A Framework Supporting The Design Of Walking Worker Assembly Line Towards Improving Productivity And Ergonomics Performance

Atiya Al-Zuheri*, Lee Luong**, Dr. Ke Xing***
*(School of Engineering, University of South Australia, Mawson Lakes, 5095 South Australia, Australia
Ministry of Science and Technology, Al-Jadriya, 10070 Baghdad, Iraq)
**(School of Engineering, University of South Australia, Mawson Lakes, 5095 South Australia, Australia)
*** (School of Engineering, University of South Australia, Mawson Lakes, 5095 South Australia, Australia)

ABSTRACT
In recent years, many flexible assembly systems have been adopted as effective and productive solutions to respond the changes and uncertainties in a competitive manufacturing environment. Successful designs of these systems must be capable of satisfying the strategic objectives of a management in manufacturing company. An example of such systems is so-called walking worker assembly line WWAL, in which each cross-trained worker travels along the line to carry out all required tasks. Design approaches for this system have not been investigated in depth both of significant role in manual assembly process design; productivity and ergonomics. Because of that, these approaches have had a limited success to real applications. This paper presents an innovative and integrated framework which offers the possibility to support the improvement of productivity and ergonomics requirements in WWAL design. To clearly demonstrate implementing the developed framework, a systematic approach established. The approach is based on the simultaneous application of mathematical and meta-heuristic techniques. The developed framework has been applied to the optimisation of a manual assembly system design from the industry.

Keywords - design approach, ergonomics, framework, productivity, walking worker assembly line

I. INTRODUCTION
The newest manufacturing system is lean manufacturing, which is specifically designed to respond quickly and economically to the fluctuating nature of the market demands. This demand represents by increasing customisation, shortening of a product lifecycle and high product variety produced in small batches [1]. One of the cornerstones of lean manufacturing is the use of workforce flexibility in manufacturing systems. As a general, the workforce flexibility is the use of cross-training workers across different processes, so that they can perform a variety of different jobs and tasks [2]. These workers can be assigned dynamically to a number of workstations or manufacturing cells. This is typically implemented either through a team concept where workers cycle through a set number of workstation on the line and workers are assigned tasks based upon varying daily workforce needs. In particular, workforce flexibility is used where firm’s manufacturing system involve are labour-intensive in nature (e.g. manual assembly line) and if bottlenecks (e.g. machine or worker) are presented in that system also [3].

In flexible work force assembly system, the workers are able to switch tasks rapidly; the line will be able to respond quickly to changing demand. This is results in improving system efficiency in the form of higher throughput, lower work in process (WIP), and shorter cycle times without significant additional investment in equipment and labour [4].

This paper explores one such system that of manning of an assembly line with fewer workers than workstations. This dynamic, flexible and reconfigurable assembly system is so-called walking worker assembly line (WWAL). In WWAL the configuration of workstations in horizontal “U” shape or straight line layout and typically manned by multifunctional workers travel by walking down the line carrying out each assembly task at each workstation as scheduled. Thereby, each walking worker completes the assembly of a product in its entirety from start to end. Fig. 1 illustrates concept of WWAL, where a walking worker completes a product assembly process at the last workstation and then moves back to the first workstation to begin the assembly of a new product. Hence, each walking worker on the line cannot be wasted away because each single worker is knitted to one single item all the time and it is his/her responsibility for completely assembling a product within an anticipated cycle time [5].
The WWAL is designed to possess the ability to be run with more or fewer workers, thus adjusting staffing levels according to varying production volumes is possible on such lines. Generally speaking, in the design of an assembly system several objectives may be desired: maximum throughput, minimum cycle time, minimum number of workstations, minimum idle time and minimum line length. The trade-off between these objectives was examined by Gurmani and Johri [6], and most objectives have shown poor correlation among themselves. The decision of which objective function is most appropriate (and whether single or multi-objective) depends on the characteristics of the assembly system environment including: technological factors, personnel and organisational factors and market demand [7].

The overall objective in designing a “lean” manual assembly system is to produce a required number of units to meet the fluctuating demand and produce these units at the lowest cost possible, while keeping within an ergonomically balanced/friendly operation [8]. For WWAL, a total cost per unit can be reduced by minimising the in-process worker cost, which consists of labour waiting time (due to blocking), the costs of worker production (processing) time, and labour walking time [9]. In addition, changes in the design of line to aid in improving the ergonomics are also needed [10]. With this requirements in design of WWAL, the problem needs to be solved is optimising the combination of operational and structural decision variables to meet overall objective stated above [11]. This paper proceeds as follows: the current approaches used in designing WWAL covered by existing literature are reviewed in section 2. Section 3 presents architecture of the framework developed for optimising WWAL design. The application of the established approach for implementing the developed framework is introduced in section 4. Section 5 describes the application of the developed framework in an industrial setting, leader in assembling of diesel injection pump. The conclusion of this paper and outline future research avenues are presented in section 6.

II. OVERVIEW OF THE EXISTING WWAL DESIGN APPROACHES

To support WWAL design different approaches were developed, each of them represents a different level of abstraction of WWAL, as do the measures the model is capable of providing. The target of these models is to assess the system performance in terms of productivity, flexibility, WIP, workers utilisation etc. based on different configurations of WWAL. Wang, Owen and Mileham [12] and Nakade and Nishiwaki [13] give a summary of research included these approaches. From reviewing this research, it can be noted the application of these approaches are directed to only solve isolated problems; have not attempted to evaluate the joint optimisation of human workers performance in terms of productivity and ergonomics at whole system design level, with implementation of WWAL in manufacturing industry. Consequently this may lead to poor solutions for the overall design of WWAL especially with limited scope given to the ergonomics aspects at the design stage. Although it is understandable the reason behind considering separately different decisions in design of WWAL is related to the ease of designing it does not consider their interrelationships. As the assembly industry in the 21st Century faces dynamic markets these isolated decisions in design approach will lead to local optimisation of WWAL designing processes. Disadvantages resulting from non-integrated design approaches in WWAL can include: greater operating costs economically and ergonomically and a duplication of design efforts. Because of this, it is easy to see that most WWAL approaches presented in the literature (even if little work is published) cannot be considered as the basis for a sound and worthwhile first step in clearly identifying and structuring the relevant WWAL approach which can be used to tackle the requirements of productivity and
ergonomics in the system design problem. However, it was recognised by Borenstein, Becker and Santos [14], Baines and Kay [15], and Wang and Chatwin [16] that the optimisation of design for flexible assembly systems (e.g. WWAL) remains a challenging problem because of the following reasons:

• The extensive interaction between available facilities for production (such as labour, tools, fixtures, information, products and assembly workstations);
• Various uncertainties in production demands (such as production schedules); and
• Presence of randomness (such as variability in task completion time).

In addition to the above-mentioned reasons, based on a specific application and other design considerations in the system, the number of performance measures to be optimised simultaneously may vary. Hence, optimisation design process for WWAL becomes more complex especially considering there exists a problem for non-linear, constrained multiple measure optimisations. The lack of appropriate approaches capable of assisting the evaluation and analysis during WWAL design becomes more complex especially its real performance, especially in terms of productivity and ergonomics, can be considered as an important factor for this system has yet to be widely adopted in the industrial environment. Taking into account the above proposed criteria, in next section is a complete description of the framework developed in order to manage this situation, describing its architecture and its logic.

III. THE DEVELOPED FRAMEWORK
ARCHITECTURE

With the requirements for designing WWAL the problem needing to be solved is that of optimising the combination of operational and structural decision variables to meet overall objective stated above [11]. Fig. 2 illustrates the framework architecture developed to assess WWAL design and optimisation and links productivity and ergonomics considerations as well as illustrating all the main data and decisions involved in the procedure. The proposed procedure consists of three different sections: the input data, decision variables, and integrated procedure. The framework aims to:

• Provide a systematic approach to support the WWAL designer during the whole project design and also using that approach in system operational design to react to changing market demands in terms of product quantities; and
• Describe all connections between input variables and set design objectives using the block diagram in Fig. 2.

As shown in Fig. 2 the framework can be considered at two levels:

(1) Structural design level which involves determining the physical assembly line layout; and
(2) Operational design level which optimises the staff workers for the system and the specified skill levels for responding to the demand. It should be noted that the operational level is intervened with structural level when designing a new system as it needs to consider the skill and employment needs.
IV. A SYSTEMATIC APPROACH TO DEVELOPED FRAMEWORK IMPLEMENTATION

The structured approach which presents the fundamental formalisms for a developed framework is presented in this section. This approach has been set to capture the specific requirements of designing WWAL that introduced in previous section. The specifications of provided approach are stated in the following order: input and output, objectives design, constraints, and tools and techniques.

A. The input and output

Recent efforts to achieve efficient and flexible assembly systems within the industry have focused on simultaneously integrating between some of these variables that influence the optimisation of the system performance particularly in the specified objectives [17]. These variables include operational and structural variables like workforce level, skills, control strategies, layout configuration etc. [18]. The optimal level of variables related to these areas provides very good, or at least reasonable, sub-optimal results [18]. Computational experiments are
often used to determine the optimal level of variables that influence the optimisation of the overall system performance [19]. Those variables are controllable factors (decision variables), whereas the uncontrollable factors (the input data) are either difficult to control in the field performance of the system, although they may be controlled for performing a specific experiment [20]. In this paper, the input to WWAL design approach is used to formalise the requirements (output) that the approach must accommodate. Here, input and output of the problem are posed as follows: select input data and decision variables to be manipulated by the approach as input, and decision variables to be supplied by the approach as an output.

1) The input data
   The product is assumed to be selected and types of assembly operations have been already selected also. The input data include four groups.
   (1) Market demand: production volume and production mix (single model, mixed model, multiple model);
   (2) Products characteristics: weights, dimensions, and components;
   (3) Assembly processes (including human workers): assembly tasks (times, variability), available time for production, anthropometric measures of workers (age, gender, weight), the operating cost (the wage of each worker), and fatigue rate of workers; and
   (4) Ergonomics and the working environment: humidity, temperature, expenditure energy required for each task, and metabolic rate for postures

2) Decision variables
   Taking into account the mentioned input data, the problem consists in finding values for the following eight decision variables of the best WWAL design that can provide better ergonomics conditions as well as improving productivity for the workers in the system. The decision variables of WWAL design problems are divided into two types; operational and structural.
   (1) Operational variables: all variables that are linked to work force aspects. It includes:
      a) Skill levels of workers;
      b) Number of slow workers;
      c) Number of workers at the line; and
      d) Walking speed.
   (2) Structural variables: all variables that are linked to the line topology and size. It includes:
      e) Distance between workstations;
      f) Number of workstations;
      g) Layout shape design; and
      h) Floor surface roughness.

B. The approach objectives design
   The WWAL should be designed with “level of improvement” for decision variables that will result in best design of the system, where the opportunity for greater impact on labour productivity and ergonomics is expected to be greatest. There are four design objectives to consider in WWAL design.
   Productivity objectives:
   (1) Enhance utilisation of labour by minimising the possibility of blocking rate between one worker and the next due to uneven skilled workers, different working speeds and/or individual abilities. This can lead to in-process waiting time in front of the bottleneck workstation and resulting in decreased production capacity. Therefore, WWAL should be designed in order to minimise the in-process waiting time.
   (2) Reduction in the operating design cost through minimising shift time labour cost which required for the desired production demand.
   Ergonomic objectives:
   (1) Lowering the amount of effort spent on the task (minimising metabolic energy consumption).
   (2) Resulting in maximisation of mechanical exposure of worker body through performing assembly work.
   Clearly, it seems each objective is unique, but all of them share the main operational objectives in designing of manual assembly systems; improve worker-hour productivity and reducing line operating costs [7, 21, 22].

C. The constraints
   The approach selects the best design of WWAL based on a setting selected design objectives (as mentioned above) and constraints. Therefore, the best design must satisfy both; objectives and constraints. The constraints that specify the requirements to be met in a set of feasible design solutions of WWAL before consider one of them as superior choice that meets the previous objectives, are as follows:
   (1) Production requirements: the expected candidate design solution has production rate equal or greater than to that with traditional assembly line FWAL. According to the economic importance of assembly operations in manufacturing [23], productivity rarely needs to be sacrificed to attain other measures. Hence, If this requirement is not met, why should be adopted this system then?
   (2) Design operating cost: the total cost associated with the assembly line design solution, specifically, the sum of costs associated with
direct labour requirement must be lower than that of FWAL. This cost reduction can result in significant product cost savings and consequently remaining competitive in increasingly competitive markets.

(3) Physical worker capacity: the workers in selected design of the system must be physically able to perform all work-related tasks required of them. With this context, it is desirable to adopt ergonomically sound system design which matches the worker’s capacity to the job’s demands. If worker’s capacity is neglected when designing and analysing of manual assembly systems, the industrial conditions can expose workers to the major risk of work related musculoskeletal disorders WRMDs [24].

D. The approach techniques

In practice, using of optimisation methods in finding the optimum design of manual assembly system involves the determination of the best combination of decision variables so as to optimise a performance criterion consider with the various objectives [25]. Decision variables optimisation in flexible production systems like WWAL, is required to be undertaken in two stages [26]:

(1) Modelling of input, decision variables and objective function relationship, and

(2) Determination of optimal combination of those variables that could achieve higher performance without violating the imposed constraints.

With this perspective, this paper establishes a two-phase systematic approach to implement the framework proposed for optimising the design of WWAL. The approach is a mechanism combining modelling and optimising procedures in two sequential phases to effectively design a WWAL. The approach has two phases; mathematical modelling phase and genetic algorithms (GAs) optimisation phase. The approach schematic is outlined in Fig. 3. In first phase, a mathematical model formulae to map and process the relationships between basic data and decision variables with objective functions of the system design; worker productivity and ergonomics. In second phase, GAs are utilised to obtain the optimal values of decision variables combinations with corresponding objective functions. The interface between the two phases is a fundamental part of this approach. It binds together the modelling and optimisation in the design of walking worker assembly line.

![Figure 3. Schematic of structure for modelling and optimisation in framework approach for WWAL design problem.](attachment:image.png)

A detailed description of the modelling process as well as the development of genetic algorithms to optimise design of WWAL in terms of productivity and ergonomics performance can be seen in Al-Zuheri research [27]. Thus, this paper focused mainly on the applicability of the proposed framework approach in handling optimising design of WWAL for addressed problem.

V. CASE STUDY

The proposed framework has been applied case problem have been taken from Ramesh, Prasad, and Srinivas research work [28]. The case study relates to one of the leading manufacture for the different types of fuel pumps in India. The diversification demand has placed the manufacture under pressure to improve his production system. These improvements targeted a number of performance measures included:

- Increasing production rate from 100 to 120 pump/hour;
- Reducing manpower to produce the target production rate; and
- Reducing operating costs.
E. The proposed alternative in literature

Owing to the needed improvements above, the team of Ramesh, Prasad, and Srinivas research work [28] were study the existing layout for the assembly line and they were proposed one-piece flow line design with introducing the following changes:

- Changing the L-layout to U-layout;
- Rearranging of the assembly workstations and adjusting the distance between workstations to avoid unnecessary bottleneck;
- Adopting milk run concept as an internal system for handling the product between workstations;
- Giving some workers multiple assembly tasks; and
- Considering ergonomics design requirements in accessing to the tools and movements from one workstation to another.

The above proposed characteristics usually result a new design for the assembly line. As cited above the one-piece flow line has been proposed for assembly the pump. The design team considered the use of simulation modelling to implement the proposed line design using PROMODEL™ package. The validated results of simulation modelling have been summarised in the Table 1.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Current state</th>
<th>One-piece line improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number units per 10 hour shift time</td>
<td>167</td>
<td>200</td>
</tr>
<tr>
<td>Number of workers</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Units per worker</td>
<td>8.35</td>
<td>14.28</td>
</tr>
<tr>
<td>Time per unit (minutes)</td>
<td>3.6</td>
<td>3</td>
</tr>
<tr>
<td>Number of workstations</td>
<td>20</td>
<td>16</td>
</tr>
</tbody>
</table>

As noted from results in Table 1, the important activity from proposing one-piece flow line for assembly process of diesel pump in case study, was the labour productivity improvement. However, the team who proposed one-piece flow line model has tried some of the lean manufacturing concepts but has not implemented all of them to an extent that almost all of the waste in the processes is eliminated. Based on the mentioned observations of the authors of this paper in Al-Zuheri research [27], the following are concluding the limitations on implementation of proposed model:

- Lack of capacity flexibility to cope with demand variation;
- The line is never fully utilised all the workers;
- Loss in simultaneously consideration for labour productivity and ergonomics in operational design of the line;
- Difficulties in integrating material handling system in internal design of the line; and
- Creating the need for repair workstation.

F. Implementation of developed framework approach

With the above limitations (in previous section) in mind, it was proposed a using the developed framework for redesigning one-piece flow lean line to eliminate these limitations. The problem is for proposing WWAL operating mode as in an approach for assembly processes instead of implementation of one-piece lean line design with FWAL. Notice that, not all necessary data set for application the proposed framework is available in selected Ramesh, Prasad and Srinivas research [28]. For this purpose, this paper assumes the missing data. The final optimal design variables combinations that simultaneously satisfy the requirements placed (i.e. optimisation criteria) on each one of the objectives and design variables (i.e. multiple-objective optimisation) are determined. The values of decision variables and objective functions results of this solution are presented in Table 2.

| Decision variables and objective functions values for optimal design solution of WWAL |
|------------------------------------------|----------|-----------------|-------------|-------------|-------------|-------------|-------------|
| Decision variables                      | x_1      | x_2            | x_3         | x_4         | x_5         | x_6         |
| Current variables                        |          |                |             |             |             |             |
| Decision variables                      | 80%      | 1%             | 0.7%        | 35%         | 3%          | 14%         |
| Objective functions                      | y_1      | y_2            | y_3         | y_4         |
| Current variables                        | 0        | 198            | 2.460       | 0.0943      |
| Current variables                        | 0        | 4              |             |             |             |

G. Benchmarking of the developed framework:

Comparisons to the proposed alternative design in the literature

In following, performance comparison between the one-piece flow line and WWAL optimal design on the basis of key aspects in design requirements. The purpose of the comparison is to show how the WWAL is most effective over one-piece flow in addressing the case study problem. The performance comparison results are presented in Table 3. The performance improvement can be seen for mostly of performance measures in terms of productivity and ergonomics. Although average metabolic energy expenditure increased with implementation of WWAL by approximately 25% and this is considers is a negative impact on worker ergonomics performance but it is still under the limit which has been specified by OSHA [29] for level of energy that the workers can spend during performing the jobs (3.20 kcal/min.). On the other hand, the
optimal design of WWAL has provided ergonomics benefits. It reduces the risk of repetitive motion injury due to increasing of rate of exposure variability of workers to 9% while such facility is not available in one-piece flow line. In short, the comparison corroborates the superiority of the WWAL over one-piece flow line.

Table 3. Comparison of performance measures of WWAL Vs. One-piece flow line

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Performance measures</th>
<th>WWAL</th>
<th>One-piece flow line</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Worker productivity (pumps per shift time)</td>
<td>25</td>
<td>14.3</td>
</tr>
<tr>
<td>2</td>
<td>Time per unit (minutes)</td>
<td>2.85</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Job span (# of workers in assembly line)</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>Number of workstations</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>Shift time labour cost($)</td>
<td>1980</td>
<td>3000</td>
</tr>
<tr>
<td>6</td>
<td>Metabolic energy expenditure (kcal/min)</td>
<td>2.46</td>
<td>2.0</td>
</tr>
<tr>
<td>7</td>
<td>Rate of exposure variability of workers</td>
<td>9%</td>
<td>0-1%</td>
</tr>
</tbody>
</table>

The optimal layout of the system with respect to a certain objectives design is L-shaped. The selected layout has profound impact on the performance of the system as the L-shaped flow pattern design is more preferable compared to the U-shaped and straight line designs. This is because in the L-shaped, a more variation in body exposure compared to the U-design and also the L-shaped presents less energy expenditure compared to U-shaped design. As explained in section 5, the performance of proposed one-piece flow line in terms of flexibility capacity depends mainly on the bottleneck workstation. Therefore, the system cannot respond to highly fluctuant market demands without shifting this bottleneck to some other convenient workstation or by neutralising the effect of bottleneck. Although the WWAL has been designed for a daily production rate 200 pumps in shift time with 10 hours, the system has the ability to rapidly respond to fluctuating demand by adjusting the workforce (skill levels, numbers, and walking speed) according to demand requirement. The obtained optimal (structural) system design can cope with product demand requirement to 300 pumps per shift hours. Table 4 shows the optimal design of WWAL, can be find for daily product demand ranging from 50 to 300 pump in 10 hours shift time.

VI. CONCLUSIONS AND FUTURE RESEARCH ISSUES

Undoubtedly, there is a large portion of capital investment of reconfigurable manufacturing systems is committed at the early design stage. Designing cost-effective yet functional manufacturing systems with agile workers that can be dynamically allocated to different tasks or workstations becomes far more complex task challenging for practitioners and researchers. The fact that existing research about designing WWAL do not provide a “mechanism” on how design decisions at various stages affect the system performance in terms of productivity and ergonomics rather than flexibility, as it takes into consideration key objectives in the design of manual assembly line. This paper presented a new framework for optimising design of WWAL. The developed framework offers a sound base for the designers to tackle the requirements of productivity and ergonomics in the system design at early stage design as well as at the operational stage design where flexibility is required for the product demand variation. The framework involves many interrelated variables concerning product, process, work force, ergonomics environment and system topology and size.

The framework approach implementation consists of two phases: mathematical modelling phase and genetic algorithms optimisation phase. In first phase, a mathematical model is developed to map the design variables and parameters relationships with objectives. In second phase, GAs are utilised to obtain the optimal values of decision variables combinations with corresponding objectives. To demonstrate the effectiveness of the proposed framework, a case study of manufacture for diesel injection pumps presented. Results of framework implementation indicated that the optimal design of WWAL performed better overall than the proposed one-piece flow line in research of Ramesh, Prasad, and Srinivas [28] to the addressed problem. Regarding that results, it was found that optimal solution design to diesel injection pump assembly system which operates for assembling 200 pumps in 10 hours shift time, has only 8 workers while proposed one-piece flow line 16 workers. The WWAL optimal design has increased the productivity of worker in shift time from 14.3 to 25 (about 70% increase) which has contributed in the reaching of the targeted production rate 200 pump/shift. This increasing in production rate associated in a significant cost saving with respect to the shift time labour from $2800 to $1980 (about 70%). As the ergonomics was another objective in this thesis, the metabolic energy expenditure of one-
piece flow line was 2 Kcal/min and the optimal design of WWAL has been designed to require 2.47 kcal/min (about 25% increases). Although this is considered as a poor improvement in this ergonomics objective, still it is below the limit which specified by OSHA 3.2 kcal/min. It is also found that huge increase improvement conditions due increasing in another ergonomics measure; rate of exposure variability (from 1% to 9%). It is noted from the flexibility analysis of the optimised design of WWAL; the system has robust flexibility to handle the market demand fluctuations.

The results confirmed that the developed framework can be very useful in finding the optimisation of the complex system design with multiple objectives at the early design stage. This enables the designers reducing design lead times, evaluate more design alternatives thoroughly, and assess their investment plans for WWs in relation to respond quickly and economically to different levels of production demand. The walking speed of workers during assembly process assumed as constant in this research. For further research, it could be useful to build a mathematical model takes stochastic velocity into account.

Table 4. Optimal WWAL designs for different demands

<table>
<thead>
<tr>
<th>Daily product demand</th>
<th>Design objectives</th>
<th>Optimal decision variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>y1 460 2.49 0.101</td>
<td>x1 0.80 2.2 0.7 3.50 3.14 0.6</td>
</tr>
<tr>
<td>100</td>
<td>y2 960 2.47 0.096</td>
<td>x2 0.80 1.4 0.7 3.50 3.14 0.6</td>
</tr>
<tr>
<td>150</td>
<td>y3 1440 2.47 0.096</td>
<td>x3 0.90 3.6 0.7 3.50 3.14 0.6</td>
</tr>
<tr>
<td>200</td>
<td>y4 1980 2.46 0.094</td>
<td>x4 0.80 1.8 0.7 3.50 3.14 0.6</td>
</tr>
<tr>
<td>250</td>
<td>y5 2420 2.46 0.095</td>
<td>x5 0.80 2.1 0.7 3.50 3.14 0.6</td>
</tr>
<tr>
<td>300</td>
<td>y6 3000 2.5 0.086</td>
<td>x6 0.70 1.2 1.4 3.50 3.14 0.6</td>
</tr>
</tbody>
</table>

VII. ACKNOWLEDGEMENTS
The authors would like to express their appreciation to anonymous referees for their helpful comments.

REFERENCES
assembly system," in 18th International Conference on Flexible Automation and Intelligent Manufacturing, University of Skövde, Sweden, 2008.


[27] A. Al-Zuheri, Modelling and optimisation of walking worker assembly line for productivity and ergonomics improvement, PhD Advanced Manufacturing & Mechanical Engineering, Doctor of philosophy, School of Engineering University of South Australia, Mawson Lakes, 2013.
