Modelling and Simulation of Ageing on Performance of Assembly Workers through a Learning Curve

Maji I. Abubakar and Qian Wang

Abstract—**In the past decade, the manufacturing environment has faced more challenges than ever since as a result of the increase of global competiveness and preferences of customer demands, which require developments of a resilient production system that is capable of providing essential flexibility and responsiveness to accommodate changes at an unpredictable circumstance. Human centred assembly systems, as an example, can offer such characteristics because of the nature of human intelligence and problem solving abilities. Nevertheless, human performance on a human centred assembly system is also largely affected by human factors during production. Ageing is one of human factors that may significantly affect human performance in completing assigned assembly tasks. When designing and analysing a human centred manufacturing system, such a human attribute is often inadequately represented in neither mathematical models nor computer-based simulation models and therefore the analysed outcomes using these approaches may not properly describe the real behaviour of the system. The result of the previous studies also indicates that human performance may start to decline from the age of 38 years old and beyond. This paper presents a study by investigating the influence of ageing on assembly worker performance using a learning curve approach. The different ageing cohorts were incorporated into a DES (discrete event simulation) model. The study concludes that worker productivity decreases by an average 1% per year as the age of workers increases from 38 to 70 years old.**

Index Terms—**Modelling simulation, learning curve, human factors, assembly systems.**

I. Introduction

Manufacturing paradigm has been shifting from mass production to mass customisation and manufacturing companies therefore must adapt tactically to the changes in order to survive in the increasingly competitive market. For a human centred assembly system, the system performance is largely affected by human performance, which is also affected by human factors. Although human factors may positively benefit the system performance in terms of such as capability of dealing with production problems, these human factors such as ageing may also negatively affect the system performance in terms of productivity and efficiency in a manufacturing system [1].

The workers' random behaviours are highly simplified when applying a DES tool for manufacturing system design and analysis [2]. A survey concluded that human performance and associated human factors are not adequately represented in the simulation models [3], there have been a number of studies in an attempt to develop modelling methods by considering human behaviour for manufacturing. Bainess et al reported that tools used for manufacturing analysis disregards human factors as a result a substantial amount of assembly line performance are overestimated [4]. Although there have been rare studies in this field, Boudreau *et al* suggested the integration of human variables into simulation models of operation systems [5]. Wang, *et al* incorporated learning curves into DES to investigate the variation of performance of walking workers during a learning process [2]. Neumann & Medbo examined the significance of learning in the ramp up phase of production [6]. Baines looked into effects of circadian rhyme on throughput [7]. Zhu et al focused on a study in varying reaction times of human workers on assembly operations [8]. Zülch examined the human decision making in manufacturing [9]. Dode et al investigated on muscular fatigue and recovery times [10]. Table I summarises a small number of the previous studies in findings relating to integration of human factors into simulation tools.

TABLE I: Incorporation of Human Factors Into Simulation Tools

Authors	Studies	Finding(s)
[11]	Limitations of simulation tools to capture human attributes	An approach for modelling interactions between humans and their performance
[7]	Impact of human factors on reliability and accuracy of simulation tools	Suitability of simulation tools to accommodate micro models
[4]	Key human factors affecting worker performance	15-20% overestimation of assembly line performance on human factors that may impact manual tasks
[2]	Learning curves of assembly of walking walker	Variations of individual performance of learning capabilities
[12]	Variations between real production systems and simulation modelling tools	Age as one of the important factors affecting individual task performance
[10]	Effects of fatigues in manufacturing	Quality defects of 21% due to fatigue in manufacturing systems where human factors are ignored during the design phase

As one of human factors, ageing may cause the persistence in the decline of biological components due to internal physiological deterioration [13]. In relation to working population, ageing workers are classified by the International Labour Organisation (ILO) as those who are liable to encounter difficulties in employment and occupation because of advancement in age [14]. Gerontologist classified the ageing population into three groups: the group at ages

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between 60 to 74 years old, the group at ages between 75 to 85 years old and the group at ages after 80 years [15]. By comparison, the World Health Organisation (WHO) defines an ageing person from the age of 45 years old and beyond [1]. Regardless of various interpretations, the trend of ageing population is expected to be more than doubled by 2050 and more than tripled by 2100 [16].

There is evidence that performance of individuals may decline from the certain age due to the natural decline of physical and physiological functions in such as visual ability, musculoskeletal force, flexibility/motion capability, memory or concentration and thermoregulation [1], [17]. By contrast, as worker's age increases, it is expected that the accumulation of experiences may also increase to offset the decline of human abilities [18],[19]. Table II summarizes the findings on the decline of human functional ability over the increase of age.

TABLE II: DECLINE OF HUMAN FUNCTIONS VS AGES

Ability	Function	Performance variation	Authors
Endurance	Aerobic capacity	Peak at 40 and decline by 1% per year	[20]
		Peak at 30 years old and decline by 0.5–1.5 % per year	[21],[22]
		Decreases by 1–1.5 % per year after the age of 40 years old	[12]
		Decline by 1% per year after the age of 30 years old	[23]
		Decrease by 1% per year after 35	[24]
Mental	Cognitive	Peak at 30 years old and decline at 1% per year	[25]
		Peak at 40 and decline by 0.8 to 1.0% per year	[26]
		Peak at 30 years old, decline by 0.5% per year up to the age of 40 years old and then decline by 1% every year up to 65 years old.	[27]
		Peak at 45 then decline by 1 to 1.5% per year	[21],[28]
		Peak at 40 years old and decline by 0.8–1% per year	[29]
Awkward posture	Flexibility	Peak at 35 years old and decrease at about 1% per year between 35 and 54 years old	[30]
Overall performance	Physiological	Peak at 35–40 years old and decline by 1% per year	[14],[22], [31]

The decline of human physiological and physical functions has always been an active research issue [19]. A study by the U.S Department of Labour reveals that human productivity may increase until the age of 35 years old and it steadily drops by 20 -25% of the full capacity, these affect workers physically and mentally in performing tasks [1]. Zwick & Gobel investigated the changes in age structure on general work ability and observed that productivity may increase until the age of 40-45 years old and significantly decline after these ages [32]. The relationship between individual performance and his/her chronological age is still not clear due to paucity of experimental evidences. Waldman and Avolio gives a positive relationship between age and work performance using job type (professional and non-professional) as controlling variables [33]. Sturman observed an inverted U shape relationship between age and job performance [34]. Salthaouse and Somberg investigated a situation where experience can offset cognitive decay and hence enhanced productivity [18]. Age related performance decline with experience and cognitive abilities as controlling variables was the focus of Skirbekk [17]. Although other human factors such as environmental factors and ergonomics may also have negative impacts on ageing worker performance. For instance, Kenny, *et al* observed that a core temperature of 30C can maintain healthy individuals. When exposure of older workers in a cold environment, this may have a negative impact [13]. Furthermore, the assembly operations are involved in the process of pinching, gripping, screwing, pulling, pushing, lifting, turning and so on, this requires repetitive wrist motion and awkward hand posture which are reasonable evidence associated with prevalence of tendon disorders in hand and wrist which may cause loss of time and productivity due to work-limiting pain and fatigue [35]. In this study, however, it was assumed that the natural decline of physical, physiological and cognitive over different ages is unavoidable. Female workers on average are weaker than male workers, strength of female workers approximately account for two third of male workers [36], subjected to individual habitual adaptation (e.g poor health, inactive lifestyle, smoking, poor diet, substance abuse) and the ability of organization to accommodate and protect the ageing workforce particularly in the context of physical employment standards [17].

II. NUMERICAL ANALYSIS

Table III shows the predicated outcomes of human functional decline in percentage over varying ages using the regression analysis. It shows that at the age of 38 years old as a base line at which human performance starts to deteriorate. Table 3 also shows the fit values denoted as loss rate which refers to the rate of decline at ages between 38 and 70 years old; and the percentage of human kinematic decline of the full capacity during the same period. The percentage of capacity remaining after this age were assessed using (2) and the trend is illustrated in Fig 1.

$$L_r = 0.57 + 0.012k \quad (1)$$

$$F_{rm} = k_2 - L_r(k_1 - 38) \quad (2)$$

where:

F_{rm} : Remaining capacity in percentage

k_2 : Peak capacity (100% at age of 38 yr)

L_r : Loss rate

k_1 : Existing age

K: Age in years

TABLE III: HUMAN FUNCTIONAL DECLINE IN PERCENTAGE OVER VARYING AGES

Age (k)	Loss rate (L_r)	Percentage of the full functional capacity at age of 38 yr (F_{rm})	Human kinematic decline rate (%) of the full capacity (F_{dl})
38	0	100	0
40	1.05	97.9	2.10
45	1.11	92.23	7.77
50	1.17	85.96	14.04
55	1.23	79.09	20.91
60	1.29	71.62	28.38
65	1.35	63.55	36.45
70	1.41	54.88	45.12

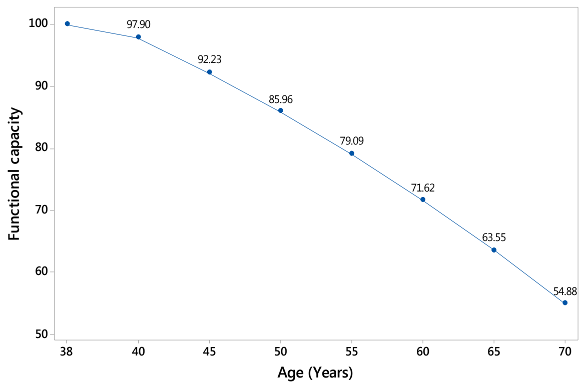

Fig. 1. Percentage of functional capacity decline over the increasing age.

A. Experience Curve

It is widely understood that efficiency of individual performance can be improved by practicing more on a job. In other words, the time for producing each unit may decrease at a uniform rate, which may reach a stable proportion after the certain quantity of units to be produced [37]. A log linear model was used for this study in predicting the assembly time for producing a unit of after the repetitive operations [38]. The relationship using log linear model is given below:

$$T_n = T_t \bullet Q^c \qquad (3)$$

where:

T_n: Average time to produce the n^{th} units

T_t: Time to produce the first unit

Q : Cumulative number of units produced

C : Learning index which determines the speed of learning occurring each time as a cumulative output increases, it is computed as $\frac{\log(R)}{\log(2)}$ where learning rate (R) is measured in percentage (0 < R < 1), i.e., 80% learning rate (R) implies a cost reductions of 20% in the direct man labour hour needed to complete a subsequent unit [38]. Note that the average time towards the steady state decreases with the increase of number of units produced as described below:

$$T_A = T_t \bullet B^C \qquad (4)$$

$$T_t = \frac{T_A}{B^C} \qquad (5)$$

T_A : The average time to reach a steady state

B: Batch size

By substituting equation 5 into equation 3, it yields:

$$T_n = \frac{T_A}{B^c} \bullet Q^c \qquad (6)$$

Hence, it gives:

$$T_n = T_A\left(\frac{Q}{B}\right)^c \qquad (7)$$

To determine the loss time (7) was multiplied by the worker kinematic decline rate (%)

$$\Delta_{Lt} = T_n \times F_{dl} \qquad (8)$$

$$\Delta_{Lt} = T_A\left(\frac{Q}{B}\right)^c \times F_{dl} \qquad (9)$$

Hence the total assembly time per worker due to ageing is computed using (10).

$$\Delta_{Lt} = T_A\left(\frac{Q}{B}\right)^c + T_A\left(\frac{Q}{B}\right)^c \times F_{dl} \qquad (10)$$

where:

Δ_{Lt} -- Average loss time due to ageing

T_{to}-- Total average assembly time

F_{dl}-- Human kinematic decline rate (%) of the full capacity

T_n-- The average time to produce the n^{th} unit

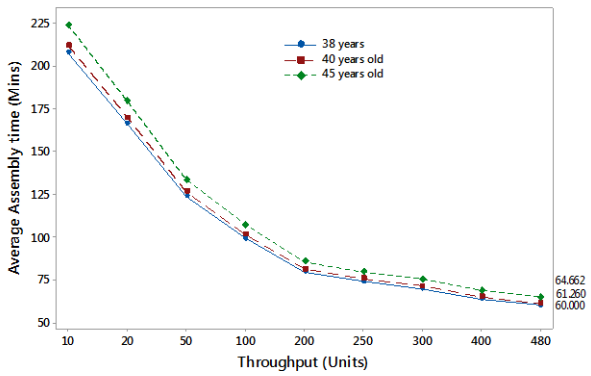

Fig. 2. Average assembly time vs number of output under ages of 38, 40 and 45 years old.

III. ANALYSIS IN A RANGE OF DIFFERENT AGEING GROUP

Fig 2 shows the trend of the average assembly time for each group of individual workers at the ages of 38, 40, 45, 50, 55, 60, 65 and 70 years respectively. It can be generally seen in Figure 2 that the average assembly time for producing a unit drops over the increasing number of output for all the ageing groups. It can also be seen in Fig 2 that the average assembly time for producing a unit at the age group of 38 years old is 60 minutes, which is less than that of 64.66 minutes for the ageing group of 45 years old, although there is an insignificant difference in the average assembly time of the ageing groups between 38 and 40 years old. Fig 3 and 4 shows the average assembly time of the ageing groups at 50, 55, 60, 65 and 70 years old over the increasing number of output. By comparing the average assembly time of the ageing group of 38 years old, it show an average of 5% in difference of the average assembly time between ageing groups.

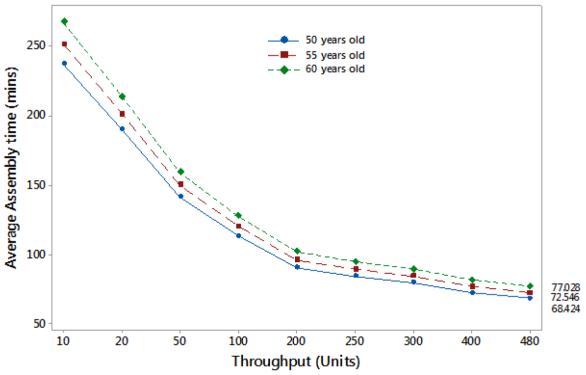

Fig. 3. Average assembly time vs number of output under ages of 50, 55 and 60 years old.

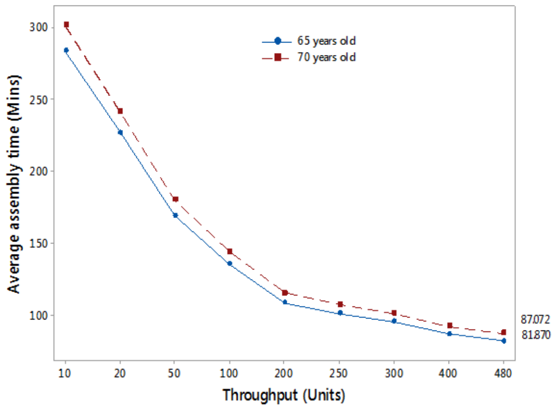

Fig. 4. Average assembly time vs number of output under the ages of 65 and 70 years old.

The calculated mean assembly time of each worker using (10) for each of ageing groups of workers.

TABLE IV: THEORETICAL MEAN ASSEMBLE TIME

Workstation	Age of the worker (years) manning the station	Mean assembly time (min)
1	38	60.00
2	40	61.26
3	45	64.66
4	50	68.42
5	55	72.54
6	60	77.03
7	65	81.87
8	70	87.07

Fig. 5 shows the assembly line model built using a DES tool with eight stations manned by eight workers under different ages shown in Table IV. The mean processing time at each station follows a negative exponential distribution. The set up time on the line was assumed to be 15 minutes in a shift of 8 hours. Table V shows the simulation result indicating the trend in throughput with the increase of ages of each worker. The result suggests the decline in throughput as the age of worker increases.

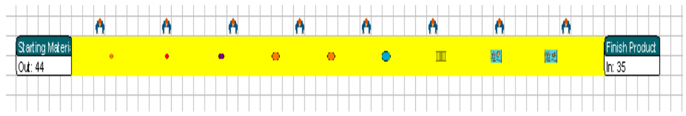

Fig. 5. A linear assembly line model operated by workers under different ages.

TABLE V: DECLINE RATE IN THROUGHPUT OVER VARYING AGES

Work station	Age (years)	Throughput decline (%)
1	38	0
2	40	2.29
3	45	6.67
4	50	12.08
5	55	17.29
6	60	22.29
7	65	26.88
8	70	30.83

IV. CONCLUSIONS

This paper presents a study on the effects of ageing on worker performance based on a literature review and its findings show that productivity of a worker may decrease by an average 1% after reaching his/her peak capacity at age of 38 years old. This result was examined using Minitab software and a DES tool was incorporating aging as one of the human factors that affect human performance into the developed model. The study provides an insight into the trend of worker performance under varying ages using the learning curve approach. It can also offer a guide for allocating a task by taking into account of the aging workers to achieve a best utilisation and productivity each individual worker can attain.

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