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Work sequence analysis and computer simulations of value flow and workers' relocations: a case study

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Abstract

Several solutions have been proposed for the workload balancing in manual assembly lines with workers' task assignment. Facing the case study of a sheet metal assembly line of transport pallets, the paper addresses the problem of the dynamic task assignment. The walking path minimization is considered in the problem, together with task sequence constraints. A real-time simulation allows to test the solution variations before their implementation.

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Keywords: Workload balancing; computer simulations; assembly; value flow improvement; simulated experiment

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1. Introduction

The problem of assembly and manufacturing lines balancing as well as the worker's assignment is widely discussed in literature [2, 6]. Different methods and models are presented and recommended to use in different situations [1, 3]. The main objective in line balancing is to distribute tasks over the workstations and workers in order to minimize the idle time of machines and operators.

The problem of a worker-task assignment is usually solved in two different ways according to literature: with a fixed assignment system or with a work sharing system [10]. In the fixed assignment systems, a worker continues doing the specific task once the assignment has been made, while in the work sharing systems workers are dynamically assigned to workstations or tasks according to the system dynamics. In the fixed assignments, an important issue is to design the assignment policy based on the given knowledge of the workers [9]. In the work sharing, workers have to be flexible, therefore, they have to be cross-trained and they are dynamically shifted from one station (task) to another in order to balance the workload and increase the throughput [4, 5, 7, 8].

Compared with mathematic models, simulation-aided approaches present a more realistic way to solve the task allocation problem. By describing the equipment layouts, the manufacturing logistic process, and the multiple system measurements, the simulation can map real and changing production environment by considering multiple objectives simultaneously [11]. Furthermore, simulation models show flexible and adaptive advantages for an experiment design and what-if analysis.

Our goal is to evaluate the impact of a number of workers and the line management approach (different buffer size) on the workload balancing of workers. In the production line taken as a case study, workload is made by both processing tasks and transportation tasks. Therefore, the objective is to balance the workload comprising process tasks, part transportation tasks and unloaded travel times. Daily travel distance needs to be balanced among operators to increase the quality of work. This a side goal.

The remaining part of the paper is organized as follows. Section 2 describes the industrial problem considered in the paper. Section 3 refers to the possibilities of the manufacturing process simulation and describes the simulation model as well as its implementation in FlexSim. Section 4 presents the

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scenarios used in the simulation, while Section 5 discusses the experimental results obtained in the different scenarios simulated. Finally, Section 6 draws conclusions and states future works.

2. Industrial problem description

The considered industrial process is the manufacturing and assembly of a transport pallet. The pallet is made of sheet, profile and frame. Each part of the pallet is manufactured by a number of stations and then assembled with the other in order to have a final pallet. The tasks are performed manually requiring one to two workers for each task.

The task allocation problem of interest for the company is described as follows. In a manufacturing line, which layout is shown in Fig. 1, workers *w* perform work tasks. A task can be a manufacturing task *mt* or a transport task *tt*. The list of manufacturing tasks is reported in Table 1, while the list of transportation tasks is reported in Table 2. Table 1 includes a description of each manufacturing task, information about the tasks duration and a number of workers needed to perform each task. In table 2 each transportation task is described by giving the starting work station or warehouse, as well as the destination work station or warehouse. Additionally, the transportation content is listed. The time needed to perform each transportation task is presented together with the number of workers needed to perform the transportation task (some parts are heavy and need two people to be carried). Transport tasks *tt* concern transport of materials or products from one work station to another as well as from material storage *MS-1* or *MS-2* to a work station, or from a work station to a ready product storage *PS*.

Manufacturing tasks are performed on work stations *s*. Some manufacturing tasks *mt* can be performed only on one work station *s*. Some other manufacturing tasks *mt* can be performed on different work stations. The list of workstations and the associated manufacturing tasks are presented in Table 3.

The sequence of manufacturing tasks needed to accomplish the whole process is shown in Fig. 2.

In fact, 10 workers work on dedicated work stations based on their experience. The manufacturing tasks as well as the transportation tasks are assigned to workers, and workers are assigned to work stations as presented in Table 4. In some cases one manufacturing task *mt* or transport task *tt* has to be performed by two workers working together.

Currently, the workload is not balanced as some operators work significantly more than others. Fig. 3 presents the workload of workers coming from performing manufacturing and transportation tasks.

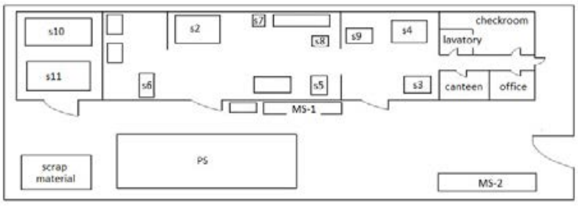

Fig. 1. Layout of a manufacturing line and warehouses.

Table 1. List of manufacturing tasks.

Manufacturing task *mt*	Description of a manufacturing task	Task duration t_{mt} [sec]	Number of workers N_w needed to perform a task
mt1	Sheet cutting	40	2
mt2	Sheet corners cutting	652	2
mt3	Sheet bending	624	2
mt4	Profile cutting	349	1
mt5	Profile incision	504	1
mt6	Holes drilling	1 026	1
mt7	Angles cutting	16	1
mt8	Cup welding	192	1
mt9	Frame welding	304	1
mt10	Sides welding	416	1
mt11	Bottoms welding	120	1
mt12	Building-up	1 187	2
mt13	Assembly	1 212	2

Table 2. List of transportation tasks.

Transportation task number	Previous-next work station *s*	Transported load	Duration time of a task t_{tt} [sec]	Numbers of workers needed to perform a task together N_w
tt1	MS-2-s2	Sheet	20	1
tt2	s2-s3	Cut sheet	20	2
tt3	s2-s5	Cut sheet	15	1
tt4	s3-s4	Sheet without corners	5	2
tt5	s4-s10	Bended sheet	25	2
tt6	s4-s11	Bended sheet	25	1
tt7	MS-1-s6	Profiles	10	1
tt8	s6-s7	Cut profiles	15	1
tt9	s7-s8	Incised profiles	5	1
tt10	s8-s5	Profiles with holes	10	1
tt11	MS-2-s9	Angles	15	1
tt12	s9-s5	Cut angles	10	1
tt13	s5-s10	Frame	20	2
tt14	s5-s11	Frame	20	2
tt15	s5-s10	Cups	15	1
tt16	s5-s11	Cups	15	1
tt17	s10-PS	Transport pallet	15	2
tt18	s11-PS	Transport pallet	15	2

Table 3. List of work stations with associated manufacturing and transport task.

Work station *s* and warehouses	Description of the workstation	Symbol of manufacturing task *mt* realized on the work station
MS-1	Profiles storage	
MS-2	Raw material storage	
s2	Sheet cutting	mt1
s3	Sheet corners cutting	mt2
s4	Sheet bending	mt3
s5	Welding	mt8, mt9, mt10, mt11
s6	Profile cutting	mt4
s7	Profile incision	mt5
s8	Holes drilling	mt6
s9	Angles cutting	mt7
s10	Building-up and assembly	mt12, mt13
s11	Building-up and assembly	mt12, mt13
PS	Ready products storage	

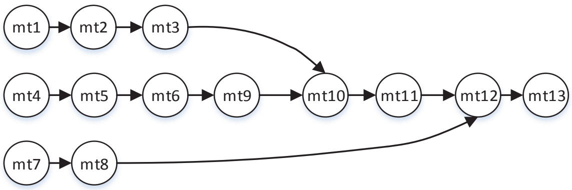

Fig. 2. Manufacturing task sequence.

Table 4. List of workers with associated manufacturing and transport task and work stations.

Worker *w*	Symbol of manufacturing task *mt*	Work station *s* on which workers work	Symbol of transportation tasks *tt* performing by workers
w1+w2	mt1, mt2, mt3	s2, s3, s4	tt1, tt2, tt3, tt4, tt5, tt6
w3	mt4, mt5	s6, s7	tt7, tt8, tt9
w4	mt6	s8	tt10
w5	mt7	s9	tt11, tt12
w6	mt8, mt9, mt10, mt11	s5	tt13, tt14, tt15, tt16
w7+w8	mt12, mt13	s10	tt17
w9+w10	mt12, mt13	s11	tt18

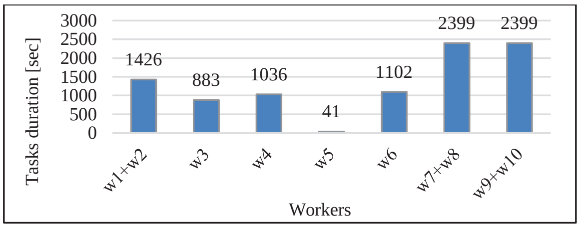

Fig. 3. Workers workload of manufacturing and transportation tasks.

The aim of the research is to balance the workload of operators while taking into consideration a manufacturing tasks sequence. It is also important whether all workers are needed to perform the mentioned manufacturing and transport tasks.

3. The simulation of the process

The model of the process must represent the features that contribute to the solution of two separate production control problems: one is the stochastic optimization of the assembly line through a heuristic strategy that both assigns the workers to the tasks and balances the workload, the other is the dynamic optimization of the plant layout by minimizing the path lengths and the distances covered by operators. As a matter of fact, several manual productions are run through simple workstations that can be easily relocated allowing a dynamic layout design.

Both problems have a wide range of literature of the analytic solution procedures based on nonlinear bounded optimization of a cost functional associated to each problem. Modern research and most of the industrial solutions prefer to utilize heuristic procedures that are validated by Discrete Event Simulations (DES). The reason is that the problem is stochastic, and practical boundary conditions are not fixed but may change during the time length of the problem.

The model for the first problem could be represented in terms of queuing networks. Line Balancing is obtained by levelling the workload across all the processes and by operating on a bottleneck machine. The model for the second problem is a kinematic representation of the travel paths followed by operators carrying an item from one machine to the following one, or simply moving to reach the assigned machine.

Both models can be implemented in the same simulation software. The recent factory simulation software is able to run at the same time a DES and a kinematic simulation. In the present research the model of an assembly process was developed on the FlexSim software (www.flexsim.com).

The data required to execute a DES are a task list, both manufacturing and transport; the resource lists: workstations and operators; the inter-arrival times and the process times. The chosen distribution function for all the process times is the triangular distribution with a mode corresponding to the task durations of Table 1. The lower and upper limits have been assumed by the company technicians based on their experience.

On the contrary to ordinary DES, in the present model, the position of every machine on the factory floor must correspond with the actual plant layout.

Another problem is the execution of multiple tasks on a single workstation, as in the welding station s5. This should not be a problem as far as every task can be executed as preemptive and be modelled as multiple processes that share a common resource. As the movements on the layout are considered in the model, it was necessary to represent many processes in the same layout location. This was accomplished in FlexSim by using the MultiProcessor object class.

Before each station a queue with a maximum length of one was inserted in order to reproduce the existing buffer for the exchange with the finished part.

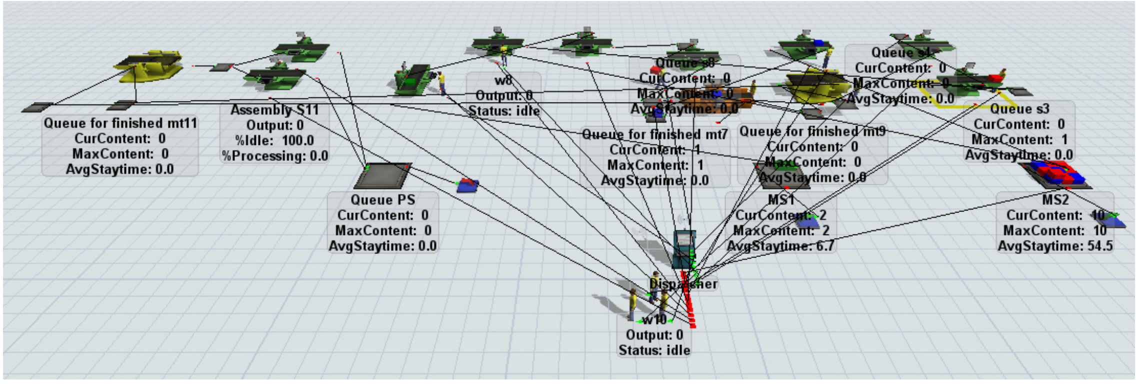

Fig. 4. Screenshot of the FlexSim model.

The workstation s8 (hole drilling), that is a bottleneck machine, is the only one with a larger buffer, presently of the size of 10 items. Therefore, this is the only actual queue in the system, with the exception for the many inventories for the raw material storage. The screenshot of the FlexSim model representing the industrial process is reported in Fig. 4.

4. Scenario configuration

Two kinds of experiments were considered in order to evaluate different scenarios based on the company needs. Each experiment is composed by a set of scenarios, described in the following experiments:

1. In the first experiment, the number of flexible operators varies from 7 to 10 (in addition to the operator fixed to a welding machine).
2. In the second experiment, the number of operators is fixed to 9, the size of the queue for items waiting for workstation 8 (hole drilling) varies among the values 1 (small buffer), 10 (medium buffer) and 20 (large buffer).

For each scenario, the following performance indicators were collected.

- For each worker:
    - Process time [sec],
    - Idle time [sec],
    - Travel loaded time [sec],
    - Travel unloaded time [sec],
- For each workstation:
    - Process time [sec],
    - Idle time [sec],
    - Blocked time [sec],
    - Waiting for operator time [sec],
    - Waiting for transporter time [sec],
- For the overall system:
    - Total and average length of travel [km],
    - Average time spent in a queue and in a process [sec],
    - Throughput rate [a number of finished products in a week].

5. Results and analysis

By analyzing the results, it can be noticed that the number of operators and the queue size strongly affect the working time of operators and workstations.

5.1 Variation in the number of operators

The results obtained in the first experiment are shown in Fig. 5-8. The comparison of the process times for a different number of operators is reported in Fig. 5. As expected, it shows a decreasing trend for the increasing number of operators. The operator assigned to a welding machine (indicated as W) presents a process time lower than the other workers in the first two scenarios (with other 7 or 8 operators). In the third scenario his process time coincides with the others, and in the last scenario his time is the highest. Accordingly to these results, the best workload balancing among workers is the third scenario, since all workers have a processing time between 80% and 92%.

In Fig. 6, the details of the division of the percentages of process time, idle time, travel loaded time and travel unloaded time for each worker are reported for the 9-operator scenario. The process time is significantly higher than all the other times. For the same 9-operator scenario, Fig. 7 shows the amount of process time, idle time, blocked time, waiting for operator time and waiting for transport time for each workstation. For the most workstations the process time exceeds the other times, except for s2 (sheet cutting), since the time of the corresponding time is much lower than the other times.

Fig. 8 shows the process time and the blocked time for each workstation for a different numbers of workers. As for the blocked time we mean the sum of actual blocked time and the times waiting for an operator or transporter. The process time slightly increases with increasing the number of operators for all the workstations. The blocked times usually decrease except for station s5 (welding machine).

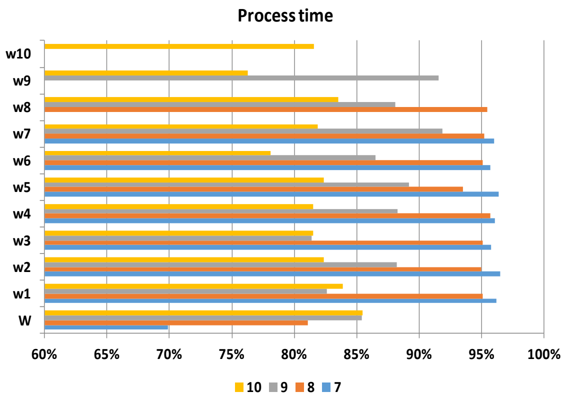

Fig. 5. Process times for a different number of operators.

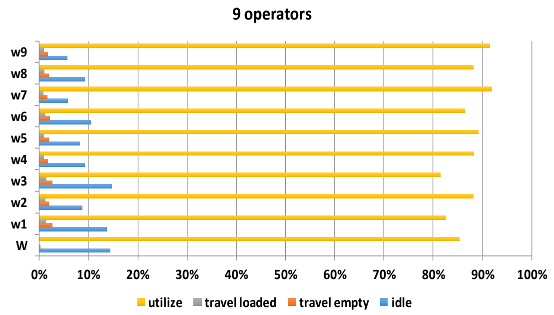

Fig. 6. Time percentages for operator in the 9-operator scenario.

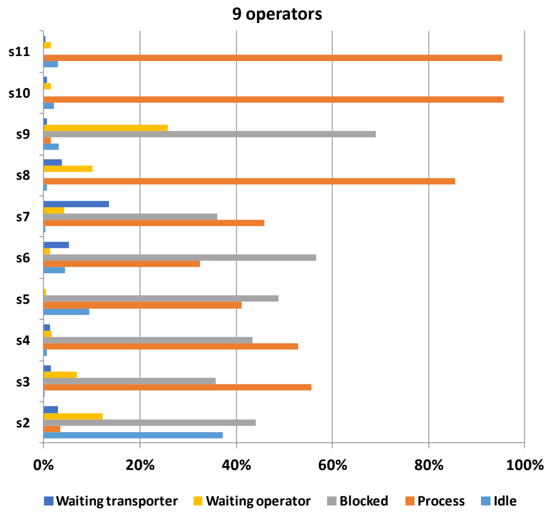

Fig. 7. Performance indicator values for each workstations in the 9-operator scenario

Table 5 presents the values of the overall system performance indicators for a different number of workers.

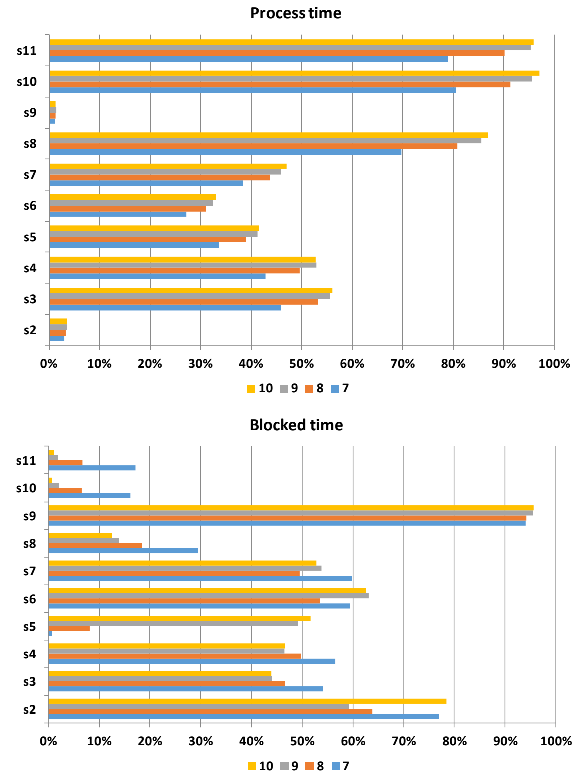

Fig. 8. Percentages of process time and blocked time for each workstation for a different number of workers (7 workers, 8 workers, 9 workers, 10 workers).

In Table 5 we can see what the total travel in km in different scenarios was, when in a manufacturing line from 7 to 10 operators were working, what the average travel for one operator was, what an average process staytime for an operator and total process staytime were, what an average queue staytime for an operator was and what a throughput of the manufacturing line was.

As in the manufacturing line 99 pallets should be produced weekly, we cannot accept the scenario where we have 7 workers, because they are able to manufacture only 90 products per week. Comparing the scenario with 8 and 9 operators we can see that the second scenario is better because the average process staytime increases while the average queue staytime decreases. Therefore, the scenario with 9 operator was preferred for the further analysis.

Table 5. Values of performance indicators for a different number of workers.

Performance indicator	Number of workers			
	7	8	9	10
Total travel [km]	38.9	41.2	41.4	38.0
Avg travel [km]	4.9	4.6	4.1	3.5
Avg process staytime [sec]	7 702	6 858	7 027	6 989
Avg queue staytime [sec]	12 746	12 055	12 516	12 708
Avg total staytime [sec]	20 448	18 912	19 543	19 696
Throughput [products/week]	90.0	103.2	107.9	108.7

5.2 Variation in the buffer size

The results obtained in the second experiment are shown in Fig. 9-10. The comparison between the process times for each worker for different buffer sizes is reported in Fig. 10. The processing times do not show strong differences in the variation of the buffer size.

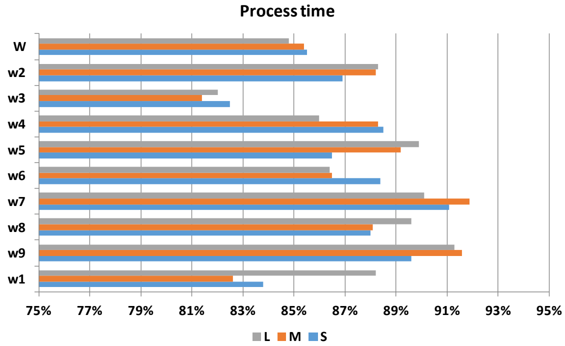

Fig. 9.Percentages of process time for each worker for different buffer sizes (S – small, M – middle, L – large).

The comparison between the process time for each workstation for a different number of workers is reported in Fig. 10.

Table 6 reports the values of the overall system performance indicators for different buffer sizes.

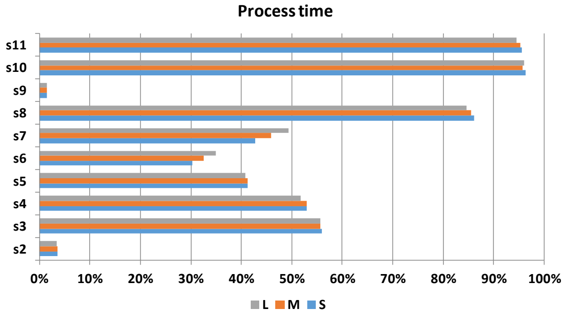

Fig. 10. Percentages of process time for each workstations for different buffer sizes (S – small, M – middle, L – large).

Table 6. Values of performance indicators for different buffer sizes.

Performance indicator	Small	Medium	Large
Total travel [km]	40.9	41.4	41.8
Avg travel [km]	4.1	4.1	4.2
Avg process staytime [sec]	7 198	7 027	6 866
Avg queue staytime [sec]	3 487	12 516	19 808
Avg total staytime [sec]	10 684	19 543	26 674
Throughput [products/week]	108.2	107.9	107.7

In Table 6 we can see the data concerning performance indicators for the scenarios when we retain small, medium and large buffer. We can see that the manufacturing line is able to manufacture 99 products in each scenario. What is worth emphasizing, the bigger buffer the smaller throughput. From the economical point of view, it is more reasonable to keep smaller buffer. Therefore, in the analyzed case, one piece flow is the best solution because performance indicators have the best values and allow to obtain the required throughput.

6. Conclusions and future research

On the basis of the performed analyses we can conclude that the best solution is to employ 9 operators who will perform the manufacturing process with the use of one piece flow manufacturing system. This way we will be able to manufacture a required number of products with the best workers and workstations use. At the same time it will be possible to ensure a good workload balance.

In the presented case study a flexible worker-task assignment has been implemented. Only one worker (a welder) has been fixed to the welding tasks and to the welding workstation. It is reasonable because a welder must have higher level skills and he is difficult to replace. Other workers have no skills to perform the welding process.

However, it could be analyzed in the future if it is reasonable to improve workers' skills to make them capable of performing each kind of work on this manufacturing line. Otherwise, we can also take into consideration assigning more workers to certain workstations and to work tasks as well as to simulate different scenarios.

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