Workforce management in manual assembly lines of large products: a case study

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Abstract:
Assembly lines are used for a large variety of products in different industrial sectors. In this paper the focus is placed on complex assembly systems and workstations used for the final assembly of large and bulk products, such as trucks, aircrafts, buses, tool machines. An high number of tasks to be performed at a single assembly station, several workers involved in parallel in the assembly process and long Takt times make such systems different from the models intensively studied in the literature (e.g. the traditional Simple Assembly Line Balancing Problem). This study firstly presents a new balancing model to address the problem of the total cost minimization when different operator skills are involved at the same time and then it applies the model to a real industrial case.

Keywords:
Assembly line; Large products; Balancing; Optimization; Integer linear programming .

1. INTRODUCTION AND LITERATURE REVIEW

Assembly lines are typically flow-oriented systems where some tasks are performed on the workpieces that are launched down the line. In paced assembly lines, the time between the exit of two consecutive units from the line is called *takt time*, or *cycle time*, and usually comes from considerations related to the desired production rate. The most simple optimization problem coming from these systems is called *simple assembly balancing problem (SALBP)* and assigns each task to a station, respecting the precedence relations of the process and the takt time at each station. The objective is to minimize the number of stations to install (*SALBP-1*). On the other hand, if the objective function is to maximize the production rate (given the number of stations), the solution is to minimize the takt time (*SALBP-2*).

Given the relevant economical interest of this class of problems in practice, *SALBP* formulation has been modified during the years resulting in a wide variety of constraints and different objective functions. In particular, the following important factors had been added in new formulations: spatial and ergonomic considerations, mixed-model production, various line layouts (U-shaped, parallel stations, ...), etc. A comprehensive and recent survey of this class of problems is presented by Battaïa and Dolgui (2013). However, several topics remain underdeveloped. One of them is the workforce management in the assembly systems used for large and bulky products assembly systems such as trucks, aircraft, buses. The size of the considered units gives the possibility for more workers to operate at the same time around the same product. In addition, because of the investment and WIP costs, such lines are usually characterized by a small number of stations, but long takt times. These peculiarities make more complex the management of work at each station since this work organisation becomes close to the project's mode and the project scheduling problems are known to be highly combinatorial. Workforce assignment has to guarantee that all tasks are performed before the deadline expires, in order to deliver the product in time. On the other hand, there is a need to size correctly the workforce taking into account the skills required for different tasks in order to avoid important idle times.

To the best of our knowledge the workforce management in assembly lines of large products has been rarely considered in the literature. However, workforce management via operational research methods is a topic of rising interest in the recent years: it may help to better organize the work distribution and manage the operators skills (for a recent and comprehensive review on workforce planning incorporating skills, see De Bruecker et al. (2015)). As a consequence, these questions are more and more frequently raised for the assembly lines.

Van den Bergh et al. (2013) review and classify the literature on personnel scheduling problems, recommending for the future research to integrate multiple decisions such as: demand forecasting, hiring and firing, machine scheduling, and considering multiple locations (workstations).

Assembling large products means having workers that have to deal with bulky (and usually massive) components: some tasks related to those components need to be executed by more than one worker at the same time, in order to accomplish them properly and to share the ergonomic

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risk. Yazgan et al. (2011), refers to this as "common job", and proposes an heuristic to assign more workers to the same task and thus to the same station of an automotive assembly line. The assignment of more workers to the same workstation in the automotive industry is addressed also by Becker and Scholl (2009), but with workers working on different tasks on the same product at the same time. Hytonen et al. (2008) use discrete event simulation to study the topic of optimizing workforce allocation in assembly lines for highly customised and low-volume products.

Corominas et al. (2008) consider the case of a motorcycle factory that hires temporary and thus unskilled workers to tackle the seasonal and market-driven change in production rate. Moreover, in assembling those motorcycles, some tasks are clean-hands tasks, some others are dirty-hands tasks: a worker can be assigned to at most one of those two sets of tasks. In fact, when the hypothesis of one worker per station holds (typical of SALPB), minimizing the number of stations equals to minimizing the number of workers as well. Obviously, this hypothesis is no more right if several workers can be assigned to a single station. Assigning workers to stations, together with assigning tasks to workers (and thus tasks to stations) is a problem that is addressed by Kara et al. (2014): in this case, also less skilled workers (*assistants*) are considered. Those assistants can only be assigned to stations where there is a skilled worker, and they help him in executing some tasks.

An example of the industrial interest in workforce minimization is assembly line can be found in Battaïa et al. (2015), where a mixed-model production system is optimized. In fact, high customization of products leads to mixed-models lines or to small lots production: the first usually requires line balancing on the average product, and also product sequencing may be taken into account, while the latter needs flexible systems and frequent rebalancing (Chica et al. (2013), Hazır and Dolgui (2013)). Workers may be very flexible with respect to different models of the same product, but they still have only some of the required skills, and thus there may be compatibility constraints in assigning workers to tasks. For this reason, from the management point of view it could be necessary to train workers to be multi-skilled or "cross-trained".

In contrary to single-skilled workers who master only one skill, cross-trained workers may have all skills required and thus can be assigned to every task. Therefore, the use of cross-trained workers can help in facing variations in product demand. Among others objectives, cross-trained workers are used in assembly lines also to substitute other workers and to respond to problems that may happen in a single station. For example, Sennotta et al. (2006) consider a serial manufacturing line with high product variety. The line is designed to be operated by a single-skilled worker per station. One cross-trained worker, who can perform any activity, is assigned to the whole line. The cross-trained worker is used to respond to congestions in dynamic way, floating between two or more stations.

Cross-trained workers' flexibility may turn out to be useful also to deal with resource disruption, e.g. when the delivery of a component is late. Large products, such as aircrafts and lorries, usually have bulky and expensive components to be assembled, that are likely not to be stored in large quantities (e.g. aircrafts wings). Thus, out-of-stocks events are likely to happen. Cross-trained workers can reduce the hardship coming from these events: in fact, especially when very long takt times are considered (one or two day, let's say) their work can be re-planned in order to take into account the late delivery of a component and optimize the workforce assignment, both before and after the delivery of the component, so to complete as many tasks as possible before the late delivery and to catch up as efficiently as possible after it. The more cross-trained the workers are, the less likely they become to face idle time because of that resource disruption, or because of absenteeism of some workers assigned to the station. This is referred to as "ease of worker assignment and reassignment" (Inman et al. (2004)).

In a general case, beside cross-trained workers, sets of workers mastering different combinations of skills can be considered. In particular, Li and Womer (2008) address a project scheduling problem in a software development department with 9 multi-skilled operators, and the aim to reduce the staffing cost. This problem belongs to a special class of the project scheduling problem, called Multi-Skill Resource Constrained Project Scheduling Problem (MSRCPSP). This class represents a recent extension of the project scheduling problem: the first contribution to the study is represented by Néron (2002). Other examples of this class of problems and proposed heuristics to solve them can be found in Almeida et al. (2016).

The use of cross-trained workers is recognized as a solution to problems related to efficiency and flexibility in ALBP (see Hopp et al. (2004) and Yang et al. (2014)). However, across industries, cross-trained workers are usually limited in number and more expensive than single-skilled workers, because of higher wages or because of the training they had. Therefore, the work assignment has to be optimized in order to provide efficient solutions to managers. The goal of this paper is to develop such a model and to apply it to an industrial case study. The paper is organized in the following way. Section 2 present the model. Section 3 describes the model application to a real case study coming from the automotive sector. Section 4 discuss the results of the model evaluation. Section 5 concludes the research study and outlines the research perspectives.

2. MODEL DESCRIPTION

The following formulation considers tasks belonging to three different classes (labelled: R,G,B), depending on the skill they require. The model can be easily adapted to the different number of skills required by the case under study and for this reason, it can be easily generalized and applied to different industrial cases.

2.1 Given Sets:

A = set of all tasks: $A = R \cup G \cup B$.
R = (subset of A) set of tasks requiring skill R;
G = (subset of A) set of tasks requiring skill G;
B = (subset of A) set of tasks requiring skill B;
E = set of ordered pairs of tasks (i, j) such that task i has to be finished before task j starts

Q = set of couples of tasks (i, j) that can not be active in the same moment (because they they occupy the same working spot around the product).
$K = \{1, \ldots, Stations\}$, set of available stations.

2.2 Given Parameters:

$Stations$ = number of available stations.
$TaktTime$ = maximum time span spent by a product in a single station [min/unit].
$TotalTime$ = maximum time span spent by a product in the assembly line:
$TotalTime = TaktTime \cdot Stations$ [min/finished unit]
p_i = processing time (duration) of task i [min/task]
n_i = need of workers for the task i [number of workers/task].
α = ratio between the cost of a cross-trained worker and the cost of a single-skilled worker ($\alpha \geq 1$)
N_R = available workers mastering only skill R
N_G = available workers mastering only skill G
N_B = available workers mastering only skill B
N_{CT} = available workers mastering every skill
N_W = total number of available workers:

$$N_W = N_R + N_G + N_B + N_{CT}$$

ES_i = Earliest starting time of task i
LS_i = meaning that the latest starting time of task i has to be lower than $(LS_i + TotalTime)$. If any of the sums $(LS_i + TotalTime)$ is lower than zero, a feasible solution can not be found, no matter how many workers are used.

ES_i and LS_i depend only on the precedence relations and on the duration of the tasks, so they are computed in preprocessing.

2.3 Decision Variables:

$$S_i = \text{starting time of task i}$$

$$x_{i,m} = \begin{cases} 1 \text{ if task } i \text{ is assigned to the } m^{th} \text{ worker} \\ 0 \text{ otherwise} \end{cases}$$

$$u_{i,j} = \begin{cases} 1 \text{ if tasks i and j are assigned } \textit{in this} \\ \quad \textit{order} \text{ to the same any worker} \\ 0 \text{ otherwise} \end{cases}$$

$$z_{i,j} = \begin{cases} 1 \text{ if tasks } i \text{ ends before } j \text{ starts} \\ 0 \text{ otherwise} \end{cases}$$

$$y_{i,s} = \begin{cases} 1 \quad \text{if tasks } i \text{ is assigned to station } s \\ 0 \quad \text{otherwise} \end{cases}$$

$$j_{m,s} = \begin{cases} 1 \text{ if the } m^{th} \text{ worker is active} \\ \quad \text{and it is assigned to station } s \\ 0 \text{ otherwise} \end{cases}$$

$$Cost = \text{total cost related to the use of workers}$$

All of the above are boolean decision variables, except for the starting time S_i, and the variable $Cost$ that are real positive decision variables.

2.4 Formulation

As explained in detail later, the cost coming from the use of workers is:

$$Cost \geq \sum_{s \in K} \left(\sum_{m=1}^{N_R+N_G+N_B} j_{m,s} + \sum_{m=(N_W-N_{CT}+1)}^{N_W} \alpha \cdot j_{m,s} \right);$$

thus the objective function is as follows:

$$\min Cost$$

subject to:

$$\sum_{m=1}^{N_W} x_{i,m} = n_i, \ \forall i \in \ A \tag{1}$$

$$\sum_{m > N_R \ \wedge \ m \leq (N_W - N_{CT})} x_{i,m} = 0, \quad \forall i \in \ R \tag{2}$$

$$\sum_{m \leq N_R \vee [m > (N_R+N_G) \wedge m \leq (N_W - N_{CT})]} x_{i,m} = 0, \quad \forall \ i \in G \tag{3}$$

$$\sum_{m \leq (N_R+N_G)} x_{i,m} = 0, \quad \forall i \in B \tag{4}$$

$$S_{LastTask} + p_{LastTask} \leq TotalTime \tag{5}$$

$$S_j - S_i \geq p_i, \ \forall (i,j) \in E \tag{6}$$

$$u_{i,j} + u_{j,i} \leq 1 \ , \ \forall i,j \in A^2, \ j > i \tag{7}$$

$$u_{i,i} = 0, \ \forall i \in A \tag{8}$$

$$u_{i,j} + u_{j,i} \geq x_{i,m} + x_{j,m} - 1, \quad \forall m = 1, ..., N_W, \ \forall \ i,j \in A^2, i > j \tag{9}$$

$$S_j - S_i \geq p_i - M(1 - u_{i,j}), \ \forall (i,j) \in A^2 \tag{10}$$

$$S_j + p_j \leq S_i + M \cdot (z_{i,j}), \ \forall (i,j) \in Q \tag{11}$$

$$S_i + p_i \leq S_j + M \cdot (z_{j,i}), \ \forall (i,j) \in Q \tag{12}$$

$$z_{i,j} + z_{j,i} = 1, \ \forall (i,j) \in Q \tag{13}$$

$$\sum_{s \in K} y_{i,s} = 1, \ \forall i \in A \tag{14}$$

$$\sum_{s \in K} s \cdot (y_{i,s} - y_{j,s}) \leq 0, \ \forall (i,j) \in E \tag{15}$$

$$\sum_{s \in K} j_{m,s} \leq 1, \ \forall m \in 1, ..., N_W \tag{16}$$

$$\sum_{m=1}^{N_W} x_{i,m} = n_i \cdot y_{i,s}, \ \forall i \in A, \forall s \in K \tag{17}$$

$$x_{i,m} \leq \sum_{s \in K} j_{m,s}, \ \forall i \in A, \ \forall m \in 1, ..., N_W \tag{18}$$

$$x_{i,m} + y_{i,s} \leq 1 + j_{m,s}, \quad \forall i \in A, \forall m \in 1, ..., N_W, \forall s \in K \tag{19}$$

$$\sum_{s \in K} (j_{m,s} - j_{m+1,s}) \geq 0, \ \forall m = 1, ..., (N_R - 1) \tag{20}$$

$$\sum_{s \in K} (j_{m,s} - j_{m+1,s}) \geq 0, \quad \forall m = (N_R + 1), ..., (N_R + N_G - 1) \tag{21}$$

$$\sum_{s \in K} (j_{m,s} - j_{m+1,s}) \geq 0, \quad \forall m = (N_R + N_G + 1), ..., (N_W - N_{CT} - 1) \tag{22}$$

$$\sum_{s \in K} (j_{m,s} - j_{m+1,s}) \geq 0, \quad \forall m = (N_W - N_{CT} + 1), ..., \ (N_W - 1) \tag{23}$$

$$S_i \geq ES_i, \ \forall \ i \in A \quad (24)$$

$$S_i \leq LS_i + TotalTime, \ \forall \ i \in A \quad (25)$$

$$S(i) \geq \left(-1 + \sum_{s \in K} (s \cdot y_{i,s})\right) \cdot TaktTime, \ \forall s \in K \quad (26)$$

$$S(i) + p(i) \leq \sum_{s \in K} (s \cdot y_{i,s}) \cdot TaktTime, \ \forall s \in K \quad (27)$$

$$\sum_{i \in A} x_{i,m} \leq 0 + M \cdot \sum_{s \in K} j_{m,s}, \ \forall m = 1, ..., N_W \quad (28)$$

$$Cost \geq \sum_{s \in K} \left(\sum_{m=1}^{N_R+N_G+N_B} j_{m,s} + \sum_{m=(N_W-N_{CT}+1)}^{N_W} \alpha \cdot j_{m,s} \right) \quad (29)$$

Constraints (1) assure that each task is assigned to the required number of workers. Constraints (2), (3), and (4) assure that each task is assigned only to workers mastering the required skill, who are single-skilled or cross-trained. Constraint (5) assures that every task ends before $TotalTime$ expires. Constraints (6) state the precedence relationships. In fact, for each couple $(i, j) \in E$, task i must finish before task j starts. Moreover, it is guaranteed that there is no overlapping between two any tasks given to the same worker, taking into account the order of the two. Given two tasks (i, j) assigned to the same worker, either i comes after j or otherwise but not both at the same time. This is stressed by constraint (7). It does not make any sense to define $u_{i,i}$, so we force all of those to be equal to zero (constraint (8)). If tasks (i, j) are assigned to the same any worker, exactly one between $u_{i,j}$ and $u_{j,i}$ has to be equal to one. To ensure that at least one of them is equal to 1, constraints (9) must be respected. Constraints (10) link the decision variables $u_{i,j}$, S_i, and S_j. M is a sufficiently large positive number. Constraint (10) is always verified for each couple of tasks that are not assigned to the same worker ($u_{i,j} = 0$), while it adds a precedence constraint (in the right order) between two tasks if they are assigned to the same any worker.

Constraints (11), (12), and (13) assure that two tasks are not active at the same moment, if they occupy the same working spot. Equation (14) assures that each task is assigned to exactly one station, while (15) is set to respect precedence relations among stations. Constraint (16) assures that each worker is assigned at most to one station. Constraint (17) states that the correct number of workers needs to be assigned to the task, only to the station that the task is assigned to, while (18) assures that tasks are assigned only to active workers. If a task is assigned to worker m and to station s, then worker m has to be assigned to station s: this is expressed by (19). It should be noted that starting times of tasks do not begin from 0 again at station 2, but go on from values reached at station 1, just like the product sees tasks being executed on itself, and goes from 0 to $TotalTime$.

Constraints from (20) to (25) are used to break the symmetry of the problem and to reduce the search space: they do not change the optimal solution of the problem but usually shorten considerably the time required to find it. In detail, constraints (20), (21), (22), and (23) guarantee that $(m+1)^{th}$ worker can be assigned to a task only if m^{th} worker is aready assigned, for each class of workers. Constraints (24) and (25) ensure that the starting time of task i is constrained to be between two values, i.e. for tasks preceding task i to finish and for the ones following task i to end before the $TotalTime$ expires. LS is computed considering a null value of $TotalTime$. If any value of $(LS_i + TotalTime)$ is negative, the problem is not feasible with that value of $TotalTime$.

Constraints (28) are used to count the total active workers across the stations. Constraint (29) takes into account the different cost of workers: the cost of a single skilled worker is supposed to be unitary, while the coefficient α expresses the ration between the salary of a cross-trained worker and the salary of a single skilled worker. If the cost of cross-trained workers is the same as a normal worker, or if there is no cross-trained worker, then minimizing $Cost$ equals minimizing the number of workers. When few units are required for each model of product, or in general when changes in product demand happen, this model may turn out to be useful to re-balance the workforce among different lines of products. Also, in light of this, it is important to note that "in real-world situations it is usually not necessary to balance an entire line with several hundreds or thousands of tasks but segments of the line with much smaller task numbers" (Becker and Scholl (2009)).

3. INDUSTRIAL CASE

3.1 Description

The company of the case study customizes mini buses. The realized study considered a portion of a product characterized by 80 tasks. All task durations of tasks are in the range [0:1369] s. The precedence constraints are shown in Figure 1. Each task requires one out of 3 specified worker skills (R, G or B), so tasks can be divided in sets depending on the needed skill, as follows:

R = {1, 2, 11, 12, 14, 15, 17, 18, 21, 22, 23, 25, 29, 33, 35, 36, 39, 40, 41, 42, 43, 45, 48, 49, 50, 51, 54, 55, 56, 57, 58, 60, 61, 64, 68, 71, 72, 73, 75, 76, 79 },

G = {8, 9, 16, 20, 24, 31, 37, 44, 47, 53, 59, 62, 66, 74, 80},

B = {3, 4, 5, 6, 7, 10, 13, 19, 26, 27, 28, 30, 32, 34, 38, 46, 52, 63, 65, 67, 69, 70, 77, 78}.

Seven tasks require to be assigned to 2 workers, in order to share the ergonomic risk (8, 9, 26, 35, 39, 50, 60).

In this case, the wage of a cross-trained worker is assumed to be 1.3 times more important that the wage of single-skilled worker.

For the considered product, different production rates can be forecast (assuming 40 working weeks a year) :

Table 1. Different production rates

units/week (units/year)	Stations	Takt time [s]
12 (480)	1	10225
15 (600)	1	8034
17 (680)	1	7304
24 (960)	2	5113
31 (1240)	2	4017
34 (1360)	2	3652

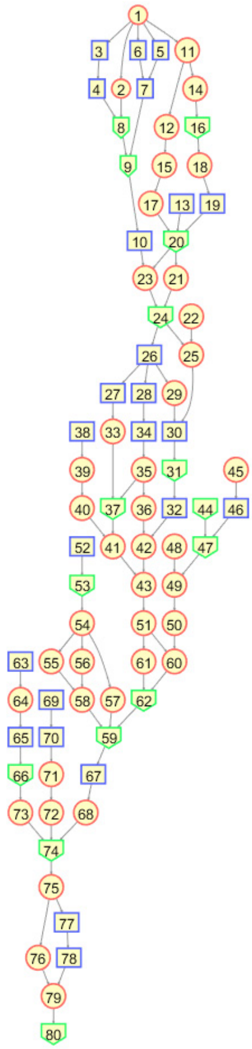

Fig. 1. Precedence constraints

The optimization objective is to determine the number of workers of each skill and to assign all tasks to them respecting the constraints among the tasks, skill requirements and minimizing the production cost. The model developed to solve this optimization problem is presented in next section.

4. RESULTS DISCUSSION

The problem is solved with *IBM ILOG CPLEX Optimization Studio*, Version 12.6.3.0 . The problem is studied by varying the maximum number of cross-trained workers of one unit at the time, starting from zero. With single-skilled workers only, the optimal number of workers is presented in Table 2 and in Fig. 2. Optimal solutions were always found in less than 13 s.

Among all cases considering also cross-trained workers, Table 3 presents the results obtained for 1 station and production rates of 680 $\frac{units}{year}$ and 480 $\frac{units}{year}$. In Table 4, the results obtained for 2 stations producing 1360 $\frac{units}{year}$ are presented. In Table 2, it is possible to note that the time to solution (Run time) is generally higher when more stations are considered, compared to situations with only one station (other data confirmed this trend). Still, given the numerous variables, sometimes it is hard to forecast the behaviour of the running time, that in some instances decreases more workers are available or when the production rate decreases (see run time for different production rate but same number of workers available).

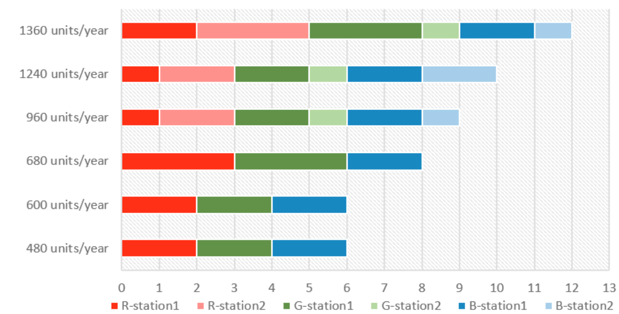

Fig. 2. Optimal solution: single-skilled workers only

Table 2. Line balancing - single skilled workers

Production rate [units/year]	480	600	680	960	1240	1360
Total workers	6	6	8	9	10	12
Workers per skill: R,G,B	2,2,2	2,2,2	3,3,2	3,3,3	3,3,4	5,4,3
At station 1: R,G,B	2,2,2	2,2,2	3,3,2	1,2,2	1,2,2	2,3,2
At station 2: R,G,B	0,0,0	0,0,0	0,0,0	2,1,1	2,1,2	3,1,1
Run time [s]	5	11	2	13	11	6

Table 3. Line balancing - with cross-trained workers ($\alpha = 1.3$), 1 station

Available cross-trained workers	0	1	2	3	4
680 $\frac{units}{year}$					
Total workers	8	6	4	3	3
Total cost	8	6.3	4.6	3.9	3.9
Workers per skill: R,G,B,CT	3,3,2,0	2,2,1,1	1,1,0,2	0,0,0,3	0,0,0,3
Run time [s]	2	5	146	339	128
480 $\frac{units}{year}$					
Total workers	6	4	3	3	3
Total cost	6	4.3	3.6	3.6	3.6
Workers per skill: R,G,B,CT	2,2,2,0	1,1,1,1	1,0,0,2	1,0,0,2	1,0,0,2
Run time [s]	5	69	139	179	94

Table 4. Line balancing - with cross-trained workers ($\alpha = 1.3$), 2 stations

Available cross-trained workers	0	1	2	3	4
1360 $\frac{units}{year}$					
Total workers	12	10	8	7	7
Total cost	12	10.3	8.6	7.9	7.9
Workers per skill: R,G,B,CT	5,4,3,0	4,3,2,1	3,2,1,2	3,1,0,3	3,1,0,3
At station 1: R,G,B,CT	2,3,2,0	2,3,2,0	1,2,1,1	1,1,0,2	1,1,0,2
At station 2: R,G,B,CT	3,1,1,0	2,0,0,1	2,0,0,1	2,0,0,1	2,0,0,1
Run time [s]	6	20	94	531	107

5. CONCLUSIONS

This paper presents a new mathematical model for workforce management in assembly lines. It is especially relevant for workforce dimensioning and assignment at lines assembling trucks, aircraft, and other large products. Due to the use of this model, it is possible to determine the optimal requirement in single-skilled and cross-trained workers involved in the assembly process.

The proposed model is applied to a real industrial case. The considered optimization problem is solved exactly within reasonable solution time. A wide variety of situations can be modelled and thus optimized with the proposed formulation especially if small portions of the line should be rebalanced because of supply disruption or workers' absenteeism. Moreover, this formulation can be used as simulation tool to determine which skill is the most useful to teach to workers.

Limitations however exist. In fact the model computation time increases when the number of tasks increases and the shape of the precedence diagram varies from thin to wide. In particular, the test cases conducted by the authors are suggesting that the solution time fast increases with a number of tasks major than 120.

For future research, a heuristic procedure should be developed to cover particularly large problem instances. Additionally, it is important to analyse the ergonomic risks related to the tasks in a more formal manner and to include them in the problem formulation. As well, as to study the reliability of each task in terms of the supply stability and to develop relevant models taking into account the fact that some tasks are more likely to be late than others.

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