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Assembly line design with tools vibration

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Abstract: This study integrates vibrations aspects in the Assembly Line Design Problem (ALDP). During the last decade, ergonomic aspects have been considered by several points of view in the assembly design problems in order to reduce work-related musculoskeletal disorders. However, the workers vibration exposure level, caused by the use of automatic tools to perform some tasks, has not still discussed as a part of ALDP. For this reason, a new model is here proposed to compare the total costs of an assembly line with and without the integration of the ISO 5349-1, the European norm that defines the vibration exposure limit for workers. The application of the model here proposed in two real industrial contexts shows the effects of the vibration level maximum exposure in the final assembly line design costs.

Keywords: Assembly line design, ergonomics, human factor, vibration measurement.

1. INTRODUCTION

Even if in the last years the automation in production systems is always more important, there are some phases of the production process that are still performed manually. This is the case of final manual assembly lines where operators perform a set of tasks manually. As defined in Dolgui and Proth (2010), the manual assembly represents one of the most important phases of production systems due to its high added value, its contribution to the final product quality and its direct connection with the final market. However, due to the tasks repetitiveness at relatively high frequency, severe forces, non-neutral postures and vibrations, workers are subjected to musculoskeletal disorders.

Some surveys (Nunes, 2009) reveal that 44 million workers in Europe suffer from work-related musculoskeletal disorders (WMSDs) while the 35% of operators and assemblers reports backaches and muscular pains regularly causing a decrease in the gross national product of the EU countries up to 2%. For these reasons, in the last decade, several studies have been conducted to introduce ergonomic aspects in the early stages of production and assembly system design. In the literature, a first attempt to integrate ergonomic aspects in the assembly line balancing problem is the study conducted by Otto and Scholl (2011) on which several objective functions are examined in an ERGO-SALBP model solved with a two-stage heuristic approach. After this work, other models and approaches have been proposed with the aim to reduce physical ergonomic risks that can cause WMSDs as defined in the interesting literature review developed by Otto and Battaïa (2017). In this literature review, only papers that integrate ergonomic risks in the assembly line balancing and scheduling problem are considered. However, other human factors like worker muscular and cardiovascular fatigue measures can be used to estimate the workers conditions during working time. Those ergonomic criteria could be integrated into the ALDP as it was done in the recent studies of Abdous et al. (2018) and Finco et al. (2018) on which muscular fatigue and human energy expenditure have been integrated into a simple assembly line balancing (SALBP) type 1 and 2 respectively.

However, in some assembly lines, there are other types of problems that can create disorders or injuries among workers and these types of problems can be more important than the classical ergonomic parameters such as postural problems or fatigue level. This is the case of the high level of vibrations at which workers can be exposed when some manual tasks are executed with automatic tools. Generally, these tools are light and handy, but they can produce a high level of vibrations with some negative aspects of the workers' health. In fact, an excessing vibration level may cause WMSDs in the upper part of the body such as the white finger disorder, neurological disorders, muscular weakness as underline by Radwin et al. (1990). According to Bovenzi and Hulshof (1996), from 1.7% to 5.8 % of workers in the European Countries, U.S. and Canada are exposed to the so-called hand-arm vibration (HAV) syndrome. In Xu et al. (2012) vibration aspects are introduced in a SALBP type 1 with other ergonomics constraints such as exertion frequency and normalized peak force according to the guidelines provided from the American Conference of Governmental Industries. In this work, the aim has been the definition of the minimum number of workstations respecting ergonomic constraints. In particular, with this

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mixed-integer programming model authors show the potential to reduce the need for task adjustments to improve ergonomic aspects after the preliminary stages of assembly line balancing. However, to the best of our knowledge, no papers have been developed until now to directly evaluate the only effect of vibration exposure measurements in the assembly line design phase.

For this reason, in this paper, we provide a new MILP approach with the aim to minimize the cost of automatic tools to use in each workstation respecting the admissible vibration level according to the ISO 5349-1 ISO (2001a,b) which defines the maximum level of vibration that workers can be exposed to avoid HAV. We assume that only automatic tools can be used and that the main ergonomic problem is linked to the vibration level. Generally, these assumptions can be considered as true especially in the final assembly of electronic devices or in the aeronautical and automotive sector on which workers have to perform the same tasks with a high frequency with the same automatic tools (Radwin and Armstrong, 1985).

The paper is structured as follows. Section 2 provides a literature review of related works and explain the ISO (2001a) used as a constraint is our model. In Section 3 the MILP approach is presented while in Section 4 we present two industrial cases and we discuss the results. Finally, conclusion and future works are presented in Section 5.

2. BACKGROUND

As defined in the previous section, manual assembly lines are often used in the last step of production, when parts are put together to obtain the final product. In an assembly line, there are several workstations on which a set of tasks are performed by operators with a set of automatic tools or manually. When several tools are used for assembly tasks, the issue of designing an assembly line becomes very important since it is necessary to avoid having same tools in several workstations as the total equipment cost could be very high. In this context, the design consists of selecting the set of tools for the workstations and addressing the related question of which tasks should be performed in which of the workstations. Due to the flexibility of the equipment and tools, there are usually several equipment alternatives for each task, and it may be the case that a particular piece of equipment is efficient for some tasks, but not for others. This has to be taken into consideration when several tasks have to be performed at the same workstation, using the same equipment. As mentioned above, through the design problem the equipment type is chosen and the set of tasks to be performed in each workstation is defined.

The combinatorial problem of assigning tasks in the ALBP could be considered before the assignment of equipment and tools in sequential order. The consideration of the assignment of tools or equipment and tasks is called the assembly line design problem (ALDP) (Baybars, 1986). As mentioned above, through the design problem the equipment type is chosen and the set of tasks to be performed in each workstation is defined. In addition, the amount of time required to obtain a product is defined (usually by the product's demand with the takt time) as well as the final cost of the assembly line.

In the literature, a lot of studies have been performed for the Simple Assembly Line Balancing problems (SALBP) in which no alternative equipment types are considered. That is, each task time is fixed, and the remaining problem is to determine the sets of tasks to be performed at each workstation minimizing the number of the workstation (SALBP-1) or the takt time (SALBP-2) or maximizing the efficiency (SALBP-E). Some interesting literature reviews about this topic are Boysen et al. (2007); Rekiek et al. (2002); Battaïa and Dolgui (2013).

The problem linked to the equipment selection is considered in relatively few studies. Graves and Redfield (1988) consider the design problem with several equipment alternatives when multi products are assembled on the same line. Through their heuristic algorithm they define all feasible workstations, the best equipment for each and after this first phase, they define the best set of workstations. Considering the single product design problem, the first works have been done by Graves and Whitney (1979) and Graves and Lamar (1983) on which, in both articles, the sequence of tasks is assumed to be fixed. Pinto et al. (1983) proposed a branch and bound to evaluate several processing alternatives in a manual assembly line. Each processing alternative is related to a given set of tasks i.e., represents a limited equipment selection which may be added to the existing equipment in the workstation, and the decision is whether to use each such alternative in order to reduce the duration of the task, at a given cost. Rubinovitz et al. (1993) present a branch and bound algorithm for the problem of designing and balancing a robotic assembly line when several robot types are available, and the objective is to minimize the number of workstations. A literature review of cost and profit-oriented ALDP is provided in Hazir et al. (2015).

The equipment selection phase is generally considered after when the takt time and the number of workstations are known. It represents also a phase that can be done several times in the same assembly line. In fact, due to technological changes and the tools usury managers can be in front of this problem more than one time for the same assembly line. Additionally, to avoid workers injuries, it is better to include ergonomic aspects in this phase. However, to the best of our knowledge, no papers until now exist that include ergonomic aspects during this phase. Considering the upper extremities, the WMSDs can be caused by a high level of exposure vibrations emitted by automatic or electronic tools (Maizurayusoff and Rahman, 2016).

The vibration exposure depends on its frequency spectrum, on its magnitude and on its duration (ISO, 2001a). Additionally, as defined in the ISO (2001b), the daily vibration exposure duration requires an evaluation of the exposure duration associated with each work phase. Indeed, in a typical working day, the operator can use different tools to complete tasks. Moreover, only some tools can produce vibrations or only some tasks can require the use of some vibrating tools. For each vibrating tool, the measure of its vibration level has to be taken with the instruments conforming to the ISO 8041 and measurements should be made for all three directions with the same weight. According to (ISO, 2001a), the first measure to evaluate for each of the three axes is the root-mean-square (r.m.s) frequency-weighted acceleration. After that, the frequency weighting has to be applied to reflect the importance of some values of r.m.s. in causing injury of the hand and the acceleration value, expressed in m/s^2, is obtained for each direction. At this point the vibration total value for a generic tool, a_{hv}, is defined as follows:

$$a_{hv} = \sqrt{a_{hvx}^2 + a_{hvy}^2 + a_{hvz}^2} \qquad (1)$$

Equation (1) defines the vibration level produced by a vibrating tool and it integrates the vibration values in all directions, x, y and z in a single value. Following the ISO (2001a) the daily exposure is defined through the vibration total value and its daily exposure duration and it is expressed in term of working time hours energy equivalent frequency weighted vibration total value according to:

$$A(T_0) = a_{hv}\sqrt{\frac{T}{T_0}} \qquad (2)$$

Where T represents the total daily exposure to a_{hv} while T_0 represents the working time (shift time, e.g. 8 hours or 28800 s).

However, as defined in ISO5349-1:2001 when several tools are used during a typical working day the daily vibration exposure shall be obtained using the following equation:

$$A(T_0) = \sqrt{\frac{1}{T_0}\sum_{i=1}^{n} a_{hvi}^2 T_i} \qquad (3)$$

where for each vibrating tool i we have to consider its vibration value a_{hvi} and its related duration T_i while T_0 the shift time. Considering a typical working day of 8 hours the ISO5349-1:2001 defines two threshold values of daily vibration exposure which are respectively equal to 2.5 m/s^2 for moderate risk threshold and to 5 m/s^2 for the maximum admissible threshold. If $A(8)$, calculated with Equation (3) is upper to 2.5 m/s^2 this means that workers are exposed to moderate ergonomic risks and that some modifications are required to avoid disorders or injuries. On the other case, if A(8) is upper to 5 m/s^2 which is the threshold of the maximum acceptable level, several modifications must be taken because the maximum exposure level has been exceeded.

However, if the daily exposure is less than 8 hours, according to Equation (3), the threshold and the maximum acceptable value of vibration increase as shown in Table 1. We can see that for an exposure period of 30 minutes the acceptable level of vibration could be very high if compared to the acceptable value related to 8 hours.

Example: if the vibration total values for exposure in a normal working day of 8 hours are respectively: 1.85 m/s^2 for 1 hour, 2.25 m/s^2 for 1 hour, 0.15 m/s^2 for 4 hours and 1.45 m/s^2 for 2 hours, then:

$$A(8) = \sqrt{\tfrac{1}{8}(1.85^2 * 1 + 2.25^2 * 1 + 0.15^2 * 4 + 1.45^2 * 2)}$$

Therefore, $A(8) = 1.26\ m/s^2$ and this means that the norm threshold value is respected and tools modifications are not required.

In the next Section, we present the approach we propose to include vibration norm into the ALDP. We propose a new MILP approach to address the problem.

Table 1. **Vibration limits according to ISO 5349-1:2001(ISO, 2001a)**

Total daily exposure $[h]$	Threshold value $[m/s^2]$	Maximum limit $[m/s^2]$
8	2.5	5
6	2.89	5.77
4	3.54	7.07
2	5	10
1	7.07	14.14
0.5	10	20

3. MATHEMATICAL MODEL

In this paper, we address the question of selecting the equipment and assigning tasks to workstations, when we minimize the design cost and when the ISO 5349-1:2001 must be respected to avoid WMSDs.The model sets the number of workstations and the takt time and it seeks to assign tasks and tools to respect the minimization of the whole design cost.

The solution consists of a series of workstations, where a set of tools is placed in each workstation, and a set of tasks assigned to this workstation must be performed by the selected equipment. The objective is to minimize the design cost, given a pre-determined takt time and a fixed number of workstations. Minimizing the tools costs, we try to reduce the total line costs and we achieve the respect of the vibration exposure limit according to ISO 5349-1:2001. In this way, we obtain benefits for the company and for workers that can be summarized in a cost saving due to a reduction of WMSDs and absenteeism.

The ALDP parameters are the following:

- $V = \{1, .., n\}$: Set of tasks;
- $W = \{1, .., m\}$: Set of workstations;
- $E = \{1, .., r\}$: Set of tools;
- P: Set of precedence relation between task;
- a_{lim}: acceleration limit $[m/s^2]$;
- T: takt time $[s]$;
- nb: the number of takt time in a daily shift;
- T_0: daily shift $[s]$;
- t_{ij}: deterministic task time of task j when performed with tool i;
- a_{ij}: vibration of tool i when performing task j $[m/s^2]$;
- C_i: cost of tool i [€];

While the decision variables are:

- x_{ijk}: that is 1 if task j is assigned to workstation k with tool i and 0 otherwise.

- y_{ik}: that is 1 if tool i is assigned to workstation k and 0 otherwise.

The objective: Minimization of the cost of tools in the assembly line.

The MILP model:

$$Minimize\{\sum_{i\in E}\sum_{k\in W} C_i y_{ik}\} \tag{4}$$

$$\sum_{i\in E}\sum_{k\in W} x_{ijk} = 1, \forall j \in V \tag{5}$$

$$\sum_{j\in V} t_{ij} x_{ijk} \leq T, \forall i \in E, \forall k \in W \tag{6}$$

$$x_{ijk} \leq y_{ik}, \quad \forall i \in E, \forall j \in V, \forall k \in W \tag{7}$$

$$\sum_{i\in E}\sum_{k\in W} k.x_{ihk} \leq \sum_{i\in E}\sum_{k\in W} k.x_{igk}, \forall (h,g) \in P \tag{8}$$

$$\frac{nb}{T_0}\sum_{i\in E}\sum_{j\in V} t_{ij} a_{ij}^2 x_{ijk} \leq a_{lim}^2, \forall k \in W \tag{9}$$

$$x_{ijk}, y_{ik} \in \{0,1\} \tag{10}$$

The objective function in (4) minimizes the design cost of the whole assembly line. Constraint (5) ensures the assignment of each task to one workstation and to one specific tool. Working time in all workstation must respect the takt time as defined in (6). Constraint (7) ensures that a tool cannot be assigned to a task if the first is not present in the workstations and link the two decision variables. The precedence relation between tasks is respected in (8). Constraint (9) is the linearized form of the Equation (3) where we consider the vibration exposure limit according to the takt time $\frac{T_0}{nb}$. Finally, constraints (10) defines the type of variables. The MILP formulation in (4)-(10) guarantees the respect of the daily vibration and the minimization of design costs. To test the approach proposed in this paper, we apply the model to two industrial cases study as illustrated in the following section.

4. NUMERICAL CASES AND DISCUSSION

We apply our model to two industrial cases study, the first concerns an assembly line of a minibus and the second the assembly line of a business jet. Both assembly lines concern big size product and the assembly phase is totally manual. Workers in both cases are subjected to ergonomics risks related to tools vibration. In order to design the two lines in the case study respecting the vibration norm, we consider the MILP proposed in Section 3. We compare the approach with vibration and without the vibration norm to assess the difference in the vibration value and the related ergonomic risks. The work shift in both cases is 8 hours, so we apply the corresponding threshold vibration limit of 2.5 m/s^2 to design the assembly line and to avoid ergonomic risks. The assumptions about the vibration values produced by tools have been made considering some tools typically used in the two industrial contexts. In particular, we consider the vibrations produced by screwdrivers, grinders and drills.

We use Cplex V12.8.0 with default parameters as a solver. We use in our experiments a personal computer with Intel(R) Core(TM) i7-6700HQ 2.60Ghz and 16Gbit RAM. In this experiment, we solve the ALDP with the MILP (4)-(10) where the vibration constraint is considered to assign tools. We also solve the ALDP without vibration constraint, (i.e. we remove constraint (9)). We seek to evaluate the difference between an assembly line design approach that neglects the vibration and that one we propose in this work.

4.1 Case study 1

The company of the first case study manufactures mass-customized mini-bus. In this case study, we consider only the assembly of a portion of the final product with 80 tasks with a takt time of 2490 seconds. Workers use tools such as grinders, automatic screwdriver, etc. We attempt to design the assembly line assigning tasks and the appropriate set of tools to workstations. For each workstation, we assign a subset of tasks that should be executed with respect to the precedence constraints and to the takt time. Furthermore, we assign tools to the workstation to execute the subset of tasks.

We consider 10 possible different tools to design the line. The average cost of tools is equal to 2330€ with a standard deviation (SD) of 42€. The cost of tools has a negative correlation with the vibration level and the required execution time to perform a task. In this way, a tool with a high vibration level that must be used for a prolonged time to complete a task has a lower cost if compared to a tool that requires a lower time to complete a task with a low vibration level.

Due to the fact that some tasks cannot be executed with a tool, we assign a big value in the t_{ij} matrix (i.e. $t_{ij} = \infty$), similarly, when a task j is completely manual, the values in the vibration matrix are equal to zero (i.e. $a_{ij} = 0$). In our case study, the minimal value of vibration is 0 m/s^2 while the maximal one is 8 m/s^2. The takt time is defined according to the customers' demand and it is equal to 7304s. The optimal number of workstations to assembly the mini-bus is 3 workstations.

Table 2. **Vibration level with and without the proposed approach for the Mini-bus assembly line**

Workstation	1	2	3
With Vibration [m/s^2]	2.47	2.49	2.44
Without Vibration [m/s^2]	**3.06***	**3.4***	**3.3***

The design cost (objective function) is 9200€ if the model here proposed is used, otherwise, it is 6900€ if vibration constraint is omitted. However, even if the design cost is 2300€ higher with our approach, the level of vibration in each workstation respects the threshold value of 2.5 m/s^2. On the other hand, when vibration aspects are not included in the model, in all workstations injuries associated with vibrations aspects can arise as the acceptable threshold value is exceeded. Furthermore, the economic gap between the two model solutions is very close to the average cost of a single tool (2330€), whereas the solution without considering the vibrations could require to make investments and modifications on all workstations, thus probably more expensive than the solution given with our methodology.

With the model here presented, the mean vibration value is 2.47 m/s^2 with a SD of 0.02 m/s^2 while, with that one without vibration constraints, the daily exposure after a shift of 8 hours can be up to 3.4 m/s^2 (more than 0.9 m/s^2 from the threshold value). Furthermore, in this last case, the mean vibration exposure value is 3.25 m/s^2 with a SD of 0.13 m/s^2. This is a significant value as it means that workers are certainly exposed to related vibration risks. However, we can note that there are no workstations on which the vibration level is higher than 5 m/s^2 so if the vibration constraint is missing only a small re-design is required (e.g. change tools, re-allocation of some tasks).

The workstation time must respect the takt time. In Table 3, we present the mean and the SD of the execution time in seconds. The mean workstation time is 5858 seconds with an SD of 1306.67 seconds if the vibration limit is included in the model. If vibration constraint is missing the mean workstation time increases to 5946 seconds. As we can note there is a difference of 88 seconds between the two average workstations time obtained with the two approaches. However, with our method, the mean workstation time is lower.

Table 3. **Mean time and standard deviation**

	Mean time [s]	SD [s]
With vibration	5858	1306.67
Without vibration	5946	1724.67

4.2 Case study 2

The second case study concerns the assembly line of a part of business jets, the fuselage. In this part of the assembly process, workers use tools and equipment that produce vibrations, thus they are subjected to WMSDs risks. The customers' demand defines the takt time to 15000 seconds and 125 tasks are needed to finish the assembly. We consider the same experimental conditions as the first industrial application presented before. We can choose between 10 possible different tools that have an average cost of 5380€ with an SD of 916€ and a vibration level between 0.7 and 33.5 m/s^2.

Table 4. **Vibration level with and without the proposed approach for the Business Jets**

Workstation	1	2	3	4
With Vibration [m/s^2]	1.99	2.45	2.44	2.46
Without Vibration [m/s^2]	**3.12***	2.00	**3.48***	2.11

After the consideration of the MILP with this case study, the design cost is 17600 € with the consideration of vibration and 17500 € without the consideration of vibration. To avoid WMSDs and ergonomic risks, only an additional investment of 100 € is necessary to design the assembly line. When we consider the vibration threshold, the level of vibration is smoothed between workstations. The mean value of vibration is 2.33 m/s^2 with a standard deviation of 0.17 m/s^2. In the case when we do not consider vibration constraints, the value of vibration in a workstation could be up to 3.48 m/s^2 with a mean value of 2.68 m/s^2 and a standard deviation of 0.62 m/s^2. In this case, without vibration constraint, there are 2 critical workstations. Only one tool is assigned to each workstation in this second case study, both with and without the consideration of the vibration aspect.

The computational time is 788s with the approach we propose and 148s without the consideration of vibration in this case study. The computational time is compatible with practical experimentation in an industrial situation.

Then as well, the mean and standard deviation of execution time assigned to the workstation in the second case study is presented in Table 5. The mean value is similar with and without the consideration of vibration norm; however, the standard deviation in the case with vibration constraint is higher. Even if the standard deviation is higher, the solution with the consideration of vibration norm presents lower ergonomic risks and it can be considered better than the second case because we have a better distribution of vibration level among workers.

Table 5. **Mean time and standard deviation**

	Mean [s]	SD [s]
With vibration	11467.5	3211.5
Without vibration	11474.75	2009.37

In both industrial cases, the consideration of workers vibration exposure level, with the approach proposed in this paper, can guarantee a correct balancing of vibration exposure among workers. Neglecting the daily vibrations limit, workers are subjected to high vibration exposure. Consequently, as stated in Section 2, when the threshold of vibration is higher than 2.5 m/s^2, workers are subjected to WMSDs and to a higher ergonomic risk.

5. CONCLUSION

Modern assembly lines use tools and equipment with a different level of vibration and for this reason, the ISO 5349-1:2001, which defines the maximum level of vibration that workers can be exposed to avoid ergonomic risks, must be considered in the assignment of task and equipment to the workstation. We introduce this normative restriction in the ALDP and we apply the model proposed in two industrial case study: the first one in a company that manufactures mini-bus and the second one in an aircraft assembly line. Workers in both cases are subjected to vibrations and the approach succeed to design the line respecting the norm. However, if the vibration constraint is missing more than half of the workstations presents a vibration value upper than the acceptable limit and, for this reason, modifications and tasks adjustments are required to avoid disorders and injuries among workers. Furthermore, companies can obtain benefits in the future due to a possible reduction of absenteeism and injuries.

Nevertheless, the limitation of this approach is the consideration of the ergonomics only for vibration aspects and risks. Indeed, tools vibration aspects should be integrated with physical ergonomic risks such as fatigue or ergonomics risk factor of physical nature. Furthermore, the cases study here analyzed should be completed with a larger experimental test on which several instances, from literature and from real industrial scenarios. In this way, we could better evaluate the performance of the MILP here proposed in term of computational time, and performance. Indeed, the ALDP is an NP-hard problem and for this reason, for instances that cannot be solved optimally a heuristic approaches should be implemented to the solve the problem and to give a solution closed to the optimal one.

In future work, a perspective of this work could be the consideration of equipment vibration with other ergonomics risks evaluation method. The objective function in this work considers the minimization of the whole line design cost and it could be considered in a multi-objective approach with ergonomics. For assembly line designers, it is important to have information on the trade-off between conflicting objectives and to design solution approaches (Cerqueus and Delorme, 2018). The consideration of different conflicting objectives (e.g. ergonomics, costs, risks) and the presentation of the trade-off between them are promising perspectives.

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