Proposing a new method to solve line balancing bottleneck problem in the single-model line [version 2; peer review: 1 approved, 1 approved with reservations]

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Abstract
Many problems occur when assigning tasks to work centres, especially in determining the required number of workstations for line balancing which requires a minimum theoretical number of workstations. The most common problem is bottleneck. In this paper, a method is proposed to solve floating tasks problem in single-model line when the actual required number of workstations exceeds the minimum theoretical number, and the standard time of the floating task (work center) exceeds the cycle time. The floating task will represent a critical bottleneck activity in line. The proposed method depends on minimizing the standard time of critical bottleneck and non-critical activities by a minimum free-floating time depends on the average of slack times of the non-critical activities, and it will increase the line efficiency from (77%) to (88%), and balance delay is minimized from (23%) to (12%).

Keywords
line balancing; bottleneck; floating activity; free float time
The proposed method improves the performances of the assembly line when a bottleneck problem is occurred with many cases such the floating tasks, number of workstations exceeds the theoretical number, and the standard time of the floating task exceeds the cycle time. These cases were not discussed by researchers in literatures, for that, the proposed method was described as a new problem and was not supported by existing literature. Because of that, the results presented were not validated against any other existing works in the literature. There was a need to define the experimental setups of the experiment on the assembly line. So it is added to the manuscript. The proposed approach must be run many times to meet the balancing requirements. Many experimental setups must be done to the system, and operations assumptions must be defined as below:

- Determine the initial state.
- Determine the minimum theoretical number of work stations.
- Assigning work load to work stations, the duration time of each work center is pre-determined.
- No handling operations, moving parts, and work in process are needed.
- Assuming that the demand is stable on the line.
- Assuming that the precedence relations are stable.
- Determining the critical bottleneck and non-critical activities.
- The approach will stop when meeting the balancing requirements, and the number of run times could not be pre-determined.
- The impact of the study as a significant increase in productivity, efficiency, and profitability was defined.

Any further responses from the reviewers can be found at the end of the article

**Introduction**

Line balancing means assigning work to a smallest number of workstations in a line process to equalize workload between these stations and achieve the desired output rates. There are many types of line models: single-model, multi-model, and mixed-model. For a single line model, two general groups depending on their configuration are commonly seen: traditional straight lines and U-shaped lines: traditional straight production line organizes the tasks sequentially in one direction to form stations, and U-shaped production line, however, is divided into two sub-lines, namely, the entrance sub-line and the exit sub-line, and, thus, an operator may perform tasks on either one of the two sub-lines or on both sub-lines simultaneously. In single-model line, there is only one model and precedence diagram. The classification of a bottleneck may vary. Normally the definitions include but are not necessarily restricted to: physical constraints, economical characteristics, output limitations, capacity utilization, work-in-process limitations and capacity in relation to demand. So, a bottleneck may simply be defined as the production system stage that has the largest influence on limiting the throughput in the system. Line balancing is a necessary task, its importance appears when there are some changes in process, such as adding or deleting tasks, change of components, changes in processing time, and also in implementing of new processes. It is also a successful tool to reduce bottleneck by balancing the task time of each work station. Line balancing is a method to balance the assignment of some work elements from an assembly line balancing to the work station to minimize the number of workstations and minimize total of idle time on the whole work station on a certain level of output, therefore it is necessary to do the line balancing to reduce the bottleneck, increase line efficiency, and reduce balance delay. The bottlenecks could be viewed from two different perspectives: bottleneck workstations and bottleneck tasks. Bottleneck workstations can be easily identified within the assembly line as the station having the maximum cycle time (greater than the takt time). Bottleneck tasks are identified within each work stations, whereas tasks having the maximum activity time. Determining the bottleneck is an essential issue to control the process, throughput, and cycle time. Since task is the smallest work element in the line, then the cycle time cannot be smaller than the largest time of a task. The proposed method aims to minimize the standard time of bottleneck workstation or bottleneck task, and assign all tasks to workstations, to avoid floating tasks and solve the problem when the actual number of workstations exceeds the minimum theoretical.

When constructing a diagram to presents the work elements, especially in project management issues, and constructing a cost-duration graph, the most difficult task is to decide which activities to shorten and how far to carry the shortening process. Shortening an activity is called **crashing**. Crashing is a useful tool in project management, and when the information about normal and crash times and costs is available. It depends on minimizing the normal time (standard time) for critical activities which have the minimum slope. In line balancing, such information is not available always, and it is sometimes difficult to estimate it. So, crashing is not an efficient tool to minimize critical activities’ standard times. The proposed method in this work will presents an approach to minimize the standard time of critical activities depending on the average of slack times of the non-critical activities.

**Problem statement and related works**

The simple assembly line balancing problems (SALBP) are fundamental versions of the general assembly line balancing problems (ALBP), which has attracted the attention of practitioners and researchers of OR. With respect to the objective functions, the SALBP was classified into SALBP-1, SALBP-2 and SALBP-E. These deterministic problems are not always applicable for real assembly and production lines, since in practice the durations of the assembly operations and other parameters may depend on many factors and are not constant values throughout the lifecycle of the assembly and production lines.

Solving actual assembly line balancing problems is difficult with the many real world constraints. So, line balancing bottlenecks are still problematic at present. Most of the literatures focus on defining and solving bottlenecks in scheduling job shops and flow shops, and different methods and heuristics were proposed to solve this problem such the Shifting Bottleneck...
Method which is considered as one of the most successful tools to identify bottlenecks, minimize total weighted tardiness, and control bottlenecks along with scheduling\textsuperscript{14}. From the other hand, researches in determining the line balancing model and minimizing takt time have long occupied a prominent place in operations management literature. Bottlenecks in line balancing when its standard time is greater than the cycle time, and the actual required number of workstations exceeds the theoretical minimum had a little concern from researchers. This paper aims to address this issue by minimizing the standard time of critical bottleneck and non-critical activities by a minimum free floating time depends on the average of slack times of the non-critical activities.

Naveen Kumar and Dalgobind Mahto (2013) discussed the minimization of idle time of man and machine through distributing tasks over the workstation. Meby Mathew and D.Samuelraj (2013) studied the distributing of work load in an assembly line across successive workstations as an approach to reduce cycle time and wastes in resource and time. Varsha Narayan and Shriram Sane (2014) discussed waste identification and elimination, and de-bottlenecking to balance the line and optimize utilization of resources for improving the productivity. Shriram Sane, Varsha Karandikar, Rahul Pulkurte, and Subodh Patil (2014) discussed the effects of Lean Manufacturing tools such as cycle time study, line imbalance calculation, bottleneck identification, Kaizen, space utilization through layout change and workstations organization on the performance of assembly lines. Jaggi et al. (2015) studied the reduction in cycle time for single model assembly line when line is balanced which increase the efficiency by reducing non value added activities and other outcomes were that assembly line balanced by recommending new layout. Manaye (2019) balanced production line by using line balancing techniques which are Ranked Positional Weight and Largest Candidate method through work study method. As a result of analysis, the Ranked Positional Weight gives better results in the line efficiency and delay time minimization which compared to largest candidate technique. So that techniques minimize bottleneck operations and arranging the workload among work stations to increase line efficiency and minimize delay time\textsuperscript{12}.

**Problem formulation**

In line balancing, a few requirements are needed for a set of tasks to be assigned to workstations. These requirements are: 1) a task that has been assigned to a workstation cannot be assigned to another workstation; 2) total time for each workstation to finish all their tasks must be less than or equal to cycle time; and 3) the precedence relationship must be followed rigidly by all tasks and cannot be disregarded\textsuperscript{13}. A single-model line instance of (11) tasks (A to K) is considered as in Table 1 to assign tasks to workstations, and balance the line. Cycle Time (Ct) and theoretical minimum number of workstations (Ws) are calculated depending on Equation (1) and Equation (2) below. Precedence diagram is constructed for assembling the line as in Figure 1 as an initial state.

\[
Ct = \frac{T_d}{D} \quad (1)
\]

\[
Ws = \frac{J_c}{Ct} \quad (2)
\]

Where: \(T_d\) is total required time of the working day, \(D\) is daily demand, and \(J_c\) is Job content which equals to (49) and represents the total of tasks standard times in Table 1.

According to Equation (1) and Equation (2), given the daily demand is (3000) unit and the available working time is (6) hours per day, then \(Ct\) is (7) seconds and \(Ws\) is (7) workstations. Table 2 presents the earliest and latest start and finish times, critical and non-critical tasks, and slack times for the tasks. Total completion time \(C_{max}\) is (30) seconds, and total slack time is (19) seconds.

The initial state indicated in Figure 1 shows that task C represents a problem in which it still floating, because its standard time is greater than cycle time, also the actual required number of workstations is (8) and exceeds the theoretical minimum. The floating task represents a critical bottleneck activity in the line, and its standard time must be reduced to meet minimum theoretical number of workstations and output rates.

**The proposed method**

Slack time is the difference between latest and earliest starting times of the non-critical activities. It means that there is a free float time for the work element. Decreasing total completion time of the (11) tasks instance presented in Figure 1 requires minimizing the standard time of the non-critical tasks by the minimum slack time of one of them.

The proposed approach must be run many times to meet the balancing requirements. Many experimental setups must be done to the system, and operations assumptions must be defined as below:

- Determine the initial state.
- Determine the minimum theoretical number of work stations.

<table>
<thead>
<tr>
<th>Task</th>
<th>Precedence</th>
<th>Standard time (sec)</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>---</td>
<td>6</td>
</tr>
<tr>
<td>B</td>
<td>A</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>A</td>
<td>8</td>
</tr>
<tr>
<td>D</td>
<td>B</td>
<td>7</td>
</tr>
<tr>
<td>E</td>
<td>C</td>
<td>2</td>
</tr>
<tr>
<td>F</td>
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<td>G</td>
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<td>H</td>
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<tr>
<td>J</td>
<td>H, I</td>
<td>4</td>
</tr>
<tr>
<td>K</td>
<td>F, J</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1. A single-model line instance.
Assigning work load to work stations, the duration time of each work center is pre-determined.

- No handling operations, moving parts, and work in process are needed.

---

**Figure 1.** Precedence diagram of the initial state.

**Table 2.** The critical bath calculations of the initial state.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>On Critical Path</th>
<th>Activity Time</th>
<th>Earliest Start</th>
<th>Earliest finish</th>
<th>Latest start</th>
<th>Latest finish</th>
<th>Slack (LS-ES)</th>
</tr>
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<tbody>
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<td>yes</td>
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<td>0</td>
<td>6</td>
<td>0</td>
<td>6</td>
<td>0</td>
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<td>B</td>
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<td>6</td>
<td>8</td>
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<td>5</td>
</tr>
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<td>6</td>
<td>14</td>
<td>6</td>
<td>14</td>
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</tr>
<tr>
<td>D</td>
<td>No</td>
<td>7</td>
<td>8</td>
<td>15</td>
<td>13</td>
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<td>5</td>
</tr>
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<td>E</td>
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<td>14</td>
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</tr>
<tr>
<td>F</td>
<td>No</td>
<td>5</td>
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<td>25</td>
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<td>2</td>
<td>14</td>
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<td>16</td>
<td>18</td>
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<td>H</td>
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</table>

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>On Critical Path</th>
<th>Activity Time</th>
<th>Earliest Start</th>
<th>Earliest finish</th>
<th>Latest start</th>
<th>Latest finish</th>
<th>Slack (LS-ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

Project Completion Time = 30 Seconds
- Assuming that the demand is stable on the line.
- Assuming that the precedence relations are stable.
- Determining the critical bottleneck and non-critical activities.
- The approach will stop when meeting the balancing requirements, and the number of run times could not be pre-determined.

This approach does not ensure solving the bottleneck problem of the line, neither allows minimizing the standard time of the critical bottleneck task, nor meeting the theoretical minimum number of workstations. The proposed method will minimize the standard time for both of critical bottleneck and non-critical activities by a minimum free floating time (I) depends on the average of slack times of non-critical activities as in the equations below:

\[
SL_{tave} = \sum SL_t / N \tag{3}
\]

\[
DFS_t = S_m - Ct \tag{4}
\]

Where \( SL_{tave} \) is the average of slack time for non-critical tasks, \( DFS_t \) is the difference in time between the standard time \( S_m \) of the bottleneck task and cycle time, and \( N \) represents the number of non-critical tasks.

\[
T_{BK} = S_{BK} - P_{BK} \tag{5}
\]

Where \( T_{BK} \) represents the bottleneck time, and \( P_{BK} \) represents the standard time of the previous task on the critical path.

Now, if \( SL_{tave} \geq DFS_t \)

\[
\text{And } DFS_t \leq T_{BK} \text{ then } I_t = DFS_t \tag{7}
\]

Otherwise, if \( SL_{tave} < DFS_t \) and \( SL_{tave} < T_{BK} < DFS_t \) then \( I_t = SL_{tave} \tag{8} \)

Else, \( I_t = T_{BK} \tag{9} \)

At first, for the non-critical tasks in Table 2 and Equation (3), the proposed method is applied to get \( SL_{tave} \) equals to (4) seconds with a predefined \( Ws = 7 \) workstations and \( Ct = 7 \) seconds, \( DFS_t = 1 \) seconds, and \( T_{BK} = 2 \) seconds. Considering Equation (6) and Equation (7) for the initial state in Figure 1, then \( I_t = 1 \) second. The tasks involved in the reduction are the critical task \( C \) and non-critical \((B, D, F, G, \text{ and } I)\) in which their standard times will be \((7, 1, 6, 4, \text{ and } 2)\) respectively as displayed in Table 3 which presents balancing the line. Figure 2 presents assigning work to workstations. Total completion time \( (C_{max}) \) is \( (29) \) seconds, and total slack time is \( (29) \) seconds.

**Line efficiency and balance delay**

To measure whether the line is efficient in producing the output rate, line efficiency and balance delay are the most measures used. To optimize line balancing, efficiency should be maximized and balance delay should be minimized. These measures are calculated by the following equations:

\[
\text{Efficiency} \% = J/C \times Ws / (Ct) \tag{10}
\]

\[
\text{Balance Delay} \% = 100 - \text{Efficiency} \tag{11}
\]

**Results**

The minimum free floating time \( (I) \) ensures minimizing both bottleneck time and completion time \( (C_{max}) \) of the line from \( (30) \) to \( (29) \) seconds, and meets the theoretical \( (Ws) \).

Table 4 presents a comparison between efficiency and balance delay before and after applying the proposed method.

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<table>
<thead>
<tr>
<th>Activity Name</th>
<th>On Critical Path</th>
<th>Activity Time</th>
<th>Earliest Start</th>
<th>Earliest finish</th>
<th>Latest start</th>
<th>Latest finish</th>
<th>Slack (LS-ES)</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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</tr>
<tr>
<td>F</td>
<td>No</td>
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<td>13</td>
<td>17</td>
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<td>7</td>
</tr>
<tr>
<td>G</td>
<td>No</td>
<td>1</td>
<td>13</td>
<td>14</td>
<td>17</td>
<td>18</td>
<td>4</td>
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<tr>
<td>H</td>
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<td>5</td>
<td>15</td>
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<td>2</td>
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<td>16</td>
<td>18</td>
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</tr>
<tr>
<td>J</td>
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<td>20</td>
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<td>Project Completion Time</td>
<td>=</td>
<td>29 Seconds</td>
<td></td>
<td></td>
<td></td>
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</tr>
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</table>
Table 4. Efficiency and balance delay before and after applying the proposed method.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Before the propose method</th>
<th>After the propose method</th>
</tr>
</thead>
<tbody>
<tr>
<td>C max(Seconds)</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>Job Content (Seconds)</td>
<td>49</td>
<td>43</td>
</tr>
<tr>
<td>Total Slack Time(Seconds)</td>
<td>19</td>
<td>29</td>
</tr>
<tr>
<td>Efficiency</td>
<td>77%</td>
<td>88%</td>
</tr>
<tr>
<td>Balance Delay</td>
<td>23%</td>
<td>12%</td>
</tr>
</tbody>
</table>

Conclusions and suggestions for future work
The bottleneck problem in assembly line balancing has become a frequently encountered problem today. The unequal and random workload assignment to the work stations, floating task (work center) with standard time exceeds the cycle time, and actual required number of workstations exceeds the minimum theoretical number cause the occurrence of floating tasks, non-optimal use of resources, and decrease the line efficiency. For this reason, if these problems are solved in the work shop floor, a significant increase in productivity, efficiency, and profitability will be achieved, contributing to a significant reduction in completion times, line balance delay, and costs at the same rate.

The results of the proposed method show that the floating tasks which represent critical bottleneck activities have a significant influence on the assembly line balancing problem when assigning tasks and work elements to workstations if at least one of the tasks considered as bottleneck when its standard time is greater than cycle time, and the actual required number of workstations exceeds the theoretical minimum. The proposed method depends on minimizing the standard time of critical bottleneck and non-critical tasks by a minimum free floating time depends on the average of slack times of the non-critical activities. This minimum free floating time ensures minimizing both bottleneck time and the completion time ($C_{\text{max}}$) of the line from (30) to (29) seconds, and meets the theoretical ($W_s$), increases the line efficiency from (77%) to (88%), and balance delay is minimized from (23%) to (12%). The proposed method could be applicable in different industrial problems where the assembly line balancing is one of them, and in job shop and flow shop process environments.

For future works, solving bottleneck problems in other line balancing models such parallel or mixed line model studies could be considered. Minimizing workstation takt time is another attractive field for study.

Data availability
No data.
References


Open Peer Review

Current Peer Review Status: ✅ ❓

Version 1

Reviewer Report 27 April 2023

https://doi.org/10.21956/emeraldopenres.16090.r28713

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The author proposed a line balancing bottleneck in a single-model line, which claimed that some performances of the assembly line were improved to some degree.

Although this is well and good, the manuscript fell short on many fronts.

Firstly, the manuscript refers to many rather outdated manuscripts, and the only manuscript that is worth considering at this time is by Manaye (2019). However, I failed to find such a paper in the reference section. Rather the reference section listed many unrelated references, some even not being cited in the main text. As such, the current contributions to the body of knowledge seem rather questionable.

Secondly, the proposed method was fully described and was not supported by existing literature. In addition, only performance measures were formulated where neither the approach's process nor any model was present. Therefore, it is challenging to determine the extent of the manuscript's contribution.

Thirdly, the experimental setups were missing entirely. Basically, what are the system settings of the experiment done on the assembly line? How many runs/simulations were conducted? How the best results were determined? Is there a parameter involved in the experiments?

Fourthly, the results presented, although they showed some improvement, it is rather arbitrary and were not validated against any other existing works in the literature. In addition, it was unclear where or how the data came to be. Also, how significant is the improvement to real-world settings (statistical analysis is needed)?

Finally, no limitations and managerial implications were discussed. Basically, the results should be discussed from an industrial standpoint, which needs to consider other/many moving parts of the
manufacturing process. As such, the impact of the study is also unclear. Due to these facts, the manuscript will be no more than a paper suited as a conference paper instead of a journal submission.

**Is the rationale for developing the new method (or application) clearly explained?**
Partly

**Is the description of the method technically sound?**
Partly

**Are sufficient details provided to allow replication of the method development and its use by others?**
Partly

**If any results are presented, are all the source data underlying the results available to ensure full reproducibility?**
Partly

**Are the conclusions about the method and its performance adequately supported by the findings presented in the article?**
Partly

**Is the argument information presented in such a way that it can be understood by a non-academic audience?**
No

**Does the piece present solutions to actual real world challenges?**
Not applicable

**Is real-world evidence provided to support any conclusions made?**
Not applicable

**Could any solutions being offered be effectively implemented in practice?**
Not applicable

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** artificial intelligence, planning and scheduling, evolutionary algorithms, game analytics, data sciences

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.
Many thanks to the reviewer for his significant comments. The proposed method improves the performances of the assembly line when a bottleneck problem is occurred with many cases such the floating tasks, number of workstations exceeds the theoretical number, and the standard time of the floating task exceeds the cycle time. These cases were not discussed by researchers in literatures, for that, the proposed method was described as a new problem and was not supported by existing literature. Because of that, the results presented were not validated against any other existing works in the literature.

I agree with the reviewer in that there is a need to define the experimental setups of the experiment on the assembly line. So it is added to the manuscript. The data is an experimentally instance. No need at this stage for statistical analysis because there is no comparison between two proposed methods.

The impact of the study as a significant increase in productivity, efficiency, and profitability was defined.

A couple of updated manuscripts were added.

**Competing Interests:** No competing interests were disclosed.
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
No source data required

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Yes

Is the argument information presented in such a way that it can be understood by a non-academic audience?
Yes

Does the piece present solutions to actual real world challenges?
Yes

Is real-world evidence provided to support any conclusions made?
Yes

Could any solutions being offered be effectively implemented in practice?
Yes

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Ergonomics and safety engineer

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

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**Author Response 15 Apr 2023**

maha Alrawi, University of Technology, Iraq, Baghdad, Iraq

Dear sir
Thank you for the reviewer comments, they were scientific.
As for the suggestion of applying on real data, I would like to point out that the manuscript is not applied research, and a hypothetical example was tested for the proposed method.

**Competing Interests:** No competing interests were disclosed.