Integrating buffer “stock” and buffer loops in an assembly line with conveyors: An automotive case study

Integrating buffer “stock” and buffer loops in an assembly line with conveyors: An automotive case study

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Abstract. The degree of automation in manufacturing systems, along with the characteristics of job handling and transport between workstations, and the product cycle time, determine the most suitable job handling system for each line. Conveyor systems allow for the management of re-entrant flows at the same workstations and more flexible system architecture through carousels, which also serve as a buffer loop to accommodate jobs awaiting machine availability. This paper explores the role of buffer stocks and blocking after service mechanisms, task allocation within the system, and operational characteristics to tackle the assembly line balancing problem in a fully automated assembly line interconnected by conveyors through discrete event simulation. Scenario analysis is employed to assess the impacts of constraining job flows through the conveyors on: fluctuations in throughput from shift to shift, its variability, and the critical WIP threshold for the CONWIP logic.

Introduction

The assembly line balancing problem (ALBP) cannot neglect the intersection between the choice of the material handling systems, the tasks performed along the line, and the selection of single processes to optimise production and operations management, particularly in the field of intelligent manufacturing [1]. The introduction of Industry 4.0 (I4.0) technologies impacted the reconfigurability and rebalancing of assembly systems, enabling the opportunity to remotely control workstations and material handling systems to increase or decrease line throughput according to the conditions of the external environment, such as workers’ stress and fatigue levels or downstream congestion.[2].

Therefore, the human-centred manufacturing of Industry 5.0 (I5.0) [3] and I4.0 are changing the paradigm for designing manufacturing lines through sensors, automation, and digitalisation. The result is the complexity in evaluating the best configuration considering inventory, job handling systems, and transports due to the increased number of alternatives often evaluated by decentralised decision-making [4].

This paper investigates the design of a part of a real assembly line of engines for electric cars in which conveyors intertwine the workstations, machines are unreliable, and buffers and conveyor carousels must be designed to control the job flow. The assembly line exploits a Constant work-in-progress (CONWIP) logic, maintaining a fixed number of jobs (namely, critical WIP level, W*) in the system by loading a new job in the conveyor when a finished product crosses the unloading bay.

The following design issues have been investigated through discrete event simulation and scenario analysis: (i) the exploitation of the conveyor carousels rather than introducing blocking mechanisms and buffers, (ii) the identification of W* for optimising the throughput (TH) of the CONWIP system, and (iii) the choice between performing some operations one shot in slower machines or partitioning them in smaller tasks to be performed sequentially in faster machines through conveyor loops.

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In the remainder of the paper, the Background section presents the literature review, while the Problem description section introduces the characteristics of the case study system and the design alternatives. The results section presents the experimental results and the managerial insights. Finally, the Conclusion section summarises the contribution of the paper, discusses the limitations of this work, and introduces the key points for future research.

Background

Generally, the Assembly Line Balancing Problem (ALBP) aims to equally divide manufacturing tasks among workstations to obtain a smoothed and constant TH; however, combining buffer allocation and workstation processing time unbalance, under some operational characteristics, can lead to better performance [5]. Moreover, recent research [6] identified the literature gaps between assembly line balancing and real-world definition of the line: (i) the integration with the logistic activities that provide raw materials, (ii) the definition of the buffer dimensions, (iii) the transfer of semi-processed jobs from one station to another, and (iv) quality-related issues like the need for reworks, the position of quality inspections and quality control activities to minimise defectives per workstation. Moreover, lines must be rebalanced in the case of changes in the demand volume or production mix, thus leading to the need to perform the analysis again to identify a novel line setup [5].

Recent literature shows that controlling the material handling systems is important to reduce system congestion and improve system performance by identifying more efficient solutions to the ALBP [7]. Computational studies showed that the integrated decision approach can lead to more efficient design and redesign of assembly lines, enhancing the exploitation of automated transport infrastructure like AGV and AMR [8].

Also, considering the operational characteristics of the assembly line in the design phase can improve the TH while reducing design costs when buffer allocation and assembly line balancing are simultaneously addressed [9]. Short-term planning impacts on ALBP are more difficult to evaluate. On the one hand, buffer allocation and sequencing can improve line performance, depending on the production mix and operational characteristics of the problem [10]. On the other hand, the impacts of short-term production planning, like scheduling problems, increase in highly utilised manufacturing environments, while in under-utilised systems, their impact is not so significant for the objectives of ALBP [11].

In general, the assembly line design, simultaneously considering production operations, material handling system, and manufacturing technologies characteristics, is not yet comprehensively explored in the literature [11], particularly for CONWIP systems where W* must be defined.

In the literature, discrete event simulation has been widely adopted to study the ALBP. In particular, it was successfully used for system design by comparing alternatives for prototyping and alternative design solutions [12]. Moreover, in smart manufacturing system design, discrete event simulation highlights the interactions between different elements, such as buffers, their location, task allocation through the line, and operational characteristics [13]. Discrete event simulation also plays a pivotal role when integrated into digital twins, which are also used for manufacturing system design, like the Function-Structure-Behavior-Control-Intelligence-Performance (FSBCIP) framework that, after having set the production goals, supports iterative design and alternative comparison [14].

This paper exploits discrete event simulation to investigate the ALBP in a CONWIP assembly line for a part of a line producing engines for electric cars, in which conveyors interconnect machines while concurrently setting W*. The addressed problem consists of (i) determining the working conditions of a critical workstation, (ii) exploring the use of buffer stocks and blocking after service mechanisms to control the job flows through the conveyor carousels, (iii) limiting congestion into the carousels.

Problem description

The alternative solutions to the ALBP coupled with different W* levels impact three main Key Performance Indicators (KPIs): (i) the average shift (one daily eight-hour shift) throughput (TH), (ii) the standard deviation of the shift TH, and (iii) the carousel congestion. Critical levels of carousel congestion can cause deadlocks, that is, a system state in which the system cannot evolve into another. A deadlock example is a carousel full of recirculating jobs that prevent the workstations from unloading worked jobs and loading new ones. The intervention of resources external to the system, like operators, to manually solve the problem is the only way to overcome a deadlock state.

The alternative solutions to the ALBP combine four different working conditions of a critical workstation of a realistic assembly line (part of a line for the production of the engine of electric cars) with two buffer designs: (i) conveyor carousel, or (ii) blocking after service policies combined with standard buffers and restricted use of conveyor carousels.

Hence, this paper analyses eight line scenarios obtained by combining the two aforementioned factors. For each scenario, different W* levels are investigated.

The assembly line. Fig. 1 shows the assembly line composed of seven workstations (WSs) with one or two identical and unreliable machines. In particular, the first and the last WSs (in Fig. 1, WS1 and WSQC, respectively) are the only workstations with reliable machines. All the other workstations from WS2 to WS6 have identically unreliable machines. The sensors at the end of the machines in such workstations detect the need for a quality inspection of the just produced job with a probability δ. WS2 and WS5 consist of two identical machines, while all the other workstations are single-machine.

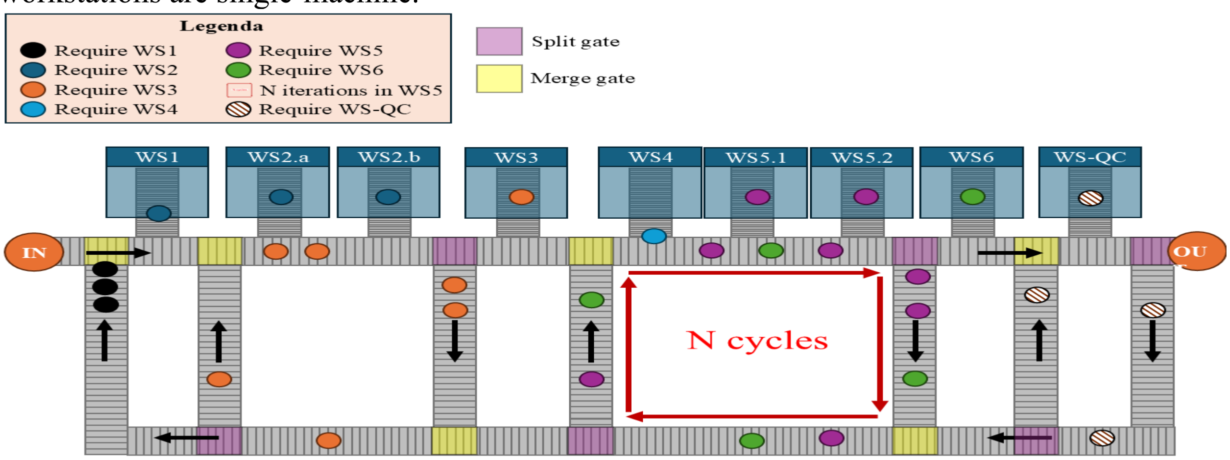


Figure 1. The assembly line has six production workstations (workstations 2 and 5 have two identical machines, namely a and b, respectively), and a final workstation is for quality inspections (WSQC).

The jobs subjected to quality inspection are sent to the quality control WS (in Fig. 1, WSQC). With probability β, they have a reparable defect that requires a rework in the station of origin; with probability γ, they were subjected to a false positive defect detection of the sensor and, hence, they are sent to the station following the one they came from, or, with probability $1-\beta-\gamma$, they have an unrepairable defect that forces them to be discarded from the system.

The CONWIP system exploits a large number of pallets in which the jobs are put in the load bay (load and unload bays are in red in Fig. 1). The load bay controls the job entering into the system by ensuring that the number of full pallets circulating in all the carousels is always equal to W*. The pallets with the jobs just released by the load bay are stocked in a FIFO buffer close to WS1.

WS1 employs a blocking after service policy that allows unloading the worked job only when at least one of the two machines in WS2 is idle. The job worked in one of the two machines in WS2 recirculate in the WS2 carousel (the first conveyor carousel from the left in Fig. 1) until WS3 is idle, then the first job closer to WS3 is allowed to exit the carousel to be worked in WS3.

After WS3, jobs are processed in WS4 and WS5. WS5 is the critical workstation that can work in four alternative working conditions. WS5 consists of two identical machines, one after the other, performing an operation that can be completed in just a single iteration or up to four sequential job iterations. The processing time is proportional to the number of iterations; that is, if the entire work is performed in four different job works rather than one, the processing time will be one out of four of the processing time required to perform the work in only one iteration.

WS4 and the two machines in WS5 are in a conveyor carousel where the jobs circulate until the machine they are waiting for is idle (WS4, WS5, or WS6). Hence, the jobs that have finished the processing in WS5 circulate in the same carousel until WS6 is idle. Jobs successfully processed in WS6 are then unloaded in the unloading bay (the red box on the right side of Fig. 1) while the pallets return to the load bay.

The simulation model. The simulation model simplifies the real system to reduce the variability propagation and highlight the impact on the TH shift average and standard deviation. Specifically, the quality control performed in WSQC always sends back the jobs in the origin WS for rework due to repairable defects. The simulation model has been implemented in the commercially available software Arena Rockwell 16.0.

Due to the complexity of the system and the simulation model, an animated version of the simulation model has been used for model validation.

The WSs processing times have been fixed to ensure a balanced line; therefore, each process time is equal to 20 minutes, including WSQC, and the probability δ of requiring a quality inspection for just processed jobs is 5% in each WS except for WS1 in which it is 0%.

The design of experiment. This paper investigates the ALBP by considering both the transport and manufacturing resources. The transport resource, i.e., the conveyor, also represents a buffer between WSs because the carousels can store the jobs until the next WS becomes idle. However, blocking after service mechanisms and rules for leaving carousels can increase congestion on specific loops. Therefore, the original model is compared to a model in which the jobs can freely flow through all the conveyor loops. The original system configuration and the second one will be named *Constrained Flowing* (CF) and *Free Flowing* (FF).

WS5 can process a job in a single time or divide the process into subprocesses up to four, thus enhancing job recircles in the conveyor carousel. This could be a strategy exploited in reconfigurable systems to adjust the shift TH according to workers' performance or the entire system TH. Therefore, four scenarios are considered by assuming the two identical machines of WS5 process jobs from one single time to four times.

Finally, the overall system performance depends on the W* jobs simultaneously admitted into the system. Therefore, an experimental campaign has been done to identify the maximum number of jobs that can be allowed in the system without causing deadlocks. The experiment involves three factors: (1) the two system types, CF and FF, (2) the number of iterations performed in WS5 (from 1 to 4), and (3) W* (from 1 to 44), leading to 352 different scenarios.

Results

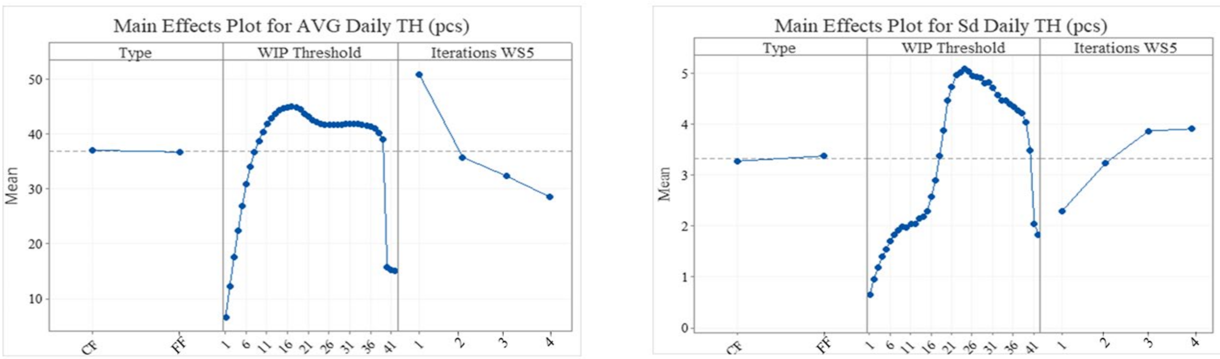
Each scenario has been simulated 30 times, and each of the 30 replications has a warm-up period of one year and a simulation horizon of another year, consisting of daily shift of 8 hours.

The average and the standard deviation of the TH in a shift are exploited to investigate (i) the number of iterations that jobs must do in WS5 and its processing time, (ii) whether the material handling system is more performant in the presence of buffer stocks and blocking mechanisms,

Materials Research Proceedings 57 (2025) 512-520 https://doi.org/10.21741/9781644903735-60

namely constrained flow (CF) or with jobs freely flowing through the conveyor carousels, namely freely flowing (FF), and (iii) W* for the CONWIP system.

Fig. 2 shows the main effects for each level of the experimental factors, highlighting that both for the TH average (Fig. 2a) and the TH standard deviation (Fig. 2b), the choice of the W* is critical to improve the TH and control its variability (charts in the middle in Figures 2a and 2b cover the widest area). The selection of a technology for working a job in a single iteration is preferable both for improving TH and reducing its standard deviation (chart “Iterations WS5”).



a) The TH average for each level of the factors

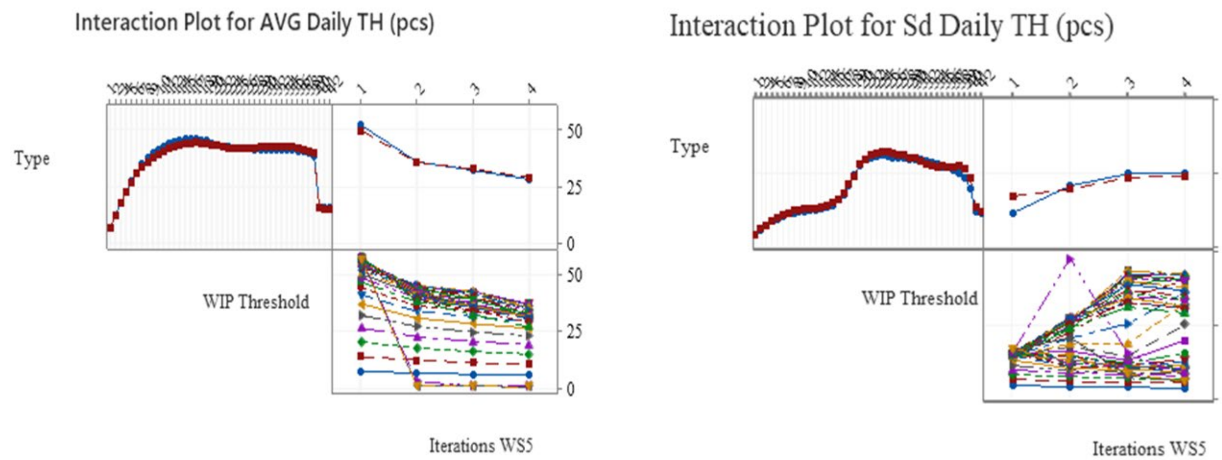
b) The TH standard deviation for each level of the factors

Figure 2. Average and standard deviation of the throughput (TH) for each level of the experimental factors.

The material handling system (chart “Type”) seems negligible; however, a deeper investigation is necessary to exclude the presence of compensation effects that hide its impacts. To this purpose, Fig. 3 presents the interaction plots to analyse the pairwise interactions among experimental factors. The chart focused on the Type-WIP* TH average (Fig. 3a, plot on the left side) shows that for some W*, the type CF seems more efficient than FF. The same chart shows a drop in TH average with the highest value of W*. The cause of the drop is a deadlock: there are too many jobs in the system, a conveyor carousel becomes congested, the machine cannot unload processed jobs, and the system is blocked until a worker manually remove or move jobs from the line.

The system type is negligible as the carousel size of WS4 and WS5 is significantly larger than the others, and it also contains the critical station required by many parts, i.e., WS5. Therefore, this carousel is a sort of bottleneck that makes the blocking mechanisms and leaving rules irrelevant.

Fig. 4 deepens the TH average and standard deviation by focusing on W* and the four scenarios of technology selection for WS5. Fig. 4 presents bar charts in which the red markers indicate the average of the CF type, while the black ones are the average of the FF solution.



a) The experimental factor pairwise interactions for the TH average

b) The experimental factor pairwise interactions for the TH standard deviation

Figure 3. The pairwise interactions of the experimental factors for the average and standard deviation of throughput (TH)

In the case of 1 iteration in WS5, the TH average asymptotically increases with the W* while the standard deviation (the segment crossing the markers of the average) remains limited. In the other three cases, the TH average has a maximum at W*=17, then decreases again while its standard deviation increases (the whiskers are longer). The CF type is always slightly more performant at the maximum average TH, but when W* increases, FF has a higher average TH and lower standard deviation. This happens because after the maximum average TH has been reached, increasing the system WIP increases the congestion into the conveyor loops, in which jobs are more constrained due to the blocking mechanisms. In this case, jobs are randomly processed by one of the two WS5 machines. Sometimes, jobs doing their first iteration are processed before the others, also increasing the average flow time of the jobs; in other cases, only jobs at the last iteration are processed. This leads to high variability in TH and a lower TH rate. At the same time, in the case of FF, jobs can occupy several parts of the conveyor rather than being constrained in limited carousels, which mitigates the adverse effect of increasing W* over the level corresponding to the maximum average TH.

W* is a critical factor because, in CONWIP systems with unreliable machines and quality inspection workstations far from the other WSs, it can be difficult to avoid machine starvation by releasing new jobs into the system at a smooth and constant rate. However, excessively increasing W* is shown to be inefficient, particularly in the case of systems with inflexible control of buffers and carousels.

The increase in TH variability with the increase of the iteration number in WS5 and of W* is explained by the increasing number of jobs in the WS4-WS5 carousel with different remaining numbers of iterations in WS5. In fact, it can happen that for some hours, only the first and second operations of many parts have been performed, achieving TH equals 0. However, after this time, there will be a moment in which only the fourth operation is performed in WS5, having large fluctuations in TH. Also, that carousel is full of many parts with different characteristics, so the maximum achievable TH decreases from 60 (scenario 1) to 36 (scenario 4). Hence, no benefits are achieved by increasing the number of iterations.

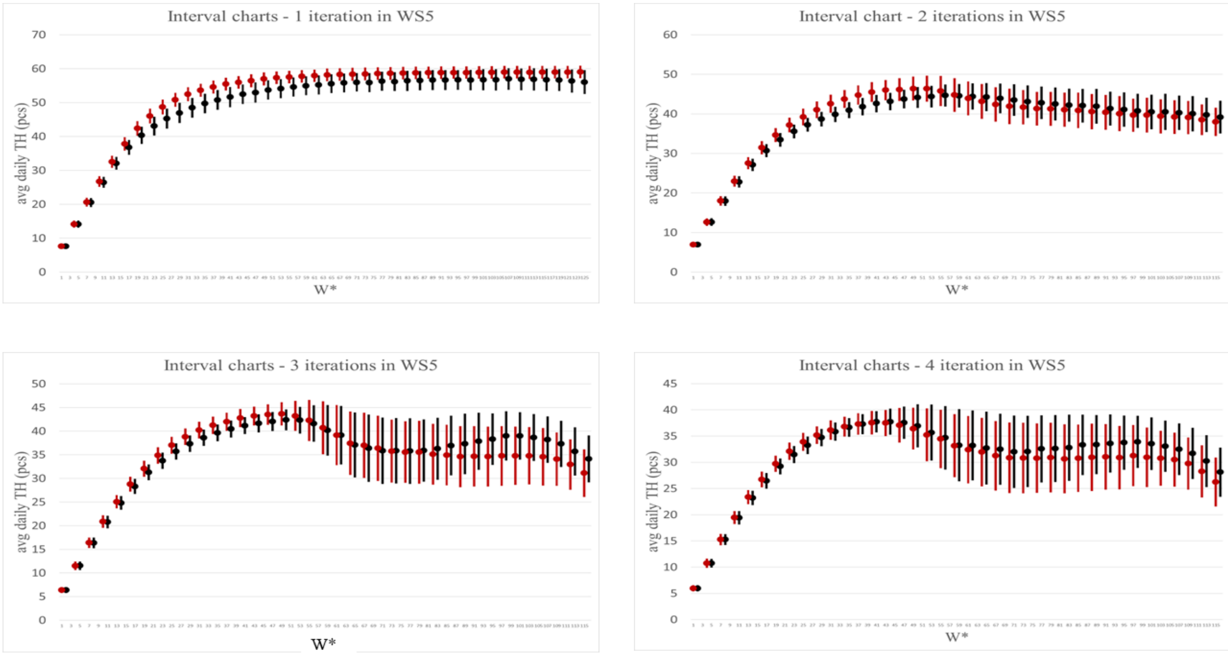


Figure 4. Interval charts showing the TH average for the two types (constrained flowing in red, free flowing in black) under the four iteration levels.

Conclusion

This paper deepens the assembly line balancing problem, taking into account material handling systems and how they are controlled, as well as the operational characteristics like the critical level of WIP in a CONWIP system and the configuration of a process that can work a job using a different number of iterations (and related processing time). Discrete event simulation has been exploited to perform scenario analyses to investigate the impacts of experimental factors and their interactions.

The results show that the control of the material handling systems, particularly the exploitation of the entire conveyor as a buffer loop or the introduction of blocking mechanisms and buffer stocks, impacts the average TH and the variability propagation in an increasing manner, proportional to W*.

This paper highlights the complexity of balancing or rebalancing lines in industrial cases in which machines can produce defective parts, and quality inspections increase variability propagation.

Moreover, advanced analyses and tools are required to exploit all the benefits of Industry 4.0 by properly configuring machines, material handling systems, and operational parameters of the lines.

This paper is tightly focused on a realistic case study, and, although the performed analyses provide insights that can affect other systems, they cannot be generalisable. An extensive design of the experiment would improve the generalisation of the results.

Future research will investigate (i) the definition of a framework for assembly line balancing problems with material handling systems and buffer allocation problems in the case of system reconfiguration; (ii) further interactions between material handling systems and production planning approaches.

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