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Studies on Waste Elimination Strategies and Assembly Line Design using Lean and Ergonomic Principles

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Abstract

In this research, an integrated methodology is proposed to investigate and redesign an assembly line by considering ergonomics and lean principles simultaneously. The impact of ergonomic interventions and lean concepts are investigated through a case study. The data collected from a machine tool assembly line are used to demonstrate the proposed methodology. The assembly activities are converted into human motions as advocated by Methods-Time Measurement (MTM) to evaluate the work methods and estimate standard time. Based on the results of the ergonomics evaluation and MTM studies, the choice of the final configuration of the workstations' is found out appropriately. This process helped to reduce the workplace risk level and subsequent non value added activities (NVA) in the assembly process. The reduction in workstation cycle time as the result of improved work postures and consequent non value added activities are quantitatively reassessed with MTM standards. The ergonomically improved assembly tasks and value added work methods are arrived at based on the proposed methodology used to redesign the assembly line (assembly line balance). The performance of the improved assembly line is investigated for different takt times. The results of computational experiments indicate that the redesigned workstations enabled by the ergonomics and lean principles improved the efficiency and smoothness level of the assembly line.

Keywords: Methods-Time Measurement, RULA analysis, lean waste, Assembly line balance, smoothness level.

1. Introduction

Many industries have realized the importance of lean manufacturing approach as it provides numerous advantages to the manufacturers by minimizing different kinds of wastes defined under lean concepts (Saravanan Arumugamurthy et al., 2019). In this context, the design of lean assembly line is having considerable importance in manufacturing where the effective utilization of resources is of prime concern. The interaction between resources such as man, machine, material, information and working environment often leads to potential sources for inefficiencies in the form of over production, motion, excessive inventory, over processing, resource idleness, waiting for materials and travel of parts, and places a premium on the ability of the manufacturing system to cope with demands. Hence, the decision on appropriate design of an effective lean assembly line for the current manufacturing situation is a challenging task (Baudin 2002).

A typical assembly line consists of workstations, material handling systems and operators in which the product moves continuously to undergo assembly operations (tasks). The act of allocating assembly activities to the workstations by optimizing pre-specified objectives without violating the precedence relations is known as assembly line balancing (ALB). Literature on assembly line design focuses mainly on balancing and sequencing of tasks in relation with different layout configurations (Battini et al., 2007, 2008, & 2011). As extensively reviewed in Scholl and Becker (2006), assembly line balancing problems are mainly concerned with the assignment of tasks to minimize number of workstations or minimizing cycle time without considering the impact of workplace ergonomics. Several activities performed in the assembly system with awkward orientation of worker relative to the work, repetitive movements with considerable level of stress and forceful exertions might have significant influence on worker's performance, task time consistency, quality of products and productivity (Resnick and Zanotti, 1997; Eswaramoorthi et al. 2010). Further, ignoring the physical demands may contribute to the development of work-related musculoskeletal disorders (WMSD) in the assembly line workers (Takala, 2002; Punnett and Wegman, 2004). Epidemiological evidence linking workplace design parameters to the incidence of low back, upper extremity, neck, and other musculoskeletal disorders dominates the ergonomics literature (Hildebrandt, 1995; Ranney et al., 1995; Snook et al., 1995; Granata et al., 1996). Most of these ergonomic analysis take place in assembly plants to evaluate how the bending or twisting of the trunk (Punnett et al., 1991), upper limb soft tissue (English et al., 1995) or shoulder disorders affect the workers' health (Punnett et al., 2000). Some studies are even more specific, such as focusing on reducing the strain of a lowering action carried out by female workers (Ciriello, 2005). However, the utility of ergonomics research is not limited to predicting and eliminating workplace injuries. The workers are not only likely to be injured when they are fatigued, but they also tend to slow down and experience subsequent decrease in output, productivity, and quality (Resnick and Zanotti, 1997). A study by Ayoup (1990) revealed that an ergonomically deficient workplace may not cause immediate pain; but, the compounding effect of deficiencies in job and/or workplace will cause physical symptoms, emotional stress, low productivity, and poor quality of work over a period of time. The effect of deficiencies in job could cause creation of non value added activities in the assembly process, affect the time required to perform the operations and pose problems on respecting the customer schedules at all time. The lack of pursuit to the different injuries that appear most frequently in the workers and not taking preventive actions would trigger different types of waste defined under lean manufacturing in the form of motion, excessive in-process inventory, resource idleness, delay/waiting for materials and defects. Concepts from the field of ergonomics has had considerable influence and contribution on improvement of leanness, particularly with regard to working smarter, not harder, and elimination of non value added activities (Konz and Johnson, 2004). Industry often views ergonomics as a safety issue rather than considering it as a way to optimize the work system. Unnecessary motion is considered lean waste particularly as it relates to ergonomics. Motion consumes time and energy but does not add any value to the process/product (Womack et al. 1990). It is essential to eliminate all motions that do not add value, such as hand motions in an assembly process to the selection of machines, stretching for tools, unnecessary setups (fixtures) and material handling within station (Askin & Goldberg 2002). Further, any change in work methods would also affect the workplace ergonomics (Laring et al. 2002; Udosen, 2006). Therefore, considering ergonomics with lean perspective would be an essential step to predispose workplace injury and improve operations in the assembly systems. Ergonomics and lean philosophies are two work disciplines and principles that can complement each other in making work environments both more safe and lean (Walder et al. 2007).

In this context, the machine tool manufacturing which serves as the mother industry for all manufacturing which is facing challenges due to uneven demand and stiff competition from international players, is chosen for this study. The automotive sector, which is extensively practicing lean concepts, is being the major end user of machine tools (Guide to Intellectual Properties Rights for Industry Machine Tool, 2005). In order to cope up with the burgeoning demand of automobile sector, the lean methods need to be systematically extended to machine tool industry as well, such that the whole value chain will become lean. Even though the roots of lean concepts are evolved from mass production, its implementation in machine tools manufacturing has so far received less attention in the scholarly literature (Eswaramoorthi et al. 2011a). The machine tool manufacturing is characterized by long makespan (months), large components/assemblies, and complex technology linkages such as materials, electrical, electronics, hydraulics, pneumatics, metallurgy, tribology, measurement controls (UNIDO, 2005). This industry seems to be experiencing different levels of ergonomic discomfort and potential source of lean wastes. This motivates the authors to develop a methodology that could estimate both ergonomic risk and lean wastes. Although ergonomics evaluations in workplace have been studied in the earlier studies, this is the first attempt focusing on machine tool manufacturing sector with lean, MTM standards and ergonomics.

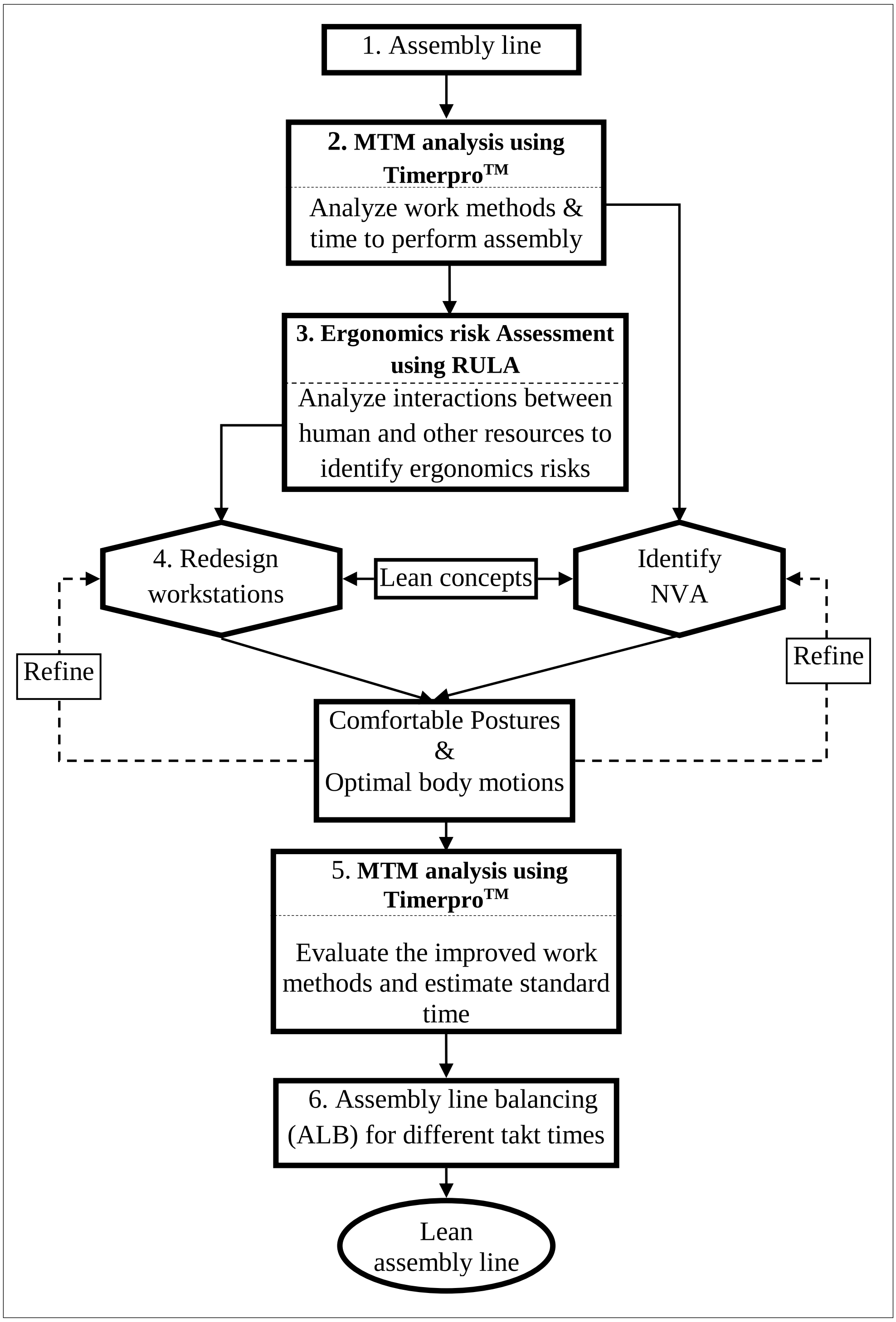
In this paper, an integrated methodology is proposed to improve assembly line performance using Rapid Upper Limp Assessment (RULA) with CATIA V5 platform to assess the ergonomic stresses, MTM standards (Maynard et al., 1948) for establishing work methods and standard time and lean concepts to improve value addition. The purpose of this work is to develop a methodology to promote lean system and to achieve improved assembly line performance using ergonomic principles. The effectiveness of the proposed method is demonstrated on a machine tool manufacturing industrial case study. The ideal situation presents opportunity for changes in both assembly system configuration and workplace design.

2. Methodology

The main principles considered for the development of proposed methodology are:

- Assessment of Ergonomic performance measures (stress level associated with work postures during human-machine/resources interaction)
- Redesign/reconfiguration of workstations and assembly line according to lean principles.
- Evaluation of assembly operation/task by Methods-Time Measurement standards (MTM analysis using Timer Pro™ platform)

A scheme of proposed methodology aims at improving the overall performance of the assembly line such as line efficiency and line balancing leading to lesser ergonomic risks and promote lean systems is illustrated in Fig. 1.



* MTM - Methods -Time Measurement, NVA - Non-Value added activities

Fig. 1 Proposed Methodology using Ergonomics and Lean Principles

The flow chart illustrates the step-by-step procedure proposed to configure the assembly line within lean and ergonomics perspective. The initial step focuses on the investigation of an assembly line and collecting data such as assembly activity/task time, precedence relations, distances of movements and different postures which are necessary to assemble the end-products. The second step of methodology enables to analyze the existing assembly operations or methods with MTM standards. The assembly activities are converted into basic motions and each motion is assigned with a predetermined time standard as defined by Maynard et al. (1948). The features available in Timerpro™ software is used to carry out the MTM analysis. During the analysis, subdivision of such tasks led to highlight the value added and non value added activities to decide on better work methods and corresponding standard times for each tasks.

One of the most common practices in assembly line design is making decisions based on average task time that seems appropriate at normal conditions. But working at a poorly designed workplace would pose problems on meeting customer schedules due to difficulties in maintaining the predefined task time in addition to risk of workplace injuries. Hence, an ergonomic assessment is performed to identify the risks using 'Ergonomic Design and Analysis' module of Computer Aided Three Dimensional Interactive Application V5 software [CATIA V5] (McAtamney and Nigel Corlett, 1993). This work posture analysis is conducted before and after the improvement suggestions to demonstrate the level of ergonomic risk and consequent changes in task time due to the elimination of non value added motions. Further, decision on providing relaxation allowances to overcome fatigue for individual tasks will be taken based on working conditions (awkward/comfortable posture) subject to ILO (1979) guidelines.

The next step of the methodology involves analysis of work methods and redesign of workstation based on the results arrived by MTM analysis and ergonomic performance measures. All the basic motions of human such as work methods, wrong work postures, wrong motions or redundant motions are identified and motions prone to human strain and non value adding activities are selected for improvement by introducing suitable lean concepts such as flow, takt time, 5S, point of use, part kitting, visual management and pull system. The integration of ergonomic evaluation, MTM standards and lean concepts allow the assembly system designer to redesign the workstations not only to be time efficient but also to provide comfort, safety and leanness. The improved workstations will be re-evaluated in the similar way as discussed in the step-2 using MTM standards to substantiate the effectiveness of the proposed methodology. The comparative results of existing and redesigned workstations would reveal the quantum of non value added activities (lean wastes) eliminated and subsequent reduction in ergonomic risk level.

The improved assembly tasks and work methods have been arrived at based on the methodology described in the above mentioned steps which will be used to redesign the assembly line (assembly line balance) for different takt times. The flow index based assembly line balancing approach (FIALB) proposed by Eswaramoorthi et al. (2011b) is used to investigate the ergonomically improved assembly line. The FIALB procedure is coded in MATLAB 7.5.0.342 and executed in Pentium IV machine.

3. Results and discussion

The methodology described in the previous section has been used to investigate an assembly line of CNC vertical machining center. The existing assembly line consists of a series of workstations like flow line. At the start, the machine tool bed is assembled at workstation-1 and shifted to subsequent workstations by overhead cranes where other sub-assemblies/parts would be added to the base structure. Assembly of a CNC vertical machining centre requires a totaled time of 2270 minutes. The application of the proposed methodology in the machine tool assembly line is discussed in the following sections.

3.1 Establishing work methods and standard time

The machine tool assembly line considered for the study consists of eight workstations and 31 assembly operations to be performed at different workstations. The MTM standards are used to evaluate the work methods and estimate standard times for the existing assembly activities. The assembly operations are divided into work elements and represented by basic motions like reach, grasp, position, and release using the in-built options of Timer pro™ software. The results of MTM analysis for bed assembly (workstation-1) is presented in Table 1.

Table 1 MTM analysis results for Bed assembly

S.No	Description of work elements	Motion sequence	Freq.	Time (min.)	Postures
1.	Walk 5ft to collect tools & screws from storage rack	WK5	1	0.045	
2.	Bend to collect tools & screws from storage rack	BDSS	1	0.021	 RULA score-5
3.	Move hand to grasp tools & screws from rack	RV12	1	0.008	
4.	Grasp the tools & screws from rack	GR05	5	0.021	
5.	Move back hands to original position	RF12	5	0.029	
6.	Arise	BDSS	1	0.021	
7.	Rotate Foot to walk towards work area	BDRF	1	0.005	
8.	Walk 5 paces while carrying object	W05	1	0.051	
9.	Bend to place the components on floor	BDSS	1	0.021	 RULA score-7
10.	Drop the components	PP01	1	0.001	
11.	Sit to do the alignment of bed	BDSS	1	0.021	
12.	Reach to get leveling screws	RF02	4	0.002	
13.	Grasp the leveling screws	GR03	4	0.004	

14.	Reach 6 inches to fix level bolts (4 nos)	RV06	4	0.024	
15.	Align	ALWP	4	0.432	
16.	Reach to get tools to tighten screws	RF02	4	0.002	
17.	Grasp the tools	GR03	4	0.004	
18.	Reach 6 inches to tighten the level bolts (4 nos)	RV06	4	0.024	RULA score-6
19.	Tighten the screws.	*M15	1	15.000	
20.	Move back 6 inches to original location	RF06	4	0.017	
21.	Drop tools	PP01	1	0.001	
22.	Arise	BDSS	1	0.021	
23.	Rotate foot to walk towards rack to collect scraper tool	BDRF	1	0.005	
24.	Walk 5ft to collect scraper tool	WK5	1	0.045	
25.	Bend & sit to collect the scraper tool	BDSS	1	0.021	
26.	Reach 6 inches to a fixed location	RF06	1	0.001	
27.	Pick up scraper tool	GR04	1	0.007	
28.	Reach 6 inches to a fixed location	RF06	1	0.001	RULA score-7
29.	Arise	BDSS	1	0.021	
30.	Rotate foot to walk towards bed	BDRF	1	0.005	
31.	Bend to start the hand scraping	BDSS	1	0.021	
32.	Reach 6 inches to a variable location	RV06	1	0.006	
33.	Inspection & scrap high points	*M15	1	15.000	
34.	Reach back 6 inches to a fixed location	RV06	1	0.006	RULA score-7
35.	Arise	BDSS	1	0.021	
36.	Drop tools	PP01	1	0.001	
37.	Rotate Foot to take cleaning acids	BDRF	1	0.005	
38.	Walk 5 paces	WK5	1	0.045	
39.	Reach to take clean acid bottle from Rack	RV06	1	0.006	
40.	Bend to take clean acid	BDSS	1	0.021	
41.	Reach 6 inches to a fixed location	RF06	1	0.001	
42.	Pick up acetone & waste	GR03	1	0.004	
43.	Reach 6 inches to a fixed location	RF06	1	0.001	
44.	Arise	BDSS	1	0.021	RULA score-5
45.	Rotate Foot to walk towards work area	BDRF	1	0.005	
46.	Walk 5 paces	WK5	1	0.225	
47.	Bend to clean the mating surface	BDSS	1	0.021	
48.	Reach the surface	RF06	2	0.008	
49.	Clean surface	*M5	1	5.000	
50.	Reach 6 inches to a fixed location	RF06	1	0.001	
51.	Drop the used cotton & acetone	PP01	2	0.002	RULA score-7
52.	Arise	BDSS	1	0.021	
53.	Rotate foot towards part kit	BDRF	1	0.005	
54.	Walk 5 feet to pick up LM guide ways	WK5	1	0.045	
55.	Bend to take LM guide ways	BDSS	5	0.105	
56.	Grasp the LM guide way	GR03	1	0.004	
57.	Arise	BDSS	1	0.021	RULA score-7
58.	Turn towards work area	BDRF	1	0.005	

59.	Walk with LM guide way	W05	1	0.051	
60.	Move 6 inches to an approximate location	MA06	2	0.011	
61.	Bend	BDSS	1	0.021	
62.	Drop LM guide on bed	PP01	2	0.002	
63.	Arise	BDSS	1	0.021	RULA score-7
64.	Rotate Foot	BDRF	1	0.005	
65.	Walk 5 feet to pick screws - 24 numbers	WK5	1	0.045	
66.	Bend	BDSS	1	0.021	
67.	Reach 6 inches to a fixed location	RF06	1	0.001	
68.	Pick screws	GR03	1	0.004	
69.	Reach 6 inches to a fixed location	RF06	1	0.001	
70.	Arise	BDSS	1	0.021	RULA score-5
71.	Turn towards work area	BDRF	1	0.005	
72.	Walk 5 paces while carrying object.	W05	1	0.051	
73.	Bend	BDSS	1	0.021	
74.	Drop	PP01	1	0.001	
75.	Reach 6 inches to a fixed location	RF06	1	0.001	
76.	Pick LM guide ways	GR03	2	0.008	
77.	Move to position	RF06	1	0.001	
78.	Position LM guide ways	*M3	2	6.000	
79.	Reach 6 inches to collect screws	RF06	24	0.101	
80.	Grasp screws	GR06	1	0.008	
81.	Reach 6 inches to a fixed location	RF06	24	0.101	
82.	Engage/Position Exact Fit	PP05	24	0.691	RULA score-7
83.	Reach 6 inches to a fixed location	RF06	1	0.001	
84.	Grasp tools	GR06	1	0.008	
85.	Reach 6 inches to a fixed location	RF06	1	0.001	
86.	Turn screwdriver w/wrist(15 times)	*B38	24	15.200	
87.	Reach back to original position	RF06	1	0.001	
88.	Drop the tools	PP01	1	0.001	
89.	Arise	BDSS	1	0.021	
90.	Turn towards part kit	BDRF	1	0.005	
91.	Walk 5 feet to take bud plate	WK5	1	0.045	
92.	Bend to collect the bud plates	BDSS	1	0.021	
93.	Reach part kit	RF06	1	0.001	
94.	Pick bud plate	GR03	6	0.025	
95.	Reach original position	RF06	1	0.001	
96.	Arise	BDSS	1	0.021	RULA score-7
97.	Turn towards work area	BDRF	1	0.005	
98.	Walk 5 paces to reach bed.	WK5	1	0.045	
99.	Bend	BDSS	1	0.021	
100.	Drop bud plates	PP01	1	0.001	
101.	Pick screws to fix bud plate	GR03	8	0.034	
102.	Pick bud plate	GR03	8	0.034	
103.	Reach 6 inches to a variable location	RV06	1	0.006	
104.	Align with precision	ALWP	8	0.864	

105.	Engage/Position Exact Fit	PP05	28	0.806	 RULA score-7
106.	Reach to pick Allen key	RF06	1	0.001	
107.	Grasp Allen key with lever	GR06	1	0.008	
108.	Reach to tighten screws	RF06	1	0.001	
109.	Turn screwdriver w/wrist to fix bud plates	*B24	28	11.200	
110.	Return to original position	RF06	1	0.004	
111.	Arise	BDSS	1	0.021	
112.	Drop tools	PP01	1	0.001	
113.	Rotate foot	BDRF	1	0.005	
114.	Walk 5 feet to bring bearing, shim & ball screw	WK5	1	0.045	
115.	Bend to pick up components	BDSS	1	0.021	 RULA score-7
116.	Reach	RF06	1	0.004	
117.	Pick up components	GR03	3	0.013	
118.	Reach back to original position	RF06	1	0.004	
119.	Arise	BDSS	1	0.021	
120.	Turn towards work area	BDRF	1	0.005	
121.	Walk back to work area	WK5	1	0.045	
122.	Bend to assemble ball screw	BDSS	1	0.021	 RULA score-7
123.	Reach to ball screw mount area	RF06	1	0.004	
124.	Assembly of bearing block & ball screw	*M25	1	25.000	
125.	Reach back to original position	RF06	1	0.004	
126.	Arise	BDSS	1	0.021	
127.	Drop tools	PP01	1	0.001	
128.	Turn towards tool box	BDRF	1	0.005	
129.	Walk to get inspection tools	WK5	1	0.045	
130.	Bend to grasp the tools	BDSS	1	0.021	 RULA score-7
131.	Reach to inspection tools	RF06	1	0.004	
132.	Grasp dial gauge and its accessories	GR05	1	0.004	
133.	Reach 6 inches to a fixed location	RF06	1	0.004	
134.	Arise	BDSS	1	0.021	
135.	Rotate Foot	BDRF	1	0.005	
136.	Walk back to work area	W05	1	0.051	
137.	Bend	BDSS	1	0.021	 RULA score-7
138.	Reach 6 inches to fix gauges	RV06	1	0.006	
139.	Inspection	*M15	1	15.000	
140.	Grasp dial gauge and its accessories	GR05	1	0.004	
141.	Reach 6 inches to a fixed location	RF06	1	0.004	
142.	Arise	BDSS	1	0.021	
143.	Rotate Foot	BDRF	1	0.005	
144.	Walk towards storage	W05	1	0.051	
145.	Bend to keep the inspection tools	BDSS	1	0.021	 RULA score-7
146.	Reach 6 inches to a fixed location	RF06	1	0.004	
147.	Drop tools	PP01	1	0.001	
148.	Reach 6 inches to a fixed location	RF06	1	0.004	
149.	Arise	BDSS	1	0.021	
150.	Turn towards storage to pick nylon sleeve	BDRF	1	0.005	

151.	Walk towards storage	W05	1	0.051	
152.	Bend to collect nylon sleeve	BDSS	1	0.021	 RULA score-5
153.	Reach	RF06	1	0.004	
154.	Grasp nylon sleeve	GR05	1	0.004	
155.	Reach 6 inches to a fixed location	RF06	1	0.004	
156.	Arise	BDSS	1	0.021	
157.	Turn	BDRF	1	0.005	
158.	Walk back to work area	W05	1	0.051	
159.	Bend	BDSS	1	0.021	 RULA score-7
160.	Reach 6 inches to a fixed location	RF06	1	0.004	
161.	Fixing nylon sleeves	*M15	1	15.000	
162.	Reach 6 inches to a fixed location	RF06	1	0.004	
163.	Arise	BDSS	1	0.021	
164.	Drop tools	PP01	1	0.001	
165.	Turn towards part kit	BDRF	1	0.005	
166.	Walk 5 feet to get brass plugs	WK5	1	0.045	
167.	Bend	BDSS	1	0.021	 RULA score-5
168.	Reach to get brass plugs	RF06	1	0.004	
169.	Pick the component (brass plugs)	GR03	1	0.004	
170.	Reach 6 inches to a fixed location	RF06	1	0.004	
171.	Arise	BDSS	1	0.021	
172.	Turn	BDRF	1	0.005	
173.	Walk 5 paces with brass plugs	W05	1	0.051	
174.	Bend	BDSS	1	0.021	 RULA score-7
175.	Reach 6 inches to a variable location to fix plug	RV06	1	0.006	
176.	Place brass bush to plug holes at LM guide ways	*B8	24	3.200	
177.	Reach 6 inches to a fixed location	RF06	1	0.004	
178.	Grasp tools	GR03	1	0.004	
179.	Reach 6 inches to a variable location to fix plug	RV06	1	0.006	
180.	Fix brass bushes to block holes on LM guide ways	*M15	1	15.000	
181.	Reach 6 inches to a fixed location	RF06	1	0.004	
182.	Arise	BDSS	1	0.021	
183.	Rotate Foot	BDRF	1	0.005	
184.	Walk 5 paces with tools	W05	1	0.051	
185.	Bend to keep the tools at tool box	BDSS	1	0.021	 RULA score-7
186.	Reach 6 inches to a fixed location	RF06	1	0.004	
187.	Drop	PP01	1	0.001	
188.	Reach 6 inches to a fixed location	RF06	1	0.004	
189.	Arise	BDSS	1	0.021	
				146.39	
Relaxation allowance @ 9 %				159.60	

The column-2 in Table 1 is used to describe the various work elements involved in assembly operation. Column-3&4 indicate the corresponding notations and frequency of each work element. The standard time for each motion is displayed in column-5. The awkward postures occupied by the worker during the assembly operation are presented in the last column. The results of MTM analysis indicate that the bed assembly process consists of 189 work elements with an estimated standard time of 159.6 minutes against the actual time of 160 minutes. It includes a relaxation allowance of 9% as per standards of ILO (1979). The total assembly time (bed assembly) estimated by MTM standard is matching with the current industry practicing times and ensures the correctness of the MTM analysis. The MTM analysis discriminates between value added and non value added activities. This is valuable data for the ergonomic analysis because of its implications as to what part of the body is involved in the movement. Knowing the time span and the body parts in motion, however, is not enough to carry out an ergonomic analysis within lean perspective. The work posture, forces exerted on body parts according to job demand and its influence on task time are vital. The RULA analysis, suggested for use in this study, further helps to identify the ergonomic risks emerging out of awkward postures.

3.2 Ergonomic risk and its influence on task time

The next phase of methodology enables to identify the potential sources which cause high ergonomic risk and tend to influence the task time. The level of ergonomic risk prevailing in workstation-1 during the bed assembly process is mapped and modeled using CATIA V5 platform. Figure 2 shows the model of workstation-1 where bed assembly operations are taking place and postures subjected to high ergonomic risks.

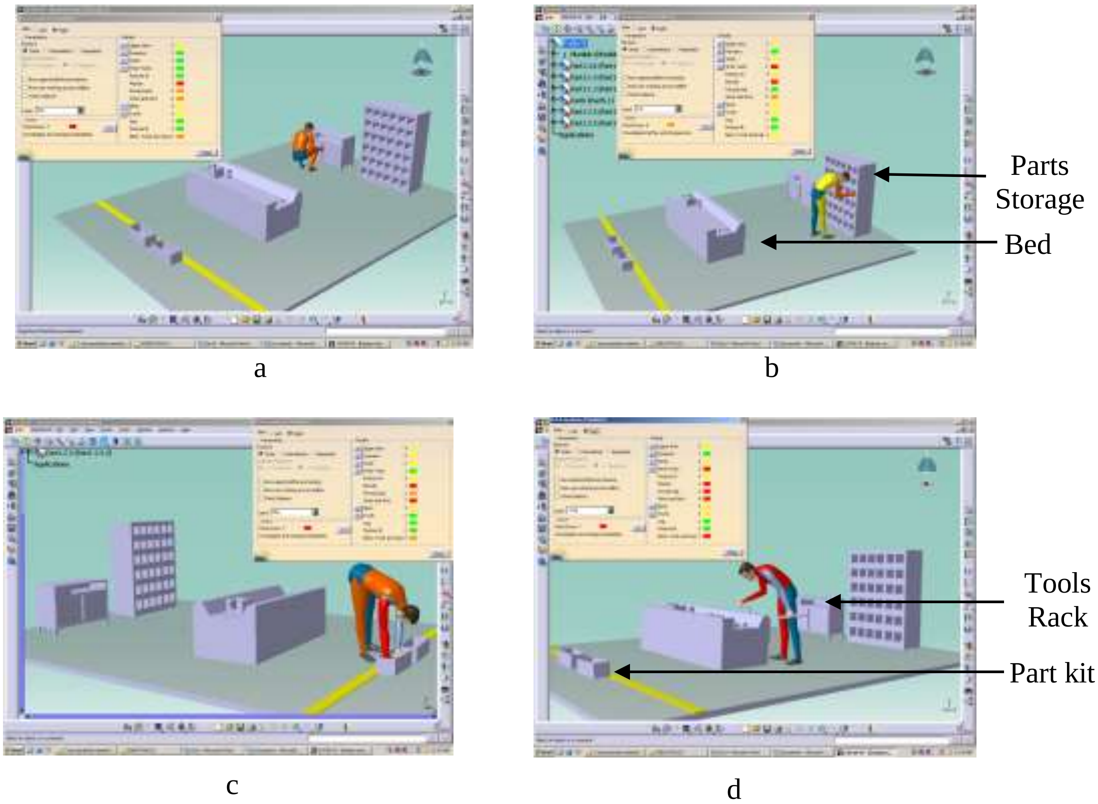


Fig.2. Model of Bed Assembly and Postures Adapted

The sequence of assembly operations involved in the machine tool bed is already investigated using MTM standards. Here, the focus is on high stress activities and identifying the scope for improvement. It is evident from Figure 2 that arrangements of tools, consumable parts and working surface of assembly operation are the significant areas where the worker interaction is frequent and risky. The assembly operation model and RULA analysis indicate that the stress level associated with each work postures are high and it ranges between 5to7 (RULA score). The reason for high risk may be due to the result of poor workplace design which demands a worker to walk around the assembly area and often occupy awkward postures. The repetitive work combined with awkward posture (as shown in Table 1 as shaded cells & Figure 2d) and higher force exerted due to push/pull mode of assembly operation emerging from tightening of LM guide ways to higher torques might have caused higher risk.

Working in awkward postures for a prolonged time will lead to increase in the instability of the body parts, decrease in the griping strength and subsequently tend to reduce the efficiency of the worker (Putz-Anderson, 1988; Wick & McKinnis, 1998). It is a well accepted fact that working in awkward posture would lead to loss of grip strength up to 42% (Bheem P. Kattel et al. 1996) and critical working situation which obstructs to maintain normal pace of work, and further increase the task time. In the mean time, the force exerted on different body parts due to frequent motions emerging from trunk flexion & extension, arms-flexion/extension, abduction/ adduction, medial/lateral rotation, pronation/Supination, leg-flexion/extension, medial/lateral rotation, hand-radial deviation/ulnar deviation and wrist twist may further affect the task time performance. In strenuous tasks, biomechanical loading from external load and muscular exertions can increase the time required to complete the assembly tasks in addition to risk of injury. Obviously the reduction of strength at awkward posture may impede assembly operation. In addition to the above effects, the worker forced to occupy an awkward posture for a prolonged time often tends to relax and make voluntary effort to change the posture. In these circumstances, it can be concluded that performing assembly activities with awkward postures and exertion of higher force on different body parts may lead to time loss, process inefficiencies and subsequent generation of lean wastes such as motion, delay, wait and scope for defects and in-process inventory. To compensate the time loss which is emerging due to awkward postures, a variable allowance up to 7% is permitted on basic time as per ILO (1979) depending on the severity of risks. The tasks which fall under this category are 19,33,49,78,86,109,124,139,161,176 & 180 as displayed in Table 1. The uneven increase of workstation cycle time would have subsequent ill effects on assembly line balancing (smoothness level) and it would further lead to creation of lean wastes as discussed in the studies of Eswaramoorthi et al. (2011b). Hence, it creates a need to prevent non value added times on assembly operations by redesigning of workstations. The issues of redesigning workstations will be discussed in the next section.

3.3 Redesign of workstation

The workstations of machine tool assembly line are redesigned to reduce the ergonomic risks and unnecessary motions identified in the preceding sections. While redesigning workstations within ergonomic perspective, all the non - neutral postures are targeted to limit the body part movements out of neutral positions using lean tools. The proposed model of an improved workstation for bed assembly process is illustrated in Fig. 3.

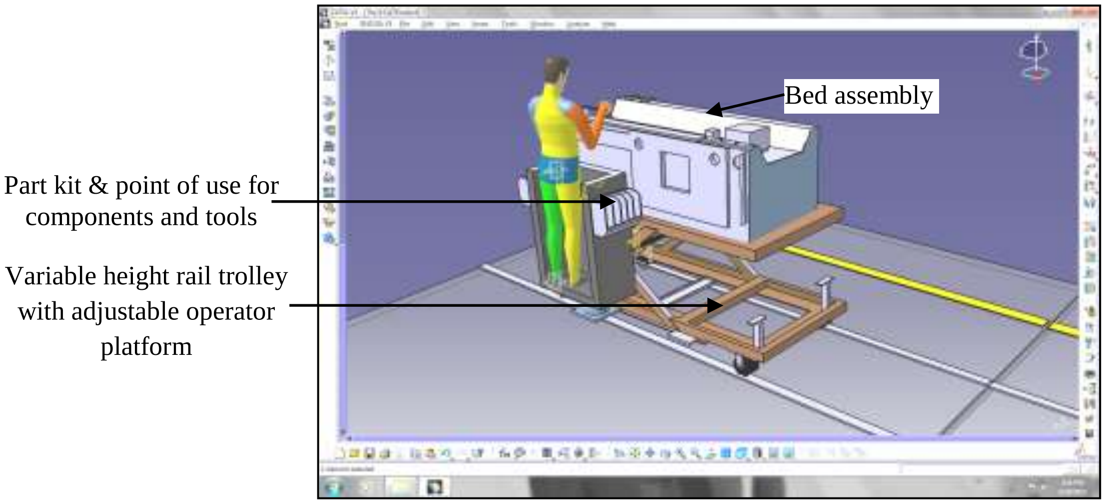
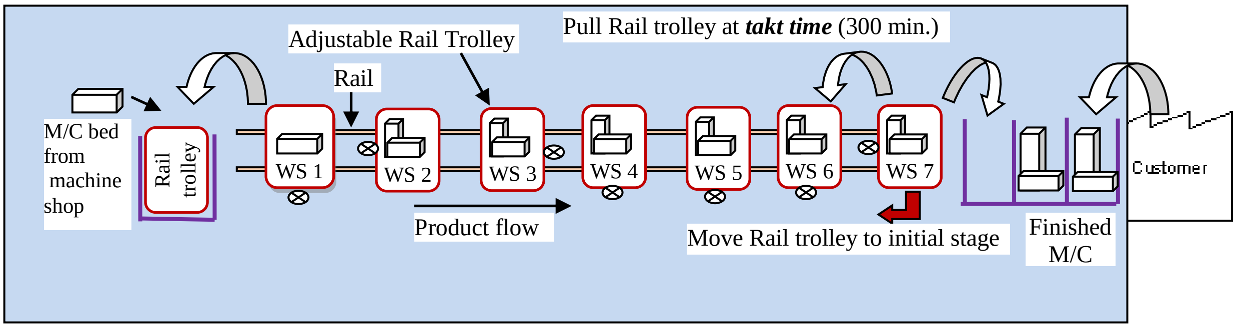
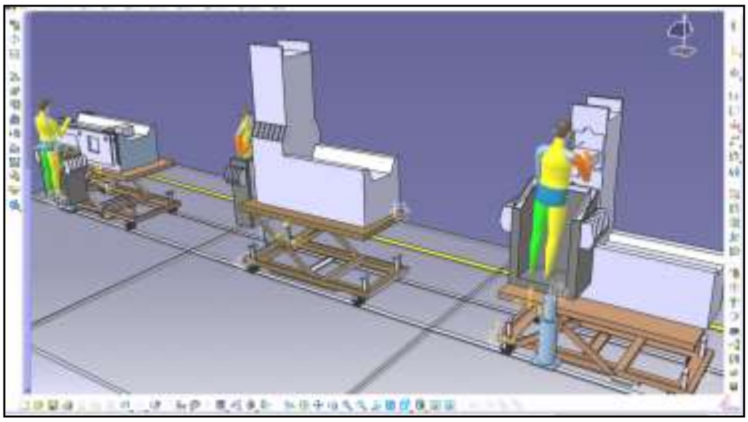


Fig.3. Model of the Redesigned Workstation with Lean principles for Bed Assembly

The assembly of CNC machines requires various components/ sub-assemblies to be fixed at various heights and locations around the base structure of machine tool. Hence, the workers are forced to bend, stretch, squat and stoop from floor level and stand on machine structure to complete the assembly operations. In this context, to improve the assembly process and promote lean systems ergonomically, a flexible rail trolley as shown in Fig. 3 is proposed. The trolley consists of two platforms, one for placing components and another for assembler to stand/sit and work. The entire rail trolley setup can be moved between workstations with the help of wheels and rails. The height of the table and worker's platform can be relatively adjusted and positioned at appropriate height based on the anthropometry of worker and requirement of work. Further, the operator's platform can be moved independently in X, Y and Z directions with rotation about Z axis, around the worktable according to the requirement of assembly work. This kind of technology adds great flexibility to the assembly line because at one workstation different heights and positions are required to assembly machine tool components/sub-assemblies. This would help to craft the working environment comfortable and stress free to the worker. The base component (bed) of the machine tool would be initially placed on the table of trolley and moved to subsequent workstations after the completion of assembly operations at current workstation. The finished assembly is taken out from the trolley at the end of final workstation and trolley is moved back to first workstation. This assembly line concept with rail trolley would also help to implement pull system in the machine tool assembly line. A schematic diagram of the proposed assembly line is presented in Fig. 4a & b below.



(a)



(b)

Fig. 4 Proposed Assembly line with Lean & Ergonomic Principles

The balanced assembly line would pull the assembly from previous station when one finished assembly is moved out off the line. Similarly the machine tool bed waiting for assembly in front of the assembly line is pulled by the workstation-1. This arrangement would help to visually see the flow of assemblies from one station to another as per takt time (visual management). Any disturbance in the assembly line/workstations will be clearly visible to the shop floor management when the assembly does not move at takt time. The provisions provided to keep tools, parts and fasteners around the guard of operator platform would lead to the use of part kit concept and act as a point of use. This arrangement helps to lessen efforts of workers such as walks, frequent awkward postures and reduce/eliminate the ergonomic stress and other non value adding activities like unnecessary motion, delay and transportation. In order to exhibit the effectiveness of the redesigned workplace, MTM analysis is carried out similar to steps discussed in section 3.1. The results of MTM analysis are presented in Table 2 below.

Table 2 MTM analysis for Redesigned workstation

S.No.	Description of work elements	Motion sequence	Freq.	Minutes	Posture
1.	Walk 5 paces to reach rail trolley	WK5	1	0.045	
2.	Check bed alignment	ALWP	4	0.432	
3.	Reach 6 inches to a fixed location to collect tools	RF06	1	0.001	
4.	Pick up tools	GR04	1	0.007	
5.	Reach 6 inches to variable location to tighten bolts	RV06	4	0.024	
6.	Tightening of screws	*M15	1	9.30	
7.	Reach back to fixed position to keep tools at bins	RF06	1	0.001	
8.	Drop tools	PP01	1	0.001	
9.	Reach 2 inches to a variable location to collect scraper tool	RF02	1	0.002	
10.	Grasp tools	GR04	1	0.007	
11.	Reach 6 inches to a variable location to do scraping	RV06	1	0.006	

12.	Inspection & scraping of high points on bed	*M15	1	13.95	
13.	Reach back 6 inches to a fixed location	RV06	1	0.006	
14.	Drop tools	PP01	1	0.001	
15.	Reach 6 inches to a fixed location	RF06	1	0.001	
16.	Grasp acetone & waste	GR03	1	0.004	
17.	Reach LM guide ways mount area	RF06	2	0.008	
18.	Cleaning of mating surface	*M5	1	4.65	
19.	Reach 6 inches to a fixed location	RF06	1	0.001	
20.	Drop the used cotton & acetone	PP01	2	0.002	
21.	Reach 6 inches to a fixed location	RF06	1	0.001	RULA score-3
22.	Grasp LM guide ways	GR03	2	0.004	
23.	Move to position	RF06	1	0.001	
24.	Position LM guide ways	*M3	2	5.58	
25.	Reach 6 inches to collect screws	RF06	12	0.0505	
26.	Grasp screws	GR06	12	0.096	
27.	Reach 6 inches to a variable location	RV06	12	0.072	
28.	Engage/Position Exact Fit	PP05	24	0.691	
29.	Reach 6 inches to a fixed location	RF06	1	0.001	
30.	Grasp tools	GR03	1	0.004	
31.	Reach 6 inches to a variable location	RV06	1	0.006	
32.	Turn screwdriver w/wrist(15 times) to tighten	*B38	24	14.136	
33.	Reach back to original position	RF06	1	0.001	
34.	Drop the tools	PP01	1	0.001	
35.	Reach 2 inches to a fixed location	RF02	1	0.002	
36.	Pick bud plate/ Pick bud plate & screws	GR03	6	0.025	
37.	Reach 6 inches to a variable location	RV06	1	0.006	
38.	Align with precision	ALWP	8	0.864	
39.	Engage/Position Exact Fit	PP05	28	0.806	
40.	Reach 6 inches to a fixed location	RF06	1	0.001	
41.	Grasp tools	GR03	1	0.004	
42.	Reach 6 inches to a variable location	RV06	1	0.006	
43.	Turn screwdriver w/wrist to fix bud plates	*B24	28	10.416	
44.	Return to original position	RF06	1	0.004	
45.	Drop tools	PP01	1	0.001	
46.	Reach 6 inches to a fixed location	RF06	1	0.001	
47.	Pick up components (shim, bearing & ball screw	GR03	3	0.013	
48.	Reach back to original position/ Reach 6 inches to fix ball screw	RV06	1	0.006	
49.	Reach 6 inches to a fixed location	RF06	1	0.001	
50.	Grasp tools	GR03	1	0.004	
51.	Reach 6 inches to a variable location	RV06	1	0.006	
52.	Assembly of bearing block & ball screw	*M25	1	23.25	
53.	Reach 6 inches to a fixed location	RF06	1	0.001	
54.	Drop tools	PP01	1	0.001	
55.	Reach 6 inches to a fixed location	RF06	1	0.001	RULA score-3

56.	Grasp dial gauge and its accessories	GR05	1	0.004	
57.	Reach 6 inches for inspection	RV06	1	0.006	
58.	Inspection	*M15	1	13.95	
59.	Reach 6 inches to a fixed location	RF06	1	0.001	
60.	Drop gauges & its accessories	PP01	1	0.001	
61.	Reach 2 inches to a fixed location	RF02	1	0.002	
62.	Grasp nylon sleeves & screws	GR05	1	0.004	
63.	Reach 6 inches to a fixed location	RF06	1	0.001	
64.	Engage/Position Exact Fit	PP05	1	0.029	
65.	Reach 6 inches to a fixed location	RF06	1	0.001	
66.	Grasp tools	GR03	1	0.004	
67.	Reach 6 inches to a variable location	RV06	1	0.006	
68.	Fix nylon sleeves	*M15	1	13.95	
69.	Reach 6 inches to a variable location	RV06	1	0.006	
70.	Drop tools	PP01	1	0.001	
71.	Reach to get brass plugs	RF06	1	0.004	
72.	Grasp the component (brass plugs)	GR03	1	0.004	
73.	Reach 6 inches to a variable location	RV06	1	0.006	
74.	Place brass bush to plug holes at LM guide ways	*B8	24	2.976	
75.	Reach 6 inches to a fixed location	RF06	1	0.001	
76.	Grasp tools	GR03	1	0.004	
77.	Reach 6 inches to a variable location	RV06	1	0.006	
78.	Fix brass bushes to block holes on LM guide ways	*M15	1	13.95	
79.	Reach 6 inches to a fixed location	RF06	1	0.001	
80.	Drop the tools in bin	PP01	1	0.001	
				129.432	
Relaxation allowance @ 5%				135.90	

It is evident from the Table 2 that all unnecessary non value added activities (109 motions) like walk, arise, bend and other motions let to emerge due to awkward postures such as twisting of the head and trunk, and prono-supination of the forearm, pushing or pulling, flexion/extension and abduction/adduction of other body parts are minimized/eliminated. The standard time for high risk work elements as discussed in section 3.2 and displayed in Table 1 are decided based on ILO standards. Further, the relaxation allowance for ergonomically improved assembly tasks are considered as 5% against 9%. The comparative results of existing and redesigned workstation for bed assembly process are presented in Table 3.

Table 3 Comparative results of bed assembly process before and after improvement

	Performance measures	**Existing**	**Improved**
Ergonomics performance	No. of postures occupied by the worker apart from walk Postural score Color score	4 > 5 Orange & Red	1 3 Yellow
Lean performance	Number of work elements Estimated time for the total assembly of machine tool bed based on MTM standard (minutes)	189 159.60	80 135.90

It is evident from the results shown in Table 3 that the number of postures required in the redesigned workstation is one and comfortable against multiple awkward postures in the existing bed assembly process. The postural score is also evidently reduced from > 5 to 3 in the proposed assembly process. It is evident from the above results that the improved posture in the redesigned workstation has helped to reduce the assembly time of machine tool bed by 14.85% or 23.70 minutes.

The same approach is further extended to remaining workstations of Vertical machining centre assembly line. The improvement expected in terms of assembly time for the remaining assembly operations are listed in the Table 4.

Table 4 Improved assembly tasks time of Vertical machining centre

Task	Activity	Task time (min)	Improved time (min)
1	Bed assembly	160	136
2	Cross slide assembly	150	127.5
3	Column assembly	165	140.25
4	Bed + cross slide assembly	45	38.25
5	Bed + cross slide + table assembly	40	34
6	Bed + cross slide + table assembly + column	20	17
7	Guard assembly	250	212.5
8	Coolant tank assembly	40	34
9	Electrical cabin	35	35
10	Transformer assembly	30	25.5
11	Pendent arm	45	38.25
12	Axis motor mounting	30	25.5
13	Cable carrier bracket	35	29.75
14	Machine wiring	185	185
15	Machine energizing	220	220
16	Counter balance	40	40
17	Stroke setting	120	120
18	Spindle head assembly	45	38.25
19	Spindle motor assembly preparation	35	29.75
20	Servo motor fixing at mill head	55	46.75
21	Geometry and swing test	60	60
22	D-clamp cylinder mount	45	38.25
23	ATC bracket fix	45	38.25
24	Tool machine fix	55	46.75
25	Pneumatic board and interface	35	29.75
26	Lubrication system fix	25	21.25
27	Encoder assembly	35	29.75
28	ATC energizing	60	51
29	ATC alignment	60	51
30	Telescopic covers	75	75
31	Other accessories	30	30
Total task time		2270	2044.25

The results of the analysis revealed that the total assembly time required for a VMC assembly is reduced from 2270 minutes to 2044.25 minutes when the workstations are redesigned with ergonomic and lean principles. In the mean time, some of the assembly activities which demand awkward postures such as electrical wiring inside the machine, Geometry and swing test, etc., cannot be improved merely by changing the workplace design due to its virtue of design/process. It needs design/process modifications to improve the assembly performance further. The assembly activities which could not be improved by the current study are shown in shaded cells in Table 4.

The improved assembly tasks arrived based on the proposed methodology in the previous sections is used to redesign the assembly line (assembly line balance) for different takt times. The flow index based assembly line balancing approach (FIALB) proposed by Eswaramoorthi et al. (2011b) is used in this study. The solutions generated from the FIALB are shown in Table 5 and 6. These tables also show the line efficiency and balancing level of assembly line in terms of smoothness level (SL).

Table 5 Assembly line performance for takt time of 800 minutes

WS	Before	After

	Assigned tasks	Station cycle time	Line efficiency /SL	Assigned tasks	Station cycle time	Line efficiency /SL
1	19 2 1 4 5 3 6 23 16 24	760	71.09 % 0.4312	19 1 3 2 4 5 6 23 24 16	647.75	85.18 % 0.1686
2	7 9 8 12 11 13 10 14	650		7 9 12 11 10 13 14 15	771.50	
3	15 17 18 20 22 25 26 28 27 29 21	760		17 18 8 20 22 25 28 21 30 29 27 26 31	625.00	
4	30 31	105		-	-	

Table 6

Assembly line performance for takt time of 300 minutes

WS	Before			After		
	Assigned tasks	Station cycle time	Line efficiency /SL	Assigned tasks	Station cycle time	Line efficiency /SL
1	1 19	195	75.83 % 0.2972	1 3	276.25	97.35 % 0.0359
2	2 4 5	235		2 4 5 6 23 16	295	
3	3 6 16 23	275		7 10 9 12	298.5	
4	7 10	280		13 11 14 8	287	
5	11 9 12 8 13 24	240		19 24 15	296.5	
6	14	185		17 18 20 22 25 26	294.25	
7	15	220		28 27 29 21 30 31	296.75	
8	17 18 20 21	280		-		
9	22 27 25 26 28 29	260				
10	30 31	105				

It is evident from the results shown in Tables 5 and 6 that the performance of assembly line after implementation of proposed methodology is improved. The line efficiency is improved from 71.09 to 85.14% for the takt time of 800 minutes with better balancing. Similarly, the assembly line performance evaluated for 300 minutes takt time also showed improvement in terms of line efficiency (97.35%) and smoothness level (0.0359). Number of workstations arrived after considering lean and ergonomics issues is also reduced in both cases. The improved smoothness level achieved by the proposed method mitigates the concerns of inequality in task assignments among workers, reduced physical stress, individual frustration and team dissention. Within the lean perspective it can be said that the sequence generated has enabled a uniform rate of progression of products through all stages from raw material to customer and reduced the waste arising due to waiting/delay of materials. The proposed method indirectly helps to reduce the behaviour waste (Emiliani 1998) and poor performance due to costly delays, rework and poor co-operation arising out of unevenness (Eswaramoorthi et al. 2010).

4. Conclusions and recommendation

The integrated methodology developed to redesign the assembly line with lean and ergonomics principles to promote lean systems allows the rapid collection and analysis of a large body of data. The study presented the advantages of ergonomic workstations to the company and worker such as reduction of NVA, reduction of different wastes, improvement in assembly line performance and workers' quality of life. The MTM methodology and its use in standard time estimation are presented along with the advantages of its application during the planning of an improved workstation. With the use of this method, it is demonstrated that the non value adding activity are quantitatively measured and improvement plans can be implemented successfully. This combined approach seems likely to make an important contribution to promote lean systems.

Further, the study revealed that the proposed method would help to improve the lean operations of assembly line by standardized work methods, better flow, minimum wastes due to improved balancing and saves time by avoiding unnecessary search, walking, awkward postures and unnecessary motions for assembly line design. All the resistance [to lean] seems to melt away when people are working in comfortable environment which would improve their jobs for their own benefit. The proposed methodology would support to implement lean concepts at an accelerated pace in machine tool manufacturing sector by removing the barriers such as anxiety in changing the mind-set of workers, lack of awareness about the lean concepts, and cost and time benefits involved in lean implementation as identified in the survey by Eswaramoorthi et al. (2011a). There is more operator involvement, not because that's what's needed for the shop floor improvement of ergonomic risk, but because that's what's needed for the cultural transformation. Ergonomics may be added as another element of the lean toolbox to quantify wastes generated due to unnecessary motion in terms of risk exposures since improvement isn't worth if it can't be measured. Having ergonomics as part of the lean initiative, it would acquire the cultural firepower to really have lean take off. Future research in this area may be considered to study the scope of introducing automations at human-resources interaction areas and its impact on lean operations and assembly line performance.

References

1. Ayoup M.A., 1990. Ergonomic deficiencies: I pain at work. Journal of Occupational Medicine, 32 (1), pp.52-57.
2. Askin R.G and Goldenberg J.B, 2002. Design and analysis of lean production systems. Johan Wiley and Sons, New York, NY, USA.
3. Bheem P. Kattel, Tycho K. Fredericks, Jeffrey E. Fernandez, Dong C. Lee, 1996. The effect of upper-extremity posture on maximum grip strength. International Journal of Industrial Ergonomics 18, 423-429.
4. Baudin, M., 2002. Lean assembly: The nuts and bolts of making assembly operations flow, productivity. New York: Productivity Press.
5. Battini, D., Faccio, M., Ferrari, E., Persona, A., Sgarbossa, F., 2007. Design configuration for a mixed-model assembly system in case of low product demand. The International Journal of Advanced Manufacturing Technology 34 (1-2), 188-200.
6. Battini, D., Faccio, M., Persona, A., Sgarbossa, F., 2008. Balancing-sequencing procedure for a mixed model assembly system in case of finite buffer capacity. International Journal Advanced Manufacturing Technology 44 (3-4), 345-359.
7. Battini, D., Faccio, M., Persona, A., and Sgarbossa, F. 2011. New methodological framework to improve productivity and ergonomics in assembly system design. International Journal of Industrial Ergonomics, 41, 30-42.
8. Ciriello, V., 2005. The effects of box size, vertical distance, and height on lowering tasks forma female industrial workers. International Journal of Industrial Ergonomics 35, 857–863.
9. English, C.J., Maclaren, W.M., Courtbrown, C., Hughes, S.P.F., Porter, R.W., Wallace, W.A., Graves, R.J., Pethick, A.J., Soutar, C.A., 1995. Relations between upper-limb soft-tissue disorders and repetitive movements at work. American Journal of Industrial Medicine 27 (1), 75–90.
10. Emiliani, M.C., 1998. Lean behaviors. Management Decision, 36(9), 615–631.
11. Eswaramoorthi, M., John,M., Arjun Rajagopal, C., Prasad, P.S.S., Mohanram, P.V., 2010. Redesigning assembly stations using ergonomic methods as a lean tool. Work: A Journal of Prevention, Assessment and Rehabilitation, 35 (2), 231 - 240.
12. Eswaramoorthi, M., Kathiresan, G.R., Prasad, P.S.S., Mohanram, P.V., 2011a. A Survey on Lean Practices in Indian Machine Tool Industries. International Journal of Advanced Manufacturing Technology, 52(9-12), 1091-1101.
13. Eswaramoorthi, M., Prasad, P.S.S., Mohanram, P.V., 2011b. Flow index based line balancing A Tool to improve the leanness of assembly line design. International Journal of Production Research. (Accepted for publication on 10.03.2011).
14. Granata K.P., Marras, W.M., and Ferguson, S.A., 1996. Relation between biomechanical spine load factors and risk of occupational low-back disorders. Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting. Philadelphia, PA 656-660.
15. Guide to Intellectual Properties Rights for Industry Machine Tool, 2005. Indian Machine Tool Industry ...Shaping the Future, http://www.imtma.in/pdf/ch1.pdf.
16. Hildebrandt, V.H., 1995. Back pain in the working population: prevalence rates in Dutch trades and professions. Ergonomics, 36(6), 1283-1298.
17. International Labor Office (ILO), 1979. Introduction to Work Study, 3rd Edition. Geneva, Switzerland.
18. Konz, S., Johnson, S., 2004. Work Design: Occupational Ergonomics, Holcomb Hathaway.
19. Laring, J., Forsman, M., Kadefors, R., O¨ rtengren, R., 2002. MTM-based ergonomic workload analysis. International Journal of Industrial Ergonomics. 30, 135–148.
20. Maynard, H.B., Stegemerten, G.J., Schwab, J.L., 1948. Methods-Time Measurement. McGraw-Hill Book Company Inc., New York.
21. McAtamney, L., Nigel Corlett, E., 1993. RULA: a survey method for the investigation of work-related upper limb disorders. Applied Ergonomics, 24 (2), 91-99.
22. National Programme for Development of the Machine Tool Industry in India: A Success Story, United Nations industrial development organization (UNIDO) Vienna. Technology Paper Series, No. 5/2005.
23. Putz-Anderson, V., 1988. Cumulative Trauma Disorders: A Manual for Musculoskeletal Diseases of the Upper Limbs, Taylor & Francis, Ltd, Bristol, PA.
24. Punnett, L., Fine, L.J., Keyserling, W.M., Herrin, G.D., Chaffin, D.B., 1991. Back disorders and non-neutral trunk postures of automobile assembly workers. Scandinavian Journal of Work Environment & Health 17 (5), 337–346.
25. Punnett, L., Fine, L.J., Keyserling,W.M., Herrin, G.D., Chaffin, D.B., 2000. Shoulder disorders and postural stress in automobile assembly work. Scandinavian Journal of Work Environment & Health 26 (4), 283–291.
26. Punnett, L., Wegman, D. H., 2004. Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. Journal of Electromyography and Kinesiology 14 (1), 13-23.
27. Ranney, D., Wells, R., and Moore, A., 1995. Upper limb musculoskeletal disorders in highly repetitive industries: precise anatomical findings. Ergonomics, 38(7), 1408-1423.
28. Resnick, M. L., Zanotti, A. 1997. Using ergonomics to target productivity improvements. Computers & Industrial Engineering. 33 (1-2), 185-188.
29. Snook S.H., Vaillancourt, D.R., Ciriello, V.M., and Webster, B, S., 1995. Psychophysical studies of repetitive wrist flexion and extension. Ergonomics, 38(7), 1488-1507.
30. Scholl, A., and Becker, C., 2006. State-of-the-art exact and heuristic solution procedures for simple assembly line balancing. European Journal of Operational Research, 168, 666–693.
31. Takala, J., 2002. Introductory Report: Decent Work – Safe work, XVIth World Congress on Safety and Health at Work.
32. Udosen, U.J., 2006. Ergonomic workplace construction, evaluation and improvement by

CADWORK. International Journal of Industrial Ergonomics. 36, 219–228.
33. Womack, J.P., Jones, D.T., and Roos, D. The Machine that Changed the World, Rawson /MacMillan, 1990.
34. Walder, J., Karlin,J., Kerk, C., 2007. Integrated Lean Thinking & Ergonomics: Utilizing Material Handling Assist Device Solutions for a Productive Workplace. A Material Handling industry of America (MHIA) White Paper, 1-20.
35. Wick, J.L., McKinnis, M., 1998. The effects of using a structured ergonomics design review process in the development of an assembly line. In: Kumar, S. (Ed.), Advances in Occupational Ergonomics and Safety. IOS Press.
36. Saravanan Arumugamurthy S., Sivanandi P., Pandian S., Choksi H., Subramanian D., "Conversion of a low value industrial waste into biodiesel using a catalyst derived from brewery waste: An activation and deactivation kinetic study", Waste Management, Volume 100, Pages 318-326, December 2019.