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Influence of task time variation in adopting Walking Worker assembly systems: a design approach

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Abstract: Unlike traditional Fixed Worker (FW) assembly systems, in which an operator remains in the same workstation performing repetitive tasks, in the Walking Worker (WW) ones the operators travel along the line stations to produce the finished product. Interestingly, such a configuration enables to achieve a greater level of production volume flexibility, without changing the assembly system layout, parts disposition, and tools assignment. The basic requirement of a WW is to be cross-trained and able to fully assemble the product from beginning to end. The WW travel activity, which increases when the number of stations increases, negatively impacts on the system performance. On the other hand, the possibility to have extra-stations, i.e., a greater number of stations compared with the number of operators, makes the WW system able to dynamically balance the work overload differences between the operators.

The aim of this paper is to investigate the effect of stations time variability, typical for example of mixed model assembly lines, on the system productivity, comparing the performance of a WW system and a FW one. A simulative study has been developed, considering as variables the task time coefficient of variation, the travel time, the number of stations, and the number of operators, to analyze when and how the WW system can outperform the FW one. The results show an assembly system design approach that defines the better system to adopt (WW or FW), the number of operators and the number of extra-stations to include, as a function of the considered target productivity and task time variation.

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1. INTRODUCTION AND AIM OF THE STUDY

Manufacturing and assembly systems are currently facing various challenges. Among others, they are required to produce always more personalised products with short lead times. Although automation in recent years has gained interesting applications, it is still considered only partially, especially if flexibility is required. Then, most of the assembly systems are manual, with human operators performing most of the tasks, able to easily adapt to requests of mix, volume and layout flexibility (Calzavara et al., 2021; Hashemi-Petroodi et al., 2021).

Traditionally, a manual assembly system has a so-called Fixed Worker (FW) configuration. Here, there are as many operators as workstations, and each operator performs the tasks assigned to his/her workstation while the product flows along the whole line. Such a system has shown to be quite good in adapting to mix flexibility, while some criticalities emerge for responding to volume and layout flexibility. For example, the system throughput depends on the number of operators (and, hence, on the number of workstations), and a change in the throughput imposes a change on the whole assembly system (i.e., increase or reduce the workstations) (Al-Zuheri et al. 2014a).

An alternative possible configuration for an assembly system is the Walking Worker (WW) one, in which the operators assemble the whole product by moving along the line together with the assembled product. In this case, the number of operators can be equal or lower to the number of workstations, depending on the required productivity. Although the operators have to spend some time for travelling among the workstations, a WW system is able to achieve a greater level of production volume flexibility, without changing the assembly system layout, and, then, also guaranteeing the layout flexibility (Wang et al. 2005).

In the years, several studies have focused on evaluating and comparing FW and WW systems, from various points of view. For sure, one of the most critical aspects is related to the understanding of when one system is preferable to the other. There are many factors that can influence this choice and that deserve to be investigated (Wang et al. 2007; Deepak et al. 2017).

This paper focuses on the study of the effects of stations time variability on system productivity. This is done through a simulative study, which allows comparing the performance of a WW system and a FW one, considering the task time coefficient of variation, the travel time, the number of stations, and the number of operators. The objective is to show in which circumstances the WW system outperforms the FW one, in order to derive some useful guidelines that can be used for the design of a manual assembly system.

The remainder of the paper is structured as follows. Section 2 reports a brief literature review about walking worker systems and previous studies concerning the comparison between FW and WW configurations. Section 3 proposes the simulative study, while section 4 focuses on the presentation of the results and their discussion. Section 5 introduces some insights of the proposed design approach. Finally, section 6 is for the conclusions.

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2. LITERATURE OVERVIEW

The concept of introducing walking workers in assembly systems is relatively new, starting from the studies of Black (1991) and Black and Hunter (2003). Bartholdi and Eisenstein (2005) and Mileham et al. (2008) are among the first who proposed mathematical models for such systems.

A detailed literature review concerning WW systems and their comparison with FW ones can be found in Calzavara et al. (2021). In the following, the focus is only on papers related to studies including simulation approaches and/or consideration of mixed-model assembly lines and variable tasks times.

Wang et al. (2005) focused on the comparison of FW and WW linear assembly lines through a simulation model. This allowed to derive which system guarantees the best performance. In particular, they concluded that the WW line brought high flexibility in terms of capacity and maintained high efficiency in terms of output per worker per hour. Moreover, they highlighted that the system capacity of a WW system can be easily adapted by adding or removing workers. Similarly, Al-Zuheri et al. (2010) used simulation for verifying a mathematical model and predicting the performance of manual assembly lines with flexible workforce.

Subsequently, the same authors evaluated the influence of stochastic tasks times (Al-Zuheri et al. 2013) and of a mixed model production (Al-Zuheri et al. 2014b) on the performance of WW systems. Their mathematical model has been tested with an industrial case study and also validated through simulation, deriving that WW systems improve flexibility, performance and reduce labour costs.

Lassalle et al. (2007) investigated the effect of in-process waiting times on a linear walking worker assembly line in a buffer-constrained flow-shop environment. They found that the in-process waiting time affects the expected throughput time and it can be adjusted by the application of walking workers.

Wang et al. (2007) analysed the interactions between the number of stations and the number of operators to understand the best setting to reach the desired system throughput and cycle time. The studies of Wang et al. (2009; 2010), applied to linear single-model WW assembly lines, had the objective of defining the main factors that can lead to production losses. They combined simulation with mathematical modelling.

Malaki (2012) deepened the study of operational time variability which can cause the imbalance of the assembly line, with a consequent loss of productivity. They proposed to reduce the impact of times variability by arranging the workers in a proper order. Similarly, Ebrahimi et al. (2022) developed a dynamic mixed-model assembly line sequencing problem, minimizing production time. Due to the complexity of the problem, their approach is based also on software simulation. Also Wang et al. (2013) concentrated on the variability due to human performance, also including the learning effect.

Cevikcan (2016) introduced two linear integer programming models to balance a multi-model walking-worker assembly line, determining the number of workers and stations to smooth the workflow. Their method is related to a rabbit-chase configuration.

Deepak et al. (2017) used simulation to derive guidelines for converting FW into WW assembly lines, with the benefit of increasing utilization of resources and reducing work-in-process. Aydin et al. (2018) defined operational design factors to derive a practical robust design approach for assembly cells with walking workers. Their findings suggested that a reduction in the expected performance is negligible compared to the reductions of performance variability.

3. SIMULATIVE STUDY

The simulation model has been implemented in FlexSim v20.1, with a simulation time of 160 hours per run. Figure 1 shows the case with 5 stations and 2 operators.

The following assumptions have been considered:

- The layout of the line is linear
- The material always flows along the line, i.e. there are no blocking or starving issues
- The stations time follows a normal distribution, with an average time that is equal for all the stations in all the simulations (CT)
- Each experiment considers a different value of standard deviation of the times
- The standard deviation of the times is equal for all the stations of a certain experiment
- In the FW configuration the number of operators is always equal to the number of stations ($O_{FW} = S$)
- In the WW configuration the number of operators can be equal or lower than the number of stations ($O_{WW} \leq S$)
- In the WW configuration the travel time of the operators is proportional to the number of stations

2.1 Input data

Table 1 reports the input data. The proper combination of all the input data led to the creation of 7,776 different scenarios.

Table 1. Input data

Parameter	Notation	Value(s)
Number of stations	S	1, 2, 3, 4, 5, 6, 7, 8
Number of operators	O_i	1, 2, 3, 4, 5, 6, 7, 8
Station average time	CT [min]	10
Station standard deviation time	σ [min]	0, 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10, 12.5, 15, 17.5, 20
Walking worker travel time	t_{tr} [s]	0, 2.5, 5, 10, 20, 30

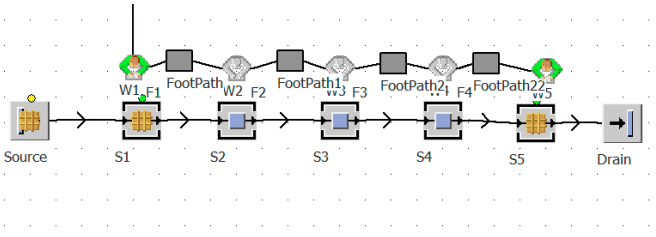

Figure 1. Simulation environment (case with 5 stations and 2 operators).

2.2 Indexes for FW and WW comparison

For each scenario, different indexes are calculated. First, G (1) is the number of extra-stations, calculated as the difference between the number of stations, S, and the number of WW operators, O_{WW}. It is also used for deriving $\%G$ (2), which refers to its percentage incidence on the number of stations:

$$G = S - O_{WW} \tag{1}$$

$$\%G = \frac{G}{S} \tag{2}$$

The number of stations S can be calculated as follows:

$$S = \left\lceil \frac{T}{CT} \right\rceil \tag{3}$$

where T is the total assembly time and CT is the cycle time. Moreover, $\%t_{tr}$ (4) allows to estimate the share of the travel time, t_{tr}, with respect to the average station time, CT, while $\%CV$ (5) represents the coefficient of variation of the station time, σ, with respect to the average station time, CT, expressed as a percentage:

$$\%t_{tr} = \frac{t_{tr}}{CT} \tag{4}$$

$$\%CV = \frac{\sigma}{CT} \tag{5}$$

Another interesting aspect is related to the comparison of the throughput of the two systems. For both FW and WW configurations, the normalized production NP (6) is defined as the ratio between the throughput coming out from the simulation runs $Q_{s,i}$ and the nominal expected throughput $Q_{n,i}$, calculated according to the number of operators:

$$NP_i = \frac{Q_{s,i}}{Q_{n,i}} \tag{6}$$

with i=WW, FW. It allows to compare FW and WW systems on the same basis, referred to the productivity of the single operator. Then, the difference between the normalized production of the WW system and of the FW one sets the value of ΔP:

$$\Delta P = NP_{WW} - NP_{FW} \tag{7}$$

This indicates the percentage of gained (if $\Delta P > 0$) or lost (if $\Delta P < 0$) production warranted by the implementation of the WW system with respect of the FW one. Then, it also represents an effective measure to understand if the operators of the WW system are performing better than the FW ones ($\Delta P > 0$).

4. RESULTS AND DISCUSSION

The indexes introduced in the previous section are useful to derive the contour plots reported in Figure 2. Each contour plot shows different convenience areas, based on the value of ΔP and that vary according to $\%t_{tr}$, $\%CV$ and $\%G$.

First of all, it can intuitively be observed that the increase of the incidence of the travel time on the station time (i.e., the increase of $\%t_{tr}$) leads to wider areas of convenience of the FW system. With the increase of $\%t_{tr}$ there are lower productivity increases ΔP for the WW, since the travel activity reduces the WW system throughput. On the other hand, for the lower values of $\%t_{tr}$ the operators of the WW system are more often the ones with the higher throughput. Looking at the contour plots with the values of $\%t_{tr}$ equal to 5%, 10% and 20%, it can be seen that the percentage of gained production ΔP increases with the increase of $\%G$, but it is not always the same with respect to $\%CV$: there are some combinations of $\%G$ and $\%CV$ that are better than others.

While the increase of $\%CV$ initially leads to an improvement of the gained production for the WW system with respect to the FW one, its further growth implies a worsening of this gap. This is due to the fact that with a higher variability of the station time (i.e., a higher $\%CV$) the productivity of the stations is less stable due to work overloads in some stations and idle times in others. If there are, on average, more products with high assembly times the overall productivity is lower.

Moreover, the increase of productivity gained with the WW configuration with respect to the FW one is higher for higher values of $\%G$. This is related to the fact that, for a certain value of $\%CV$, the WW system performs better of the FW one if it has more extra-stations, which allow to better smooth the times variability. For example, if $\%CV$=100% the throughput of the FW system is on average halved. On the other side, for the same value of $\%CV$ the throughput of the WW system is better, and it has a higher increase when the number of extra-stations G is higher. In fact, the extra-stations allow to better cover the variability of the stations times and, then, to produce more.

Figure 3 proposes a further comparison between FW and WW systems based on the results of the simulative study. Here, the graphs show how the normalized production NP_i varies according to $\%CV$, S and $\%t_{tr}$. In each graph there are NP_{FW} and NP_{WW}, the latter also changing with the number of installed extra-stations G. It is important to highlight that for the WW system the maximum number of workstations is equal to the one of the FW system (i.e. 3, 5 and 8 in the illustrated cases). Here, the number of extra-stations G changes because the number of operators O_{WW} changes. For example, in the graphs of S=3, G=0 corresponds to 3 walking workers, G=1 corresponds to 2 walking workers, while G=2 corresponds to 1 walking worker, always working in an assembly line made of 3 stations.

Figure 3 shows with a different perspective and a greater detail the results of the contour plots of Figure 2. Unlike Figure 2, Figure 3 allows to see also the influence of the number of stations. First of all, it can be seen that the normalized productivity of the FW system NP_{FW} is always better than the one obtained with the WWs NP_{WW} with G=0. On the other side, the WW operators outperform the FW ones when extra-stations are considered, and the benefit is higher for the greater values of $\%CV$ and lower values of $\%t_{tr}$. Another interesting outcome is related to the improvement of productivity obtained through the use of extra-stations: the higher values of extra-stations guarantee the higher benefits. Looking at the productivity of the single operator, this also means that for the walking workers it is better to work in a configuration with few operators and more extra-stations. This aspect could be due to the possible work overload, that usually arises when there is more than one walking worker in the same assembly system. In fact, the stations times variability influences the capability of the workers to complete their tasks on time.

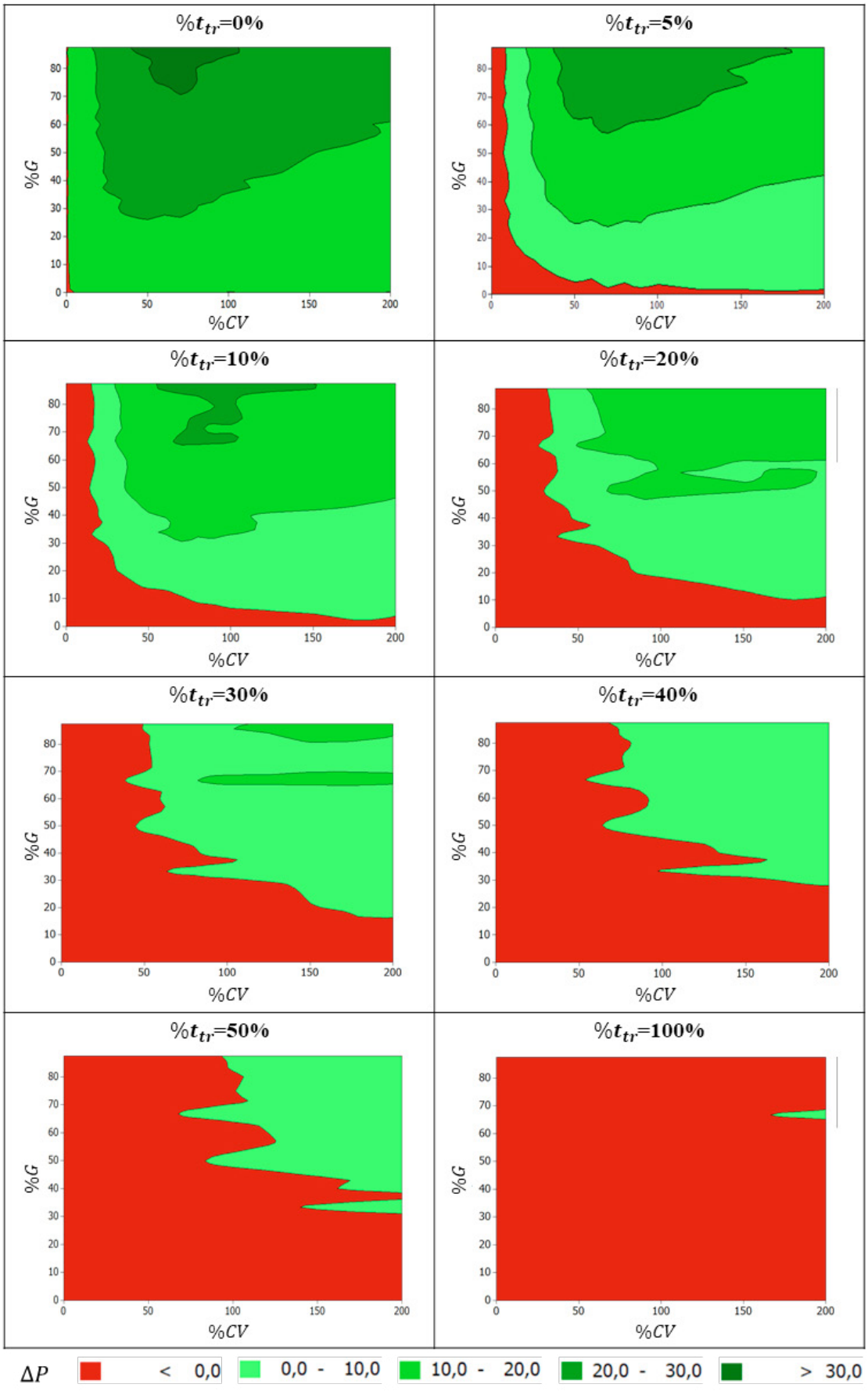

Figure 2. Contour plots varying $\%CV$ and $\%G$ for different values of $\%t_{tr}$.

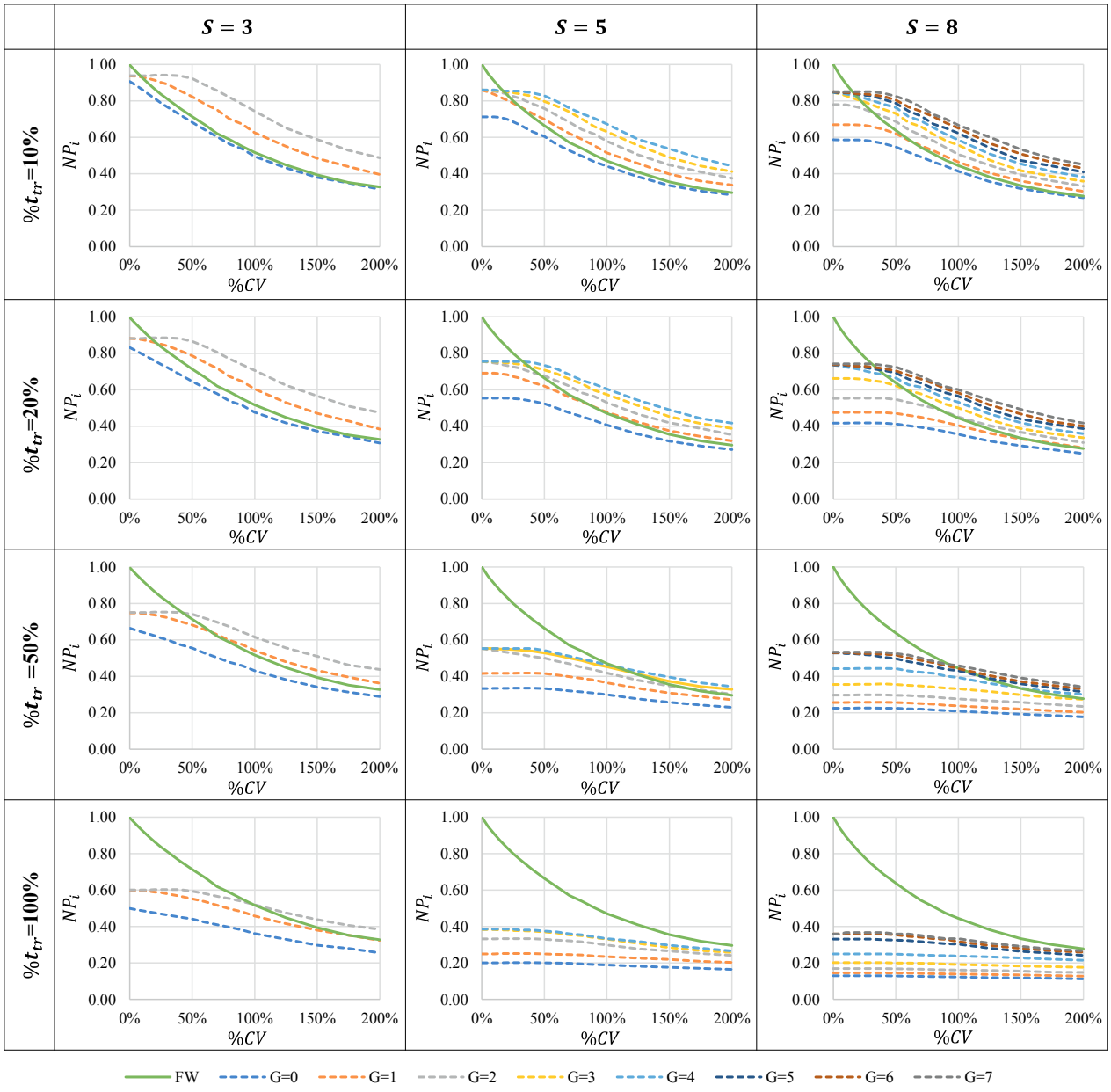

Figure 3. Comparison of NP_i for FW and WW (case of $\%t_{tr}$=10%, 20%, 50%, 100% and S=3, 5, 8).

5. PROPOSED DESIGN APPROACH

The results reported in the previous section have shown that FW and WW systems can have different scopes of applicability. Therefore, it can be interesting to structure an approach to support the evaluation of the most proper system, which also takes into account all the variables that can have an effect on the final outcome.

As a first step, the minimum number of assembly stations S can be calculated with (3). This amount sets the quantity of assembly FW operators O_{FW} ($S = O_{FW}$), while the number of WW operators O_{WW} can be lower, in case there are some extra-stations G ($S = O_{WW} + G$).

Subsequently, the focus can be on the choice of the best configuration. First of all, given the average stations times variability $\%CV$ and the incidence of the travel time on the station time $\%t_{tr}$, it can be understood if it is better to have a FW system or a WW one. Then, in case of choice of the WW system, it can be derived the number of extra-stations G and, by difference, the number of operators O_{WW}. The number of extra-stations to choose should be the one that guarantees at least an increase of the productivity with respect to the FW system. For example, looking at the graph on the right of Figure 4, referring to an assembly system with 8 stations and $\%t_{tr}$=10%, if we consider $\%CV$=50% we see that the WW configuration with G=2 (O_{WW}=6) is the first one having the single operators performing better than the ones of the FW system.

Generalizing the results reported in Figure 2 and 3, we can say that if there is no stations times variability ($\%CV$=0) the FW is always preferable. On the other side, when $\%CV$ increases, the choice could be the WW system, with a higher convenience when $\%t_{tr}$ is low.

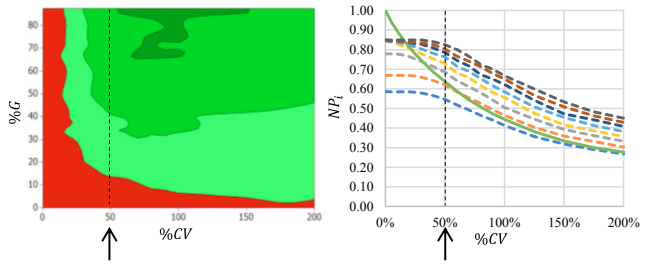

Figure 4. Example of application of the proposed design procedure.

6. CONCLUSIONS

Walking workers' assembly lines represent an interesting approach to cope with the need of mix and volume flexibility. Considering the growing spread of mixed model assembly systems and the frequent changes of the demand volume, the present paper analysed the effects of stations times variability on the system throughput. The simulative study compared the performance of the operators working in a FW system and in a WW one. The results showed that there are some circumstances in which the walking workers with extra-stations are more productive than the fixed workers.

Further research on this topic will deepen the study of the relations among the factors that can impact on the productivity. Moreover, the design approach will be completed with the evaluation and the comparison of the whole system productivity (further to the single operators' one), also including the most important emerging related costs.

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