KEY HUMAN FACTORS AND THEIR EFFECTS ON HUMAN CENTERED ASSEMBLY PERFORMANCE

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Abstract—

Today in the increasingly competitive market, consumers prefer to have a great variety of products to choose from; this preference is often coupled with demands for a relatively smaller lot size, shorter lead time, higher quality and lower cost. Consequently, manufacturing companies are being forced to consistently increase flexibility and responsiveness of their production systems in order to accommodate changes of the fluctuating market. Among various forms of production systems, human-centred manufacturing systems can offer such a capability in dealing with product variations and production volumes as human workers can always adapt themselves to perform multiple tasks after a learning process. However, human performance can also be unpredictable and it may alter due to varying psychological and physiological states, which are often overlooked by researchers when designing, implementing or evaluating a manufacturing system. This paper presents a study aiming to address these issues by exploring human factors and their interactions that may affect human performance on human-centred assembly systems. The study was carried out based on a literature review and an industrial survey. Critical system performance indicators, which are affected by human factors, were evaluated and the most significant human factors were identified using the fuzzy extent analysis method. The research findings show that experience is the most significant human factor that affects individual human performance, compared to age and general cognitive abilities in human-centred assembly. By contrast, both human reaction time and job satisfaction have the least effect on human performance. The significance of ageing on human performance was also studied and it was concluded that average assembly time of human workers rises by average 1% per year after the age of 38 years old.

Keywords: *manufacturing systems, human factors, assembly, fuzzy extent analysis, ageing*

1. Introduction

In the past decade, most industrial companies have been shifting their manufacturing activities from mass production to mass customization aiming to increase product varieties and production volumes with small lot sizes, short lead times, high quality and low cost. One form of production systems is human-centred assembly systems, which can deal with variations in term of product mix and production volume as human workers can always adapt to production changes with varying demands from the competitive market. However, human capacity or performance in production is often affected by a variety of human factors interacting in a complex way (Schmid 2005). Nevertheless, such a phenomenon is often under or overestimated or simply neglected in manufacturing systems design, evaluation and implementation (Boenzi et al. 2015; Digiesi 2006; Baines et al. 2004).

Most studies have focused on the impact of human factors on human performance in general terms, which are not specifically related to manufacturing activities or production systems. Govindaraju et al. (2001) investigated the relations among ergonomic work conditions, human performance and quality based on a number of case studies. Boenzi et al. (2015) examined the variation of human performance between older workers and younger workers and concluded that this was insignificant. Giniger et al. (1983) observed that the effects of age and physiological fuctions were not significant, and both cognitive and physiological decline can be compensated by experience. By contrast, Hunter (1986) argued that some cognitive abilities may decline with age, while others may stablise over the life cycle, although fluid abilities (such as reasoning and working memory) can decline over age. However, crystallised abilities, which depend on accumulated knowledge, tend to remain stable (Zwick & Gobel 2009; Deary et al. 2001; Warr 1994). Hunter et al. (1996) observed that a higher human performance can be attained by people who learn and transfer their skills to new tasks, although varying levels of individual performance may depend on their individual learning rates. Hunter (1986) concluded that it is the general cognitive ability that may determine human performance as it controls human capability with how much and how quick a person can learn.

A study by Belbase & Sanzenbacher (2016) indicated that even workers with less ability to process information may also maintain productivity with the advancing age. Zwick et al. (2009) observed that the average muscle strength of a human decreases by roughly 10% per decade from 20 to 60 years old, 15% from 60 to 80 years old and 30% after 80 years old. This may be due to aerobic capacity that reaches its peak at ages of 20s and after these ages it declines by around 1% per year. Shephard (2000) reported that age affects the occupational performance of older individuals due to their decline in aerobic power. Moreover, Wang et al. (2012) stated that some costs in production may incure due to learning and forgetting of human operators who offer flexibility and responsiveness of a manufacturing system. Reagans et al. (2005) examined the relationship between worker experience and human learning and forgetting; it was observed that effect of forgetting was not significant when dealing with relatively less complex tasks.

A study shows that human reaction time tends to be fastest at the age of 20 years old; after this age it declines slowly until the age of 60 years old. It declines much faster after age of 70 years old and onwards. The study also shows that the reaction times of females are more volatile, compared to males (Deary et al. 2001). Doroudgar et al. (2017) used a simple visual reaction test to measure reaction times between a group of younger adult drivers (age from 18 to 40 years old) and a group of older adult drivers (60 years old and above), the experiemental result shows that the group of older drivers had the significantly poorer performance in reaction time leading to slower driving speed and more accidents. Adam et al. (1999) investigated the relationship between general cognitive ability and reaction time and concluded that there is a correlation between intelligence and reaction time, which, for males, is faster than females in almost all aging groups. However, Berg et al. (2006) stated that human reaction time can be affected by other issues of such as distraction and mental fatigue.

This paper reports an investigation of human factors and their interactions that may affect human performance on human-centred assembly systems; the work was carried out based on a literature study and an industrial survey. Critical system performance indicators, which are affected by human factors, were also evaluated, and the most significant human factors were identified using the fuzzy extent analysis approach.

2. Review of previous studies

A study by Broadbent (1971) indicated that human activity, which requires visual alertness, may be affected by sound, which distracts information intake and analysis. Avolio et al. (1990) used the polynomial regression analysis to predict work performance in connection with age and experience; the research outcome indicates that experience rather than age determines human performance. Schmidt et al. (1986) developed a model using a path analysis approach to examine the underlying influence of worker experience and job knowledge. The research result suggested that worker experience is the most influencial factor affecting human performance. The study by McDaniel et al. (1988) indicated that there is a direct relationship between job experience and job performance regardless of job complexity. Llmarinen (2001) observed that age may negatively affect general cognitive abilities but positively affect experience of a human worker, although experience may positively affect cognitive skills, which directly affect job peformance. Llmarinen (2001) also stated that physiological ability may decline due to aging; but it can also be compensated by experience gained as the age increases. Despite the decline of both cognitive and physical functions of a human worker due to aging, Giniger et al. (1983) and Stead et al. (1983) argued that the influence is not significant for older workers who may attain satisfactory job performance by applying cautions and restraints. Zwick et al. (2009) stated that human performance may be affected more by experience than aging. Kenny et al. (2015) investigated the physiological effect on decline of aerobic and musculoskeletal capacity due to aging; the study shows an average drop of 20% of physical work capacity at ages from 40 to 60 years old. A study by Avolio et al. (1990) shows experience rather than age of older workers is the key factor that is used for determining human performance as experience may offer an equal or even higher performance in comparison with their younger counterparts. In particlar the effect of experience appears to be more significant when performing a complex task. Rhodes (1983) suggested that human performance is more affected by age and Waldman et al. (1986) challenged some of Rhodes's conclusions arguing that the method used for the study may lead to unclear or even wrong interpretations. Furthermore, a study by McEvoy et al. (1989) showed that there is no clear relationship between age and job performance. Waldman et al. (1986) suggested that the effects of age and experience on performance may be subject to the cognitive demand of a task. Stanley (1985) investigated the influence of age on productivity of individuals and concluded that the effect of age on job performance may depend on the complexity of a task as complexity requires a strong mental capability that may deteriorate with ageing. A study by Skirbekk (2008) showed that the performance of individuals may differ for many reasons; this includes length of work experience, cognitive abilities, physical abilities and other relevant factors (such as environmental factors). Table 1 provides a summary of the effects of human factors on human performance for production, the results were obtained based on a literature review.

Table 1 Effect of human factors on human performance for production

Effects from	Effects on	Authors

Physical work capacity	Cycle time	Galen (1987); Govindaraju et al. (2001); Boenzi et al. (2015)
	Job satisfaction	Govindaraju et al. (2001); Narahari & Koneru (2017)
Age	Physical work capacity	Shepherd (1999); Schibye & Hansen (2001); Bridger (2009); Stead & page (1983); Zwick & Gobel (2009); Kenny et al. (2015).
	Cycle time	N/A
	Reaction time	Woodson et al. (1992); Der & Deary (2006); Salvia et al. (2016), Svetina (2016); Doroudgar et al. (2017)
	Idle time	N/A
	Learning and forgetting	Zwick & Gobel (2009); Stanley (1985); Boenzi et al. (2015)
	Throughput	Baines, et al (2004)
	General Cognitive Abilities	Warr (1994); Boenzi et al. (2015); Stanley (1985); Llmarinen (2001)
	Job satisfaction	Rhodes (1983); Drabe et al. (2015); Clark & Oswald (1996); Kumar (2017)
Gender	Physical work capacity	Bridger (2009)
	Reaction time	Woodson (1992); Der & Deary (2006); Adam et al. (1999)
Experience	Cycle time	Reagans et al. (2005)
	Throughput	Reagans et al. (2005); Hunter (1986)
	Learning and forgetting	Shafer et al. (2001); Hunter & Schmidt (1996); Reagans et al. (2005)
	Physical work capacity	Giniger et al. (1983)
	Reaction time	Ando et al. (2004); Visser et al. (2007)
	General Cognitive Abilities	Giniger et al. (1983); Llmarinen (2001); Boenzi et al. (2015)
	In-process inventory	N/A
	Idle time	N/A
Learning and forgetting	Cycle time	Nembhard & Osothsilp (2002); Falck & Rosenqvist (2012a)
	Throughput	Shafer et al. (2001); Nembhard & Osothsilp (2002); Hunter (1986); Wang et al. (2012); Digiesi et al. (2006)
	In process inventory	N/A
	Idle time	N/A
Job satisfaction	Throughput	Rodriguez et al. (2016)
	Throughput	Bridger (2009); Bainess & Kay (2002)
	Reaction time	Welford (1968); Moskaliuk et al. (2017)
General Cognitive Abilities	Reaction time	Deary et al. (2001), Govindaraju et al. (2001)
	Learning and forgetting	Hunter (1986); Wirojanagud et al. (2007)
	Throughput	Hunter & Schmidt (1996); Wirojanagud et al. (2007)

	Cycle time	Govindaraju et al. (2001)
	Idle time	N/A
Circadian rhythms	Reaction time	Berg & Neely (2006)

In this work, an industrial survey was also conducted to compare the findings with the corresponding outcomes obtained based on the literature study. This process was involved in testing and selecting 33 effective respondents, of whom, 60% were researchers in the field of engineering, 30% were industrialists and 10% were from other sectors. The relationship between identified human factors on human-centred performance were rated using the Likert scale (Allen & Seaman 2007). Respondents were asked to rate the influence of one human factor over another using a five-point scale; it gave a mean of 3.0 based on scales rated by respondents to all the questions. Table 2 shows the calculated mean value of the cumulative responses for each question using a statistical package for social science (SPSS). In this study, any value obtained below 3.0 was considered as a weak relationship and these values were filtered out. The mean values, as shown in Table 2, were assigned to the linguistic terms depicting the amplitude of effects between human factors. As an example, a mean value of 3.54 indicates a relatively weaker impact of ageing on learning and forgetting. Further, these mean values are categorised into four classes as shown in Table 3.

Table 2 Measurement of the effective-relationships between human factors

Human factor	Mean	Std dev.
Experience (EX) vs Age (AG)	4.48	0.50
Experience (EX) vs Reaction Time (RT)	4.27	0.67
General Cognitive Abilities (GCA) vs Learning and Forgetting (LF)	4.27	1.03
Experience (EX) vs Reaction Time (RT)	4.27	0.67
Experience (EX) vs Physical Work Capacity (PW)	4.24	0.86
Age (AG) vs Physical Work Capacity (PW)	4.15	1.00
Experience (EX) vs Learning and Forgetting (LF)	4.06	0.86
Age (AG) vs Job satisfaction (JS)	4.06	1.14
Age (AG) vs General Cognitive Abilities (GC)	4.00	0.75
General Cognitive Abilities (GC) vs Reaction Time (RT)	3.93	0.86
Physical Work Capacity (PW) vs Job satisfaction (JS)	3.93	1.27
Age (AG) vs Reaction Time (RT)	3.81	1.01

Age (AG) vs Learning and Forgetting (L,F)	3.54	1.25
Gender (GD) vs Reaction Time (RT)	2.87	0.89
Circadian Rhythms (CR) vs Reaction Time (RT)	2.87	0.85
Gender (GD) vs Physical Work Capacity (PW)	2.72	0.94

3. Analytical hierarchy process and fuzzy set theory

Human behaviours can be difficult to measure; their interdependence or relationships are often ambiguous and still not well understood. Descriptions of human behaviour or performance are generally linguistic (Karwowski & Mital 1986). Therefore, a multi-criteria decision making tool, namely the analytical hierarchy process (AHP), was used for selecting the solution based on the subjective judgements. AHP, however, is criticised for disregarding the vagueness and prejudice of human judgements, i.e., it does not account for human thinking, especially as it relates to human attributes or human traits, which may not be easily evaluated using conventional numbers, apart from the language expression (Tzeng & Huang 2011; Saaty 2008; Aggarwal & Singh 2013). Zadeh (1965) developed a methodology using fuzzy sets as a way in which sharp numerical values can be represented using overlapping boundaries of fuzzy numbers taking into account inherent human imprecision in a decision making process (Mikhailov 2003; Fan et al. 2004; Chen 2001; Chou et al. 2008; Hwang & Yoon 2004). Fuzzy set theories are introduced and defined in the literature by Buckley (1985) and Laarhoven & Pedrycz (1983). The concept of fuzzy AHP was developed by embedding the standard AHP approach into a fuzzy domain; the earlier study on the fuzzy AHP approach was made by Laarhoven & Pedrycz (1983). The triangular fuzzy numbers (TFNs) are widely used in the fuzzy analytical hierarchy process (FAHP) (Laarhoven & Pedrycz 1983; Buckley 1985; Chang 1996). The triangular fuzzy number may be described as $\tilde{A}\ (a_1, a_2, a_3\ ),$ which denotes that $\tilde{A}$ is a fuzzy set with membership $a_1, a_2\ and\ a_3$, as illustrated in Figure 1. Thus, $\mu_{\tilde{A}}\,(x)$ refers to the degree of membership of element x in fuzzy set A, which consists of a set of numbers $(a_1, a_2, a_3\ )$ in the interval $[0, 1]$ (Tseng, Ding & Chang 2017). It is described by Ross (1995) as:

$$\mu\tilde{A}(x)\begin{cases} 0, x\langle a_1 \\ \dfrac{x-a_1}{a_2-a_1}, a_1 \le x \le a_2 \\ \dfrac{a_3-x}{a_3-a_2}, a_2 \le x \le a_3 \\ 0, x\rangle a_3 \end{cases} \qquad (1)$$

Figure 1 shows a triangular fuzzy number represented by the triplet a_1, a_2 *and* a_3.

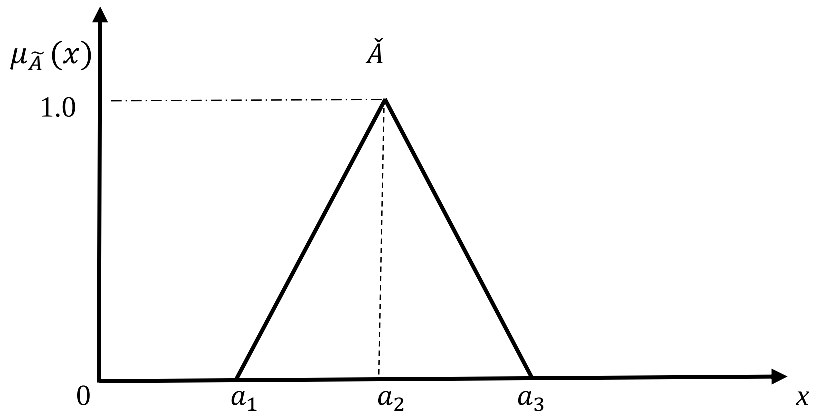
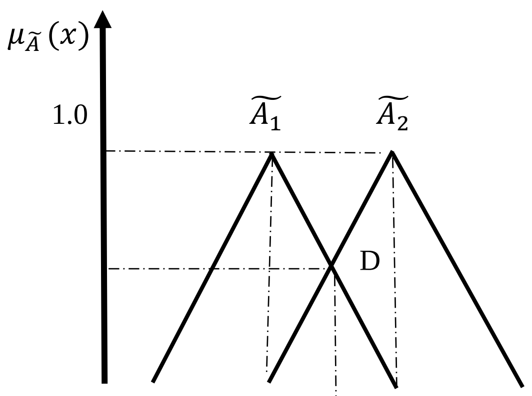


Figure: 1 Membership as the triangle fuzzy number

Figure 2 shows a triangular fuzzy number as $\tilde{A} = (\delta, b, \alpha)$ with two sets of fuzzy numbers $\tilde{A}_1 = (\delta_1, b_1, \alpha_1)$ and $\tilde{A}_2 = (\delta_2, b_2, \alpha_2)$, which can be computed as follows (Chang 1996; Chou 2008; Kwong & Bai 2003; Tseng 2017):

- $\tilde{A}_1 + \tilde{A}_2 = (\delta_1 + \delta_2, b_1 - b_2, \alpha_1 - \alpha_2)$ (2)
- $\tilde{A}_1 - \tilde{A}_2 = \tilde{A}_1 + (-\tilde{A}_2) = (\delta_1 - \delta_2, b_1 - b_2, \alpha_1 - \alpha_2)$ (3)
- $\tilde{A}_1 \times \tilde{A}_2 = (\delta_1\delta_2, b_1 b_2, \alpha_1\alpha_2)$ (4)
- $K \times \tilde{A}_1 = (K\delta_1, Kb_1, K\alpha_1)$ (5)
- $A^{-1} = \left(\frac{1}{\alpha}, \frac{1}{b}, \frac{1}{\delta}\right)$ (6)



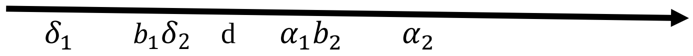


Figure: 2 Membership of two sets of triangular fuzzy numbers

The concept of fuzzy membership function was adopted in this study to evaluate the significance of human factors that may have an impact on human-centred performance using the mean values obtained as shown in Table 2. The mean values are classified and described by linguistic terms as absolutely important, very strongly important, strongly important, and weakly important and equally important, respectively. Column 1 and 2 in Table 3 shows a classification of mean value and linguistic term in response to the triangular fuzzy scale and the triangular fuzzy reciprocal scale in column 3, and 4 respectively. Figure 3 shows the degree of membership in triangular fuzzy numbers corresponding to the linguistic terms.

Table 3 Mean values and linguistic terms vs trangualar fuzzy scale/triangular fuzzy reciprocal scale

Mean	Linguistic terms	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
	Equal	(1, 1, 1)	(1, 1, 1)
	Equally important (EI)	(1/2, 1, 3/2)	(1/2, 1, 3/2)
3.5 – 3.7	Weakly important (WMI)	(1, 3/2, 2)	(1/2, 2/3, 1)
3.8 – 4.0	Strongly important (SMI)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
4.1 – 4.3	Very strongly important (VSMI)	(2, 5/2, 3)	(1/3, 2/5, 1/2)
4.4 – 5.0	Absolutely important (AMI)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

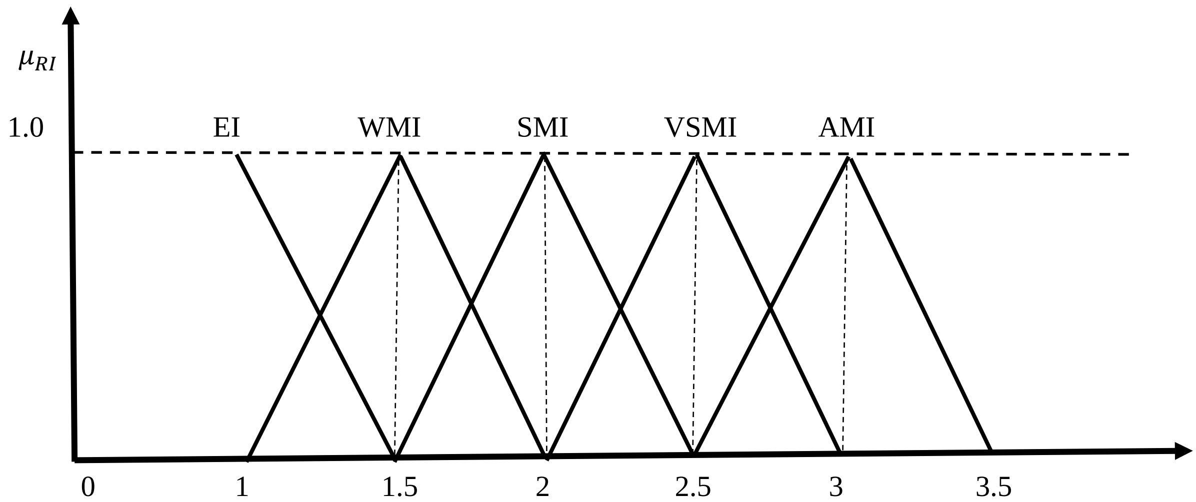


Figure: 3 Degree of membership of triangular fuzzy numbers

Table 4 shows the linguistic scale corresponding to the fuzzy numbers for rating the linguistic terms.

Table 4 linguistic scale corresponding to the fuzzy numbers for rating the linguistic terms

Linguistic scale	fuzzy numbers
Very high (VH)	(0.25, 0.5, 0.75)
High (H)	(0, 0.25, 0.5)
Low (L)	(0, 0.25, 0.25)

Table 5 shows a fuzzy decision matrix on which elements are transformed into triangular fuzzy numbers.

Table 5 Decision matrix using the triangular fuzzy numbers

	Physical Work Ability	Job Satisfaction	Age	Reaction Time	Learning & Forgetting	General C. Ability	Experience
Physical W. C.	(1,1,1)	(3/2,2,5/2)	(1/3,2/5,1/2)	(1/2,1,3/2)	(1/2,1,3/2)	(1/2,1,3/2)	(1/3,2/5,1/2)
Job S.	(2/5,1/2,2/3)	(1,1,1)	(2/5,1/2,2/3)	(1/2,1,3/2)	(1/2,1,3/2)	(1/2,1,3/2)	(1/2,1,3/2)
Age	(2,5/2,3)	(3/2,2,5/2)	(1,1,1)	(3/2,2,5/2)	(1,3/2,2)	(3/2,2,5/2))	(2/7,1/3,2/5)
Reaction Time	(2/3,1,2)	(2/3,1,2)	(2/5,1/2,2/3)	(1,1,1)	(1/2,1,3/2)	(2/5,1/2,2/3)	(1/3,2/5,1/2)
Learning & F	(2/3,1,2)	(2/3,1,2)	(1/2,2/3,1)	(1/2,1,3/2)	(1,1,1)	(1/3,2/5,1/2)	(2/5,1/2,2/3)
General C. A.	(2/3,1,2)	(2/3,1,2)	(2/5,1/2,2/3)	(3/2,2,5/2)	(2,5/2,3)	(1,1,1)	(2/5,1/2,2/3)
Experience	(2,5/2,3)	(2/3,1,2)	(5/2,3,7/2)	(2,5/2,3)	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)

3.1 Fuzzy Extent analysis

In this study, an extent analysis method was used, which is an extension of fuzzy analytical hierarchy process (FAHP). The fuzzy extent analysis approach was used as a multi-criteria decision tool (Isik & Aladag 2017; Yuksel & Dagdeviren 2008; Divesh et al. 2017; Kahraman et al. 2006; Aggarwal & Singh 2013; Adebanjo et al. 2017). Extent analysis method is applied in decision making with objective set K towards a goal set $G = (g_1, g_2, g_3 ....g_m)$

Let $K^1_{gi}K^2_{gi}.....K^n_{gi}$ be an objects set towards a goal set $G = (g_1, g_2, g_3 ....g_n)$, i.e., each individual object is performed towards each goal g, respectively. The value for each alternative decision can be obtained using the extent analysis described below (Chang 1996; Kahraman 2006; Tolga 2005):

$$\tilde{M} = \sum_{j=1}^{m} K^j_{gi} \left(\sum_{i=1}^{n} \sum_{j=1}^{m} K_{gi}{}^j \right)^{-1} \tag{7}$$

where K^j_{gi} (j = 1, 2, 3 ……n) are the triangular fuzzy numbers. To obtain $\sum_{i=1}^{n} K^j_{gi}$, we perform the fuzzy addition of m extent analysis for a particular matrix, which is given:

$$\sum_{i=1}^{n} K^j_{gi} = \left(\sum_{i=1}^{n} l_j, \sum_{i=1}^{n} m_j, \sum_{i=1}^{n} u_j \right) \tag{8}$$

And, to obtain $\left(\sum_{i=1}^{n} \sum_{j=1}^{m} K_{gi}{}^j \right)^{-1}$, operation for addition of fuzzy numbers is performed on $K^j_{gi}\ (j = 1, 2, 3....n)$ such that

$$\left(\sum_{i=1}^{n} \sum_{j=1}^{m} K^j_{gi} \right)^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_1}, \frac{1}{\sum_{i=1}^{n} m_1}, \frac{1}{\sum_{i=1}^{n} l_1} \right) \quad \text{Where } \forall l_1, m_1, u_1 \rangle 0 \tag{9}$$

Table 6 shows the calculated synthetic extent values for the decision alternatives using equations 7 to 9, where l, m, u denotes the lower, medium and upper bounds of the degree of membership.

Table 6 Synthetic extent values computed for each of decision alternatives

	l	m	u
$S_{physical\ work\ capacity}\ (S_{pwc})$	0.07	0.11	0.21
$S_{job\ satisfaction}\ (S_{js})$	0.06	0.10	0.19
$S_{age}\ (S_{ag})$	0.13	0.19	0.32
$S_{reaction\ time}\ (S_{rt})$	0.06	0.09	0.19
$S_{learning\ and\ forgetting}\ (S_{lf})$	0.06	0.09	0.21
$S_{general\ cognitive\ ability}\ (S_{gca})$	0.10	0.14	0.40
$S_{experience}\ (S_{exp})$	0.17	0.24	0.37

The estimation for sets of weight values under each criterion was obtained by comparing fuzzy numbers K_1 and K_2. And whether the degree of possibility of K_1 is greater or equal to K_2 is determined by the intersection of the two fuzzy numbers $\tilde{K}_2(l_2, m_2, u_2)$ and $\tilde{K}_1(l_1, m_1, u_1)$. $\vee(\tilde{K}_1 \geq \tilde{K}_2) = 1$, since $\tilde{K}_1$ and $\tilde{K}_2$ are convex set fuzzy numbers (Zhu, 1999), thus, it can be expressed as:

$$\vee(\tilde{K}_1 \geq \tilde{K}_2) = hgt(\tilde{K}_1 \geq \tilde{K}_2) = \vee(\tilde{K}_1 \cap K_2) = \left(\frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \right) = \mu K(d) \tag{10}$$

And this can be represented as:

$$\vee(K_1 \geq K_2) = \mu_A(d) = \begin{cases} 1 iff m_2 \geq m_1 \\ 0 iff l_1 \geq u_2 & otherwise \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \end{cases} \tag{11}$$

$\vee(K_1 \geq K_2) = 1$ iff $\tilde{K}_1 = \tilde{K}_2$

Where, if and only if d is the ordinate of the highest intersection D between $\mu\tilde{K}_1$ and $\mu\tilde{K}_2$ (see Figure 4) (Zhu 1999).

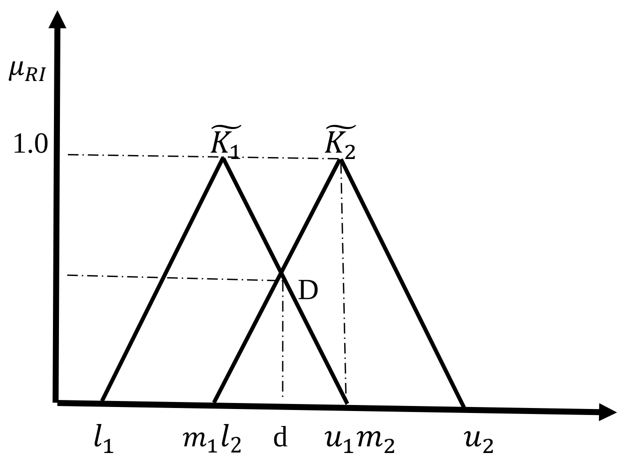


Figure: 4 The degree of intersection of two fuzzy sets

Using equations 10 and 11, Table 7 shows the weight vector for each decision alternative.

Table 7 Weight vector for each decision alternative

V ($S_{pwc} \geq S_{js}$)	1	V ($S_{js} \geq S_{pwc}$)	1	V ($S_{ag} \geq S_{pwc}$)	1	V ($S_{rt} \geq S_{pwc}$)	0.91
V ($S_{pwc} \geq S_{ag}$)	0.53	V ($S_{js} \geq S_{ag}$)	0.56	V ($S_{ag} \geq S_{js}$)	1	V ($S_{rt} \geq S_{js}$)	0.92
V ($S_{pwc} \geq S_{rt}$)	1	V ($S_{js} \geq S_{rt}$)	1	V ($S_{ag} \geq S_{rt}$)	1	V ($S_{rt} \geq S_{ag}$)	0.42
V ($S_{pwc} \geq S_{lf}$)	1	V ($S_{js} \geq S_{lf}$)	1	V ($S_{ag} \geq S_{lf}$)	1	V ($S_{rt} \geq S_{lf}$)	1
V ($S_{pwc} \geq S_{gca}$)	1	V ($S_{js} \geq S_{gca}$)	1	V ($S_{ag} \geq S_{gca}$)	1	V ($S_{rt} \geq S_{gca}$)	0.90
V ($S_{pwc} \geq S_{exp}$)	0.35	V ($S_{js} \geq S_{exp}$)	0.38	V ($S_{ag} \geq S_{exp}$)	0.81	V ($S_{rt} \geq S_{exp}$)	0.25
V ($S_{pwc} \geq S_{ef}$)	0.80	V ($S_{js} \geq S_{ef}$)	0.81	V ($S_{ag} \geq S_{ef}$)	1	V ($S_{rt} \geq S_{ef}$)	0.71
V ($S_{lf} \geq S_{pwc}$)	0.80	V ($S_{gca} \geq S_{pwc}$)	1	V ($S_{exp} \geq S_{pwc}$	1	V ($S_{ef} \geq S_{pwc}$)	1
V ($S_{lf} \geq S_{js}$)	0.92	V ($S_{gca} \geq S_{js}$)	1	V ($S_{exp} \geq S_{js}$)	1	V ($S_{ef} \geq S_{js}$)	1
V ($S_{lf} \geq S_{ag}$)	0.46	V ($S_{exp} \geq S_{ag}$)	0.66	V ($S_{exp} \geq S_{ag}$)	1	V ($S_{ef} \geq S_{ag}$)	0.78
V ($S_{lf} \geq S_{rt}$)	1	V ($S_{gca} \geq S_{rt}$)	1	V ($S_{exp} \geq S_{rt}$)	1	V ($S_{ef} \geq S_{rt}$)	1
V ($S_{lf} \geq S_{gca}$)	0.90	V ($S_{gca} \geq S_{lf}$)	1	V ($S_{exp} \geq S_{lf}$)	1	V ($S_{ef} \geq S_{lf}$)	1
V ($S_{lf} \geq S_{exp}$)	0.29	V ($S_{gca} \geq S_{exp}$)	0.52	V ($S_{exp} \geq S_{gca}$)	1	V ($S_{ef} \geq S_{gca}$)	1
V ($S_{lf} \geq S_{ef}$)	0.73	V ($S_{gca} \geq S_{ef}$)	0.85	V ($S_{exp} \geq S_{ef}$)	1	V ($S_{ef} \geq S_{exp}$)	0.60

The degree of possibility for a convex set fuzzy number to be greater than another convex set fuzzy numbers M_i $(i = 1, 2,3, 4,5,6, \dots \dots k)$ is given as (Kahraman 2006; Tolga 2005 & Zhu 1999):

$$\vee\left(M \geq M_1, M_2, M_3 \dots\dots M_k\right) = \vee\left[\left(M \geq M_1\right), \left(M \geq M_2\right) \dots\dots \left(M \geq M_n\right)\right] \quad (12)$$

$$= \min\ \vee\left(M \geq M_i\right), i = 1, 2, 3 \dots\dots\dots\dots n$$

Assuming that

$$A_i \min \vee\left(S_1 \geq S_k\right) \text{for k = 1... 3... 5…n} \qquad k \neq i. \quad (13)$$

Thus, the weight vector W is:

$$W' = \left[d'\left(A_1\right), d'\left(A_2\right), d'\left(A_3\right), d'\left(A_4\right) \dots\dots d'\left(A_n\right)\right] \quad (14)$$

Where, $A_i \in n$

The normalized weight vectors W (non-fuzzy number) can be gained below:

W = $(d'(A_1), d'(A_2), d'(A_3), d'(A_4), \ldots\ldots d'(A_n))$ (15)

Where, $d'(A_1)$ .... $d'(A_n)$ are decision alternatives

Table 8 shows the minimum weight vectors for each decision alternative, which were obtained from equation 12 to 13 (Chang 1996).

Table 8 The minimum decision vector for each decision alternative

d´(A_1)	V $(S_{pwc} \geq S_{js.}\ S_{ag.}\ S_{rt.}\ S_{lf.}\ S_{gca.}\ S_{exp.})$ = min (1, 0.47, 1, 1, 0.78, 0.21) = 0.21
d´(A_2)	V $(S_{js} \geq S_{pwc.}\ S_{ag.}\ S_{rt.}\ S_{lf.}\ S_{gca.}\ S_{exp.})$ = min (0.89, 0.37, 1, 1, 0.67, 0.11) = 0.11
d´(A_3)	(V $S_{ag} \geq S_{pwc.}\ S_{js.}\ S_{rt.}\ S_{lf.}\ S_{gca.}\ S_{exp.}$) = min (1, 1, 1, 1, 1, 0.76) = 0.76
d´(A_4)	V $(S_{rt} \geq S_{pwc.}\ S_{js.}\ S_{ag.}\ S_{lf.}\ S_{gca.}\ S_{exp.})$ = min (0.93, 1, 0.35, 1, 0.62, 0.11) = 0.11
d´(A_5)	V $(S_{lf} \geq S_{pwc.}\ S_{js.}\ S_{ag.}\ S_{rt.}\ S_{lf.}\ S_{exp.})$ = min (1, 1, 0.42, 1, 0.69, 0.2) = 0.20
d´(A_6)	V $(S_{gca} \geq S_{pwc.}\ S_{js.}\ S_{ag.}\ S_{rt.}\ S_{lf,}S_{exp.})$ = min (1, 1, 0.73, 1, 1, 0.51) = 0.51
d´(A_7)	V $(S_{exp} \geq S_{pwc.}\ S_{js.}\ S_{ag.}\ S_{rt.}\ S_{lf.}\ S_{gca.})$ = min (1, 1, 1, 1, 1, 1) = 1
The weight decision alternative based on their influence and the normalization.	W = (0.21, 0.11, 0.76, 0.11, 0.20, 0.51, 1) W = (0.07, 0.04, 0.26, 0.04, 0.07, 0.18, 0.34)

Figure 5 illustrates the importance of each decision alternative using the extent analysis procedure. It ranks experience as the most critical human factor that affects human-centred performance as it accounts for 34% of the effect, followed by age (26%), general cognitive abilities (18%), physical work capacity (7%), learning and forgetting (7%), reaction time (4%) and job satisfaction (4%), which have the least effect on human performance.

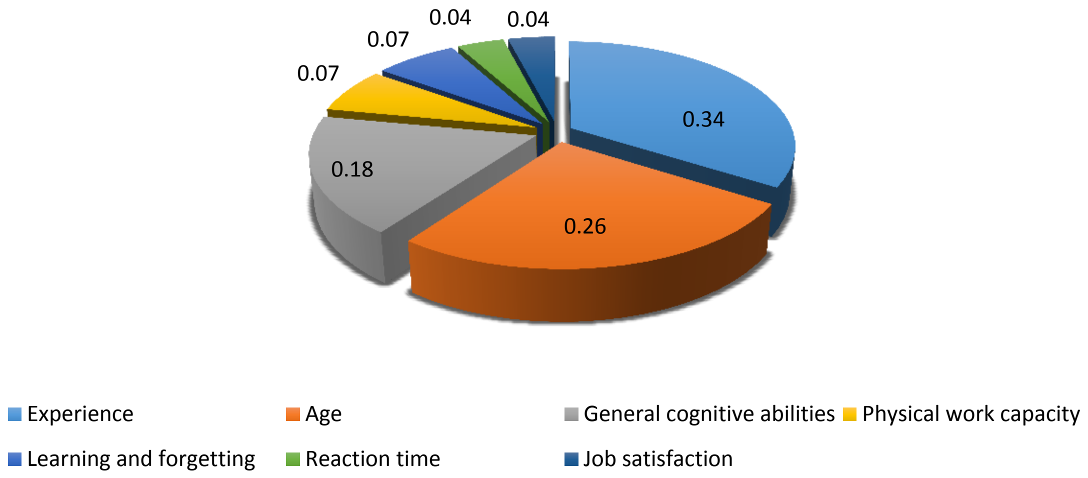


Figure: 5 Synthesized priorities of human factors affecting human-centred performance

The significance of each of human factors was converted into a global weight as shown in Table 9.

Table 9 Rating of human factors significance on human-centred assembly performance

Human Factors	Global weight	Level of influence
Experience	1	Very high
Age	0.76	Very high
General cognitive abilities	0.51	High
Physical work capacity	0.21	Low
Learning and forgetting	0.20	Low
Reaction time	0.11	Low
Job satisfaction	0.11	Low

According to the study, one of critical human factors that significantly affect human-centred assembly performance is the effect of ageing. Ageing workers are defined by the International Labour Organisation (ILO) as workers who are liable to encounter difficulties in employment and occupation because of advancement in age (Asogwa et al. 1993). Gerontologists classified the ageing population into three groups: group at ages between 60 to 74 years old, group at ages between 75 to 85 years old, and group at ages of 80 years old and beyond (Mendonca 2017). Whilist World Health Organisation (WHO) defines an ageing person older than 45 years old (Asogwa et al. 1993; Peruzzini & Pellicciari, 2017). Regardless of various interpretations, the percentage of older workers at ages between 55 to

64 years have risen by 50% in the past two decades, and may continue to rise (Boenzi et al. 2015). Ageing can cause the persistant decline in the biological components due to the internal physiological deterioration (Kenny et al. 2015). There is evidence that individual performance may decline from a certain age due to the natural decline of physical and physiological functions, such as visual ability, musculoskeletal force, flexibility/motion capability, memory/concentration and thermoregulation (Skirbekk 2008; Peruzzini & Pellicciari 2017; Robertson & Tracy 1998).

In manufacturing, assembly by human workers involve operations of pinching, gripping, screwing, pulling, pushing, lifting, turning and so on. It requires repetitive wrist motions and hand postures, which may be associated with tendon disorders of hands and wrists leading to loss of productivity due to pain and fatigue (Palmer et al. 2006). Studies indicated that job performance of most individuals may increase until the age of 35 years old; after this age it may steadily decline. It can decline up to 25% at ages from 45 to 64 years old (Skirbekk 2008; Peruzzini & Pellicciari 2017). Zwick & Gobel (2009) investigated the effects of ageing on productivity and observed that productivity may increase until the age of 40 years old; with more significant decline after the age of 60 years old. However, Leyk et al. (2010) argued that losses in human performance are primarily related to a sedentary lifestyle rather than a chronological number of years. Generally, female workers are physically weaker than male workers and strength of female workers is approximately two thirds of male workers. Nevertheless, as worker's age increases, it is expected that their experience also increases. And this may offset the decline of human abilities (Warr 1994; Salthaouse & Somberg 1982; Giniger 1983). In this study, however, it was assumed that human natural decline of physical, physiological and cognitive systems over increase of age is unavoidable, subjected to individual habitual adaptation (such as poor health, inactive lifestyle, smoking, poor diet, substance abuse and so on). And the ability of an organizations to accommodate and protect workforce particularly in the context of employment standards (Chaffin 2006; Skirbekk, 2008). Table 10 shows a summary of findings through a literature review relating to the decline of human functons over age.

Table 10 Literature studies in decline on of human functional abilities over age

Ability	Functions	Performance variations	Authors
Endurance	Aerobic capacity	Peak at the age of 40 and decline by 1% per year after this age	Robertson & Tracy 1998

		Peak at the age of 30 and decline by 0.5–1.5 % per year	Bellew 2005; Savinainen 2004a
		Decline by 1–1.5 % per year after the age of 40	Boenzi et al. 2015
		Decline by 1% per year after the age 30	Hawkins & Wiswel 2003
		Decrease by 1% per year after the age of 35	Crawford 2010
Psychomotor	Spatial ability	Peak at the age of 30 and decline at 1% per year after this age	Ellis et al. 1999
		Peak at the age of 40 and decline between 0.8 and 1.0% per year after this age	Basu 2002
		Peak at the age of 30, decline by 0.5% per year up to the age of 40 and then decline by 1% every yeat up to the age of 65	Aoyagi 1992; Gall 2004
		Peak at the age of 45 and decline by 1–1.5% per year after this age	Savinainen 2004b
		Peak at the age of 40 and decline by 0.8–1% per year after this age	Fleg et al. 2005
Akward posture	Flexibility	Peak at the age of 35 and decrease at about 1.0% per year from 35 to 54	Alaranta 1994
Overall performance	Physiological function	Peak at the age of 35– 40 and decline by 1% per year after these ages	Asogwa 1993; Savinainen 2004; Ilmarinen 2002

4. Numerical result and analysis

Based on studies shown in Table 10, Table 11 shows the remaining functional capacity (%) of his/her peak at age 38 due to human functional decline over varying ages using the regression analysis equation 16. It shows that human performance starts to deteriorate at 38 years old as a base line. It also shows loss rate, which refers to the rate of decline after the age of 38 years old. Figure 6 shows the trend in decline of human functional capacity at varying ages after 38 years old.

$L_r = 0.57 + 0.012k_1$

(16)

Where

L_r = Loss rate in percentage

k = Age in years

$F_{rm} = k_2 - L_r\left(k_1 - 38\right)$

(17)

Where:

F_{rm} : Remaining capacity in percentage of the peak at 38 years old

k_2: Peak capacity (100%) at 38 years old

L_r: Loss rate in percentage

k_1 : Existing age in years

Table 11 Human functional decline in percentage over age

Age	Loss rate (L_r)	Remaining functional capacity (%) of his/her peak at age 38 (F_{rm})	Human kinematic decline rate (%) of his/her full capacity
38	0	100	0
40	1.05	97.9	2.01
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
75	1.47	45.61	54.39
80	1.53	35.74	64.26

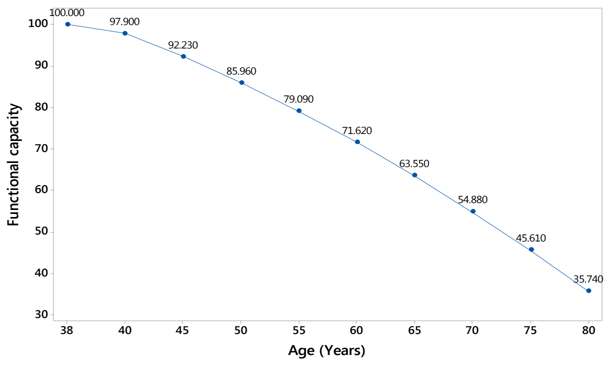


Figure: 6 Decline in human functional capacity after 38 years old

4.1 Learning effects

One of learning effects refers to a trend in reduction of production time as quantity of products increases (Jaber & Bonney 1997). Human learning pattern during production cycles can be represented by a log linear model (equation 18), which is widely used as a learning curve for predicting individuals' performance through a learning process (Jaber 2001):

$$T_n = T_t \,.\, Q^c \tag{18}$$

Where

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

T_t: Assembly 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 the learning rate R is measured in percentage (0 < R < 1) (Anzanello & Fogliatto, 2011). Note that the average time towards the steady state decreases with the increase in numbers of units produced. Thus, the average time towards a steady stage can be given as:

$$T_A = T_t \bullet B^R$$

(19)

or

$$T_t = \frac{T_A}{B^R}$$

(20)

Where

T_A: The average-time towards a steady stage

B: Batch size

By substituting equation 20 into equation 18, it yields:

$$T_n = \frac{T_A}{B^R} \bullet Q^R$$

(21)

Hence

$$T_n = T_A \left(\frac{Q}{B} \right)^R$$

(22)

Figure 7 shows the trend of average assembly time corresponding to accumulative number of units produced by workers at the age of 38 years old during a learning process of repetitive operations of assembling a unit based on the result obtained using equation 22. It can be seen that the average assembly time tends to be stabilised after performing over 480 units.

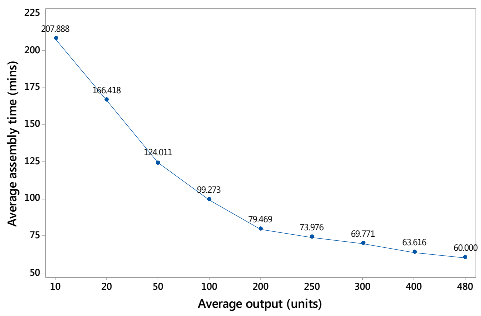


Figure: 7 Average assembly time (mins) vs accumulated output of workers at 38 years old

The loss in average assembly time per worker due to ageing is given below:

$$\Delta_{Lt} = T_n \times F_{dl}$$

(23)

Where

F_{dl} : Kinematic decline rate (%) of human full capacity (as shown in Table 11)

$$\Delta_{LT} = T_A \left(\frac{Q}{B} \right)^R \times F_{dl}$$

(24)

Hence, average total assembly time per worker associated to ageing is computed below:

$$T_{At} = T_A \left(\frac{Q}{B} \right)^R + T_A \left(\frac{Q}{B} \right)^R \times F_{dl}$$

(25)

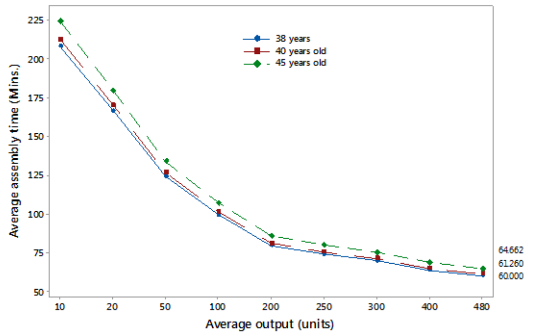
Where

Δ_{Lt}: Average assembly time loss due to ageing

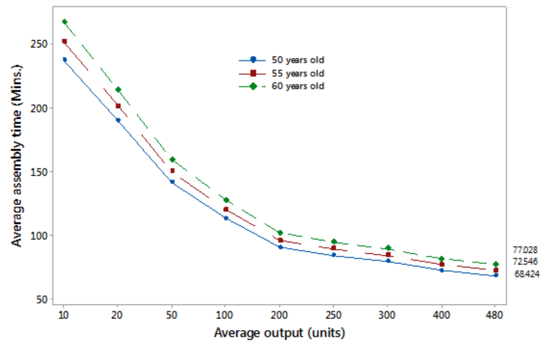
T_{At}: Average total assembly time per worker due to ageing

4.2 Analysis in a range of ageing groups

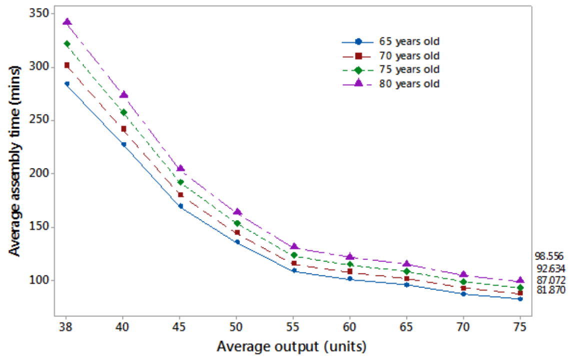
Assuming an assembly line in which a worker has to assemble 480 units of a product and he/she is expected to be proficient at the job after 60 minutes. Figure 8 shows the average assembly time for each group of assembly workers over the accumulative number of assembled units at varying ages from 38 to 80 years old. Overall, it can be seen in Figure 9a that average assembly time drops over the increasing number of output (in units) for all the ageing groups. It can also be seen that average assembly time for the ageing group of 38 years old is 60 minutes, which is less than 64.66 minutes for the ageing group of 45 years old. Although there is an insignificant difference in average assembly time of the ageing groups between 38 and 40 years old. Figure 8b and c show an average assembly time of the ageing groups from 50 to 80 years old. By comparing the average assembly time of the ageing group at 38 years old, it can be seen that the average assembly time increases approximate 1% per year from the ages of 38 to 70 years old and about 1.5% from the ages of 70 to 80 years old.



(a)



(b)



(c)

Figure: 8 Average assembly time of an ageing group of workers

5 Summary and discussions

Through the literature study, although there were some investigations into human factors relating to human performance, there were few studies by examining human factors and their interections on human performance of human-centred assembly systems. This paper presents a study by identifying the relevant human factors that may have impacts on human-centred assembly based on findings of the literature review and the industrial survey. This includes the proposed alternative methods used for quantifying the influential levels between one of key human factors and one of key performance indicators. The study shows that individual performances of human workers usually approach their full capacity at the age of 38 years old. After this age, it may decline over the increase of ages of workers. By contrast, the literature study also implies that work experience grows over the increase of age of workers leading to improvements of individual performance, which may also compensate the loss of assembly time of ageing workers. The study concludes age and experience are the most influential human factors that may affect human performance; this can be useful for line managers for decision makings in selection or evaluation of assembly workers for production. An on-going study is being carried out by incorporating the identified human factors into a DES (discrete even simulation) tool that is often applied as an aid for manufacturing systems design and evaluation. Current DES tools in the market do not have functionality allowing manufacturing systems designers to create a DES model that considers effects of human factors or human performance for production. This is because, for example, in a DES model, the workers are defined and treated as a simple resource the same as parts, machines, conveyors and so on. The application of DES simulation models is therefore restricted to predicting such variables as the required number of workers, their shift patterns and routes (Wang et al. 2012). These issues need also to be addressed more in future for DES packages in applications and development of manufacturing system related designs and operations.

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