performance. Bartholdi et al. (1999) studied the dynamics of two and three workers in a BB production line. Starting with different combinations of worker speeds, they found different asymptotic behaviors depending on the ratio of the workers' speeds. Armbruster and Gel (2002) studied the behavior of a BB with two workers, where one worker has a constant speed over the entire assembly line, and where the other worker is slower in the first part of the line, and faster in the second part. They showed that BB is a good self-organizing concept also when one worker passes the other, as the system is able to maintain its benefits also in such an environment. In a follow-up work, Armbruster et al. (2007) studied the impact of learning effects in a BB. They showed that the stability of the BB is non-uniform over the production line since the workers learn only in those parts of the system where they work. The behavior of the system therefore depends on the starting positions of the workers. Bartholdi et al. (2004, 2009) argued that, under certain conditions, a BB system can be chaotic, even if the model is completely deterministic. When the system is chaotic, it is impossible to predict the future state of the BB, in terms of hand-off positions and time. In particular, this could happen if walking back along the line is not infinitely fast. The authors showed that if the system is chaotic, its behavior depends a lot on the starting positions of the workers.

Few works investigated the BB concept in OP. The first work in this area is the one of Bartholdi and Eisenstein (1996b) that compared zone picking and BBOP. The results imply that BB has higher pick rates (30% larger than in zone picking) and can reduce managers' interventions. Moreover, it can easily be implemented for given routing schemes without requiring changes in layout, equipment or the control system. The authors also studied the behavior of a BB in an OP aisle considering independent and identically distributed orders and exponentially distributed workload. Bartholdi et al. (2001) extended their earlier works on BB taking account of stochastic workload and applying it in an OP system. They showed that BB still remains an effective management approach even if the workload is variable. Koo (2009) presented a new procedure for BBOP systems when blocking or hand-off losses occur. The authors compared traditional BB and zone picking using simulation experiments. Lim (2012) discussed a case study and derived managerial recommendations for a BBOP system where the workers were required to pick products in both directions of the aisle. Webster et al. (2012) showed which decisions have a large impact on throughput, such as a high variation in worker skills, a high variation in SKU volume, and a low percentage of time dedicated to travel activities. The impact of picker blocking in BBOP systems was investigated by Hong et al. (2015, 2016). They demonstrated that aggregating orders into batches reduces the variability of the picker's workload. Bukchin et al. (2016) studied the BB model of Bartholdi and Eisenstein (1996a) under the assumption of stochastic worker speeds. They demonstrated that also in this case, the maximum throughput can be obtained by ordering the workers from the slowest to the fastest along the picking route. In some cases, when partial blocking can occur, the reverse worker order can perform better. Recently, Hong (2018) proposed an analytical model to quantify the delay in hand-offs in case of stochastic worker speed and non-instantaneous return times. Simulation studies illustrated the impact of pick time, its variability and of the walking time on BBOP performance.

2.2 Fatigue models

Fatigue can be defined both in psychological and physiological terms (Gawron et al. 2001). Psychological fatigue refers to mental fatigue of a worker performing a task for a long time, and it is considered very subjective. Physiological fatigue, in turn, is experienced during a physical effort. This kind of fatigue is common in OP systems due to the manual handling activities that need to be executed by the warehouse workers. It can lead to a reduction in generating force and/or to an increased reaction time (Battini et al. 2017). Several fatigue models have been proposed in the past that describe the accumulation of fatigue over time during the performance of a manual task or as a function of task repetitions. Jaber et al. (2013), for example, proposed a model to describe the level of physiological fatigue of the workers. The authors proposed an exponential fatigue function, $F(t) = 1 - e^{\lambda t}$, where $F(t)$ is the level of fatigue at time t, with λ indicating how fast a worker gets tired. Recently, Calzavara et al. (2018a) studied a wearable device for estimating the fatigue level of OP workers by measuring the heart-rate. The authors analyzed alternative devices and tools for calculating fatigue and compared their applicability in an OP context. Calzavara et al. (2018b) proposed an analytical model to estimate fatigue accumulation and the required recovery time. Also in this case, the fatigue accumulation function followed an exponential model. They applied the model to an OP system, demonstrating the accuracy of the model compared to existing recovery models. The authors also illustrated the impact of fatigue accumulation and recovery time on the scheduling of manual activities. Glock et al. (2019) proposed another exponential fatigue model for a manual materials handling process, for example.

To the best of the authors' knowledge, the influence of fatigue on the performance of a BBOP system has not been investigated so far. It is therefore investigated in this work.

3. MODEL DEVELOPMENT

3.1 Bucket brigade OP system

We build our model starting from the assumptions of the *normative model* studied by Bartholdi and Eisenstein (1996a) for two workers. The dynamics of the BBOP system with two workers can be modelled with discrete events and a succession of hand-offs. Each cycle that starts with a hand-off and ends with a hand-off is referred to as an iteration. For each iteration, the position where the hand-offs take place and the time between two hand-offs are defined. Moreover, we assume without loss of generality that the length of the picking route (or aisle) is $l = 1$ (Bukchin et al. 2016). Based on Bartholdi and Eisenstein (1996a), the dynamics of a two-workers BB system can be described as follows:

$$t_n = \frac{1-x_2^{(n-1)}}{v_2^{n-1}} \qquad (1)$$

$$x_1^{(n)} = 0 \qquad (2)$$

$$x_2^{(n)} = v_1^{(n-1)} \cdot t_n \qquad (3)$$

where n is the number of hand-offs (iterations), t_n is the time between the hand-offs $n-1$ and n, $x_1^{(n)}$ is the hand-off position of the first worker after the n^{th} iteration (it is always equal to 0), $x_2^{(n)}$ is the hand-off position of the second worker after the n^{th} iteration, v_1 is the working speed (in the following referred to just as "speed") of the first worker and v_2 is the working speed of the second worker. In the basic model, the speeds are constant. After a few iterations, the system converges to a steady state both with respect to hand-off position (x_2^*) and time between two consecutive hand-offs (t^*):

$$x_2^* = \frac{v_1}{v_1+v_2} \qquad (4)$$

$$t^* = \frac{1}{v_1+v_2} \qquad (5)$$

Under these conditions, the throughput rate [orders/unit of time] is:

$$TR = v_1 + v_2 \qquad (6)$$

3.2. Consideration of worker fatigue

Fatigue has been associated with a reduction in the performance of human workers (Winkelhaus et al. 2018). In this paper, we assume that the speed of workers during a work shift reduces as fatigue increases. Building on the models of Jaber et al. (2013) and Calzavara et al. (2018b) that describe an exponential growth of muscular fatigue over time, we assume the following function that describes the slowdown of the picker's speed:

$$v_i(t) = v_{i-max} \cdot e^{-\mu_i t} \qquad (7)$$

where $v_i(t)$ is the speed of worker i at time t, v_{i-max} is the worker's maximum speed (at the beginning of the work shift), μ_i is the worker's fatigue constant and t is the time in seconds from the beginning of the work shift. We consider four different levels of workload during OP: zero effort, easy work, average work and hard work, corresponding to a 0% (μ_i= 0 [1/s]), a 10%, (μ_i=3.66·10^{-6} [1/s]), a 20% (μ_i=7.75·10^{-6} [1/s]), and a 30% (μ_i=12.39·10^{-6} [1/s]) speed slowdown after eight hours (i.e., one work shift), respectively, as shown in Figure 1. We assume these reductions in speed as average values taking into account the different breaks that could be present in a work shift. Eq. (7) can be approximated by a piecewise linear function as shown in Figure 2. The piecewise linear approximation assumes that the speed of the workers is constant between two consecutive hand-offs, as shown in Figures 2 and 3.

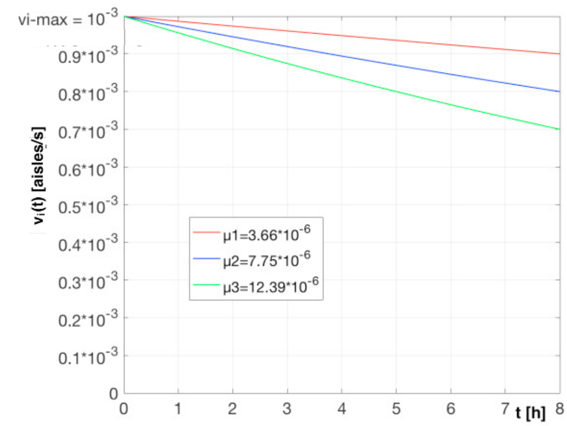

Fig. 1. Reduction in work speed in one work shift for alternative values of μ_i.

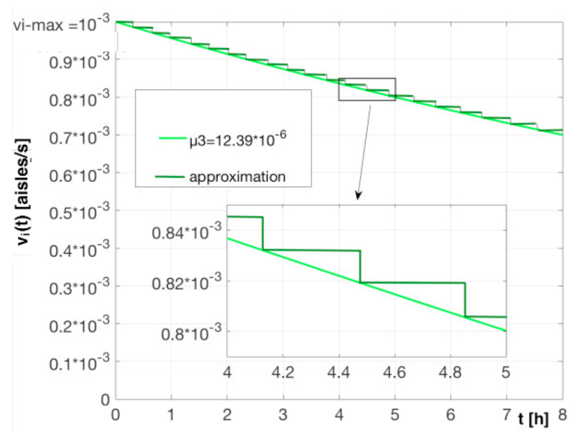

Fig. 2. Approximation of the fatigue function by a piecewise linear function.

To determine the worker's (constant) speed $v_i^{(n)}$ in the time span between t_n (time of the n^{th} hand-off) and t_{n+1} (time of the $(n+1)^{th}$ hand-off), it is sufficient to calculate $v_i(t_n) = v_{i-max} \cdot e^{-\mu_i t_n}$. Then, Eqs. (1) to (3) are adjusted by substituting the constant value of speed v_i by $v_i^{(n)} = v_{i-max} \cdot e^{-\mu_i \cdot (t_1+t_2+\cdots+t_n)}$. Under these conditions, the throughput rate for each iteration is:

$$TR^{(n)} = v_1^{(n-1)} + v_2^{(n-1)} \qquad (8)$$

Assume that N is the total number of hand-offs in an eight-hours shift. The total throughput T_{8h}, expressed as the number of orders completed in eight hours, is exactly N, since each hand-off corresponds to a completed order:

$$T_{8h} = N \qquad (9)$$

To study the behaviour of the BBOP system with worker fatigue, numerical experiments are conducted in the next section. In particular, we analyse if there is still a unique fixed point in the case where workers are ordered from the slowest to the fastest, and how the successions of hand-off positions and the time between two consecutive hand-offs behave.

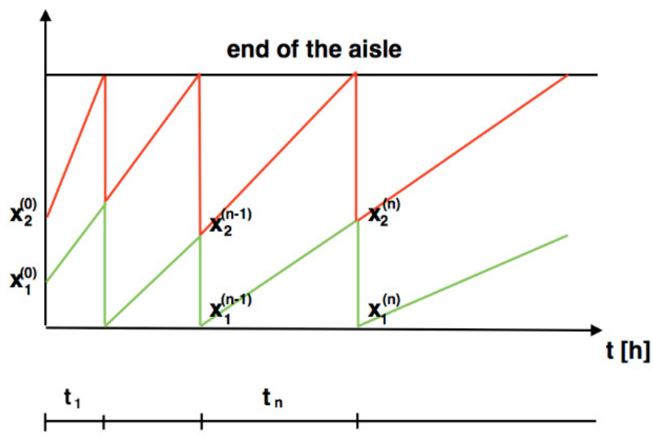

Fig. 3. Dynamics of a two-workers BBOP system considering fatigue.

4. NUMERICAL ANALYSIS

4.1. Assumptions

The model was implemented in MATLAB 9.5, and an eight-hours work shift in a BBOP system with two workers was simulated. The runtime of the model *was less than two* seconds. We calculated the hand-off position ($x_2^{(n)}$) and the time between two consecutive hand-offs (t_n) for each iteration as well as the throughput at the end of the work shift (T_{8h}). The hand-off position (x_2^*) and the time between two consecutive hand-offs (t^*) in the steady state were estimated for each scenario. We considered two different levels of v_{i-max} and four different levels of μ_i, following these two different cases:

Scenario 1: Workers with different v_{i-max} and the same μ_i.

Scenario 2: Workers with different v_{i-max} and different μ_i.

4.2. Workers with different v_{i-max} and the same μ_i

In the first scenario, we consider the following parameters: v_{1-max}= 0.001 aisles/s, v_{2-max}= 0.002 aisles/s and the starting positions are random. We investigated all four levels of μ introduced earlier. The case where $\mu_i = \mu = 0$ corresponds to the case studied by Bartholdi and Eisenstein (1996a). The system converges both in hand-off position and time between two consecutive hand-offs. While it is possible to find a fixed point x^* for the succession of hand-off positions, the time between two consecutive hand-offs converges, but increases over time (see Figure 4). Adapting the results of Bartholdi and Eisenstein (1996a) and considering that $v_i(t)$ decreases over time, it is possible to derive the functions that describe the behavior of the system over time after convergence:

$$x_2^* = \frac{v_{1-max}}{v_{1-max} + v_{2-max}} \tag{10}$$

$$t^*(t) = \frac{1}{(v_{1-max} + v_{2-max}) \cdot e^{-\mu t}} \tag{11}$$

x_2^* does not depend on μ, but instead only on the ratio between the two v_{i-max}, and hence it remains constant over the entire work shift; t^* increases over time due to worker fatigue; if μ increases, the throughput T_{8h} (cf. Eq. (9)) is reduced, since the speed decrease over time. The results of a numerical experiment with the four different values of μ introduced above are summarized in Table 1.

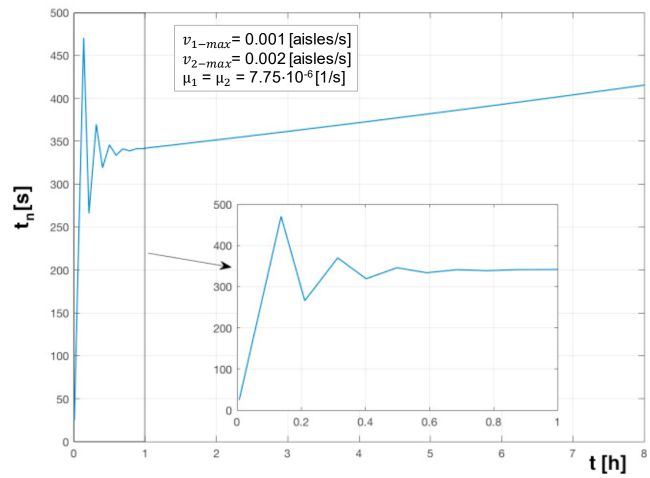

Fig. 4. Behavior of the BBOP system in scenario 1.

Table 1. Throughput after a work shift for scenario 1.

μ	T_{8h}	$T_{8h}/T_{8h}^{\mu=0}$ [%]
No effort, $\mu_i = \mu = 0$	88	100.00%
Easy work, $\mu_i = \mu = 3.66 \cdot 10^{-6}$	83	94.32%
Average work, $\mu_i = \mu = 7.75 \cdot 10^{-6}$	78	88.64%
Hard work, $\mu_i = \mu = 12.39 \cdot 10^{-6}$	74	84.09%

As expected, fatigue reduces the system's throughput, but the system behaves stable as the hand-offs are always in the same part of the aisle. The time between two consecutive hand-offs is calculated using Eq. (11).

4.3. Workers with different v_{i-max} and different μ_i

In the second scenario investigated here, the parameters are set as follows: v_{1-max} = 0.001 aisles/s, v_{2-max} = 0.002 aisles/s, the starting positions are random, and we study all possible combinations of μ_i. As in Section 4.2, it is possible to derive the functions that describe the behavior of the system over time after convergence:

$$x_2^*(t) = \frac{v_{1-max} \cdot e^{-\mu_1 t}}{v_{1-max} \cdot e^{-\mu_1 t} + v_{2-max} \cdot e^{-\mu_2 t}} \tag{12}$$

$$t^*(t) = \frac{1}{v_{1-max} \cdot e^{-\mu_1 t} + v_{2-max} \cdot e^{-\mu_2 t}} \tag{13}$$

The results obtained for the system throughput are summarized in Table 2, where the total throughput T_{8h} and a comparison to the case without fatigue, $T_{8h}/T_{8h}^{\mu=0}$, are reported. The bold values have been obtained for the previous scenario. As can be seen, the throughput decreases as μ_i adopts larger values, which reflects the reduction in worker speed due to fatigue. In particular, the throughput after eight hours is lower when the second worker slows down faster than the first one. In all cases considered in Table 2, the speed of worker 2 is always higher than that of worker 1. As a result, in none of the cases investigated here, blocking can occur. Otherwise, especially when the maximum speeds of the two workers are similar, the possibility of blocking exists, since the speeds decrease under the effect of fatigue. If t^s is defined as the point in time when the speed of worker 1 becomes higher than the speed of worker 2, the system behaviour can be illustrated as shown in Figure 5.

Table 2. Throughput after a work shift for scenario 2.

T_{8h}		μ_2			
$T_{8h}/T_{8h}^{\mu=0}$		0	$3.66 \cdot 10^{-6}$	$7.75 \cdot 10^{-6}$	$12.39 \cdot 10^{-6}$
μ_1	0	**88**	84	82	79
		100%	95.45%	93.18%	89.77%
	$3.66 \cdot 10^{-6}$	86	**83**	80	77
		97.72%	**94.32%**	90.90%	87.50%
	$7.75 \cdot 10^{-6}$	85	81	**78**	76
		96.59%	92.05%	**88.64%**	86.36%
	$12.39 \cdot 10^{-6}$	83	80	77	**74**
		94.31%	90.90%	87.50%	**84.09%**

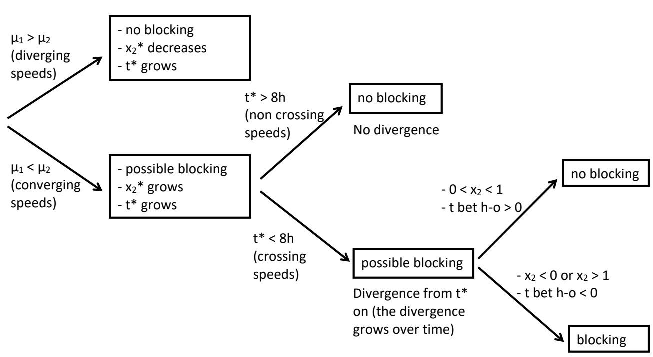

Fig. 5. System behaviour for alternative parameter settings in scenario 2.

If t^s < 8h, the system starts to diverge after time t^s. However, this does not mean that blocking definitely occurs. Blocking exists only when the hand-off position is not in the interval [0, 1] anymore and when the time between two consecutive hand-offs becomes negative (cf. the red dots in Figure 6). In this case, the manager can solve the problem by switching the workers, such that the system will behave at its best for the whole work shift (Armbruster and Gel 2002).

4.4. Discussion

The results of the simulation experiments imply that in the two scenarios we investigated, the behaviour of the system at convergence does not depend on the starting positions of the workers. This becomes clear also from Eqs. (10) to (13), where $x_2^*(t)$ and $t^*(t)$ do not depend on $x_1^{(0)}$ and $x_2^{(0)}$. The starting positions affect only the behaviour of the system before convergence: the closer the starting positions of the workers are to the ones they have at the steady state, the faster the system converges. In addition, it was shown that x_2^* depends on the ratio of worker speeds (Eqs. (10) and (12)): the higher the ratio, the closer is the hand-off position to the end of the BBOP line, and vice versa. If the workers have the same speed, the hand-off position is in the middle of the line (x_2^*= 0.5). We also observed that t^* increases over time because of the reduction in the workers' speeds that results from fatigue. Based on our results, it is possible to choose the vector of the starting positions in such a way that the system converges early in a work shift. This allows to have a stable system with a higher throughput.

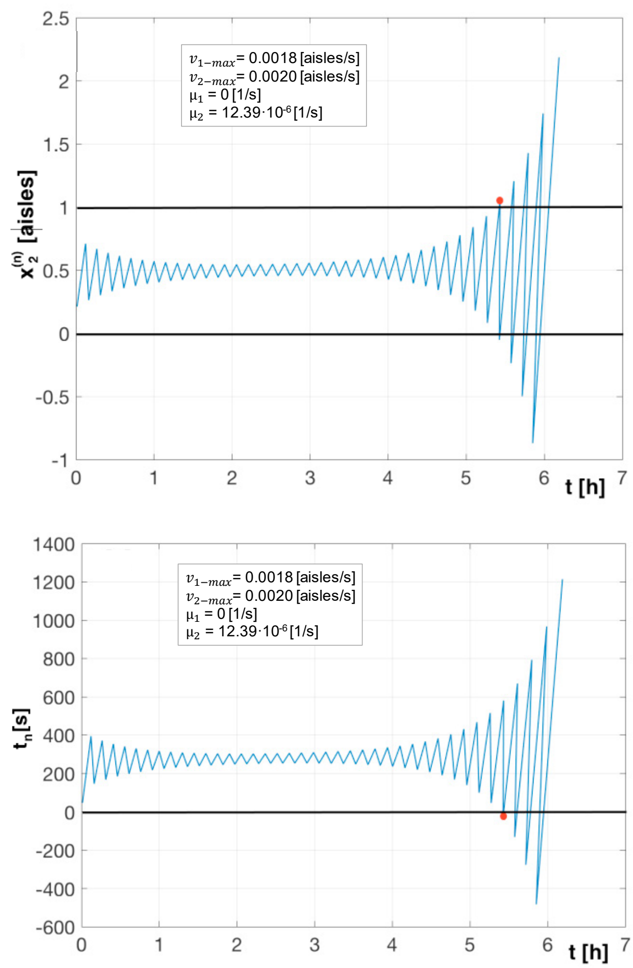

Fig. 6. Occurrence of picker blocking in scenario 2 when worker 2 is slower than worker 1.

5. CONCLUSIONS

This paper investigated the impact of worker fatigue on the throughput of a two-workers BBOP system. We showed that fatigue lowers the BBOP system's throughput (due to the slowdown of the pickers) and effects a shift of the hand-off position along the OP picking route over time (due to the changing of the ratio of the workers' speeds). This paper proposed a function to model the slowdown of the order pickers during the work shift over time. We considered two different cases of BBOP systems that differ in the characteristics of the workers employed, and analyzed their behaviors. We showed that the systems differ with respect to convergence and throughput. Considering fatigue in the planning of a BBOP system allowed us to obtain more realistic results, and the proposed model enables managers to better predict the behavior of their system. This paper is the first to consider human fatigue in a BBOP system and can be seen as a starting point for future research in this direction. Possible extensions of the proposed model are, for example, the consideration of multi-workers and a multi-aisles OP system. In addition, alternative fatigue models could be investigated including also the consideration of breaks during the work shift. Finally, the simulation experiments could be combined with a field study.

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