

2. REVIEW OF LITERATURE

2.1 Speed-Accuracy Tradeoff

A number of researchers have shown that there is a relationship between speed and accuracy for a reachable movement task (Fitts, 1954; Meyer et al., 1988; Schmidt et al., 1979; Welford, 1968). Many formulas for predicting movement time have been proposed.

In step-tracking tasks such as assembling a chip on a printed circuit board, movement time would be affected by the distance of the movement as well as the accuracy. Fitts defined the index of difficulty to characterize the task by using distance or amplitude (A) and tolerance (W) values:

$$Id = \log_2\left(\frac{2A}{W}\right), A > \frac{W}{2} \quad (1)$$

As the amplitude increases or the tolerance decreases, the value of index of difficulty (Id) increases, indicating that it is harder to complete the task. In addition, the equation essentially indicates that Fitts justifies the ratio between movement distance and accuracy equally.

Inspired by analogy from Shannon's Theorem 17 (Shannon et al., 1949), Fitts developed an equation to predict movement times in upper extremity movement tasks. Fitts conducted three sets of experiments involving reciprocal tapping, disc transfer, and pin transfer tasks. The results showed a linear relationship between Movement time (MT) and Id :

$$MT = a + b * Id \quad (2)$$

where a and b are empirical constants varying upon nature of movement. Various investigators have simplified this equation by applying this formula without the first term of the equation “ a ” (Barfield et al., 1987; Repperger et al., 1995)

Next, Fitts defined an Index of Performance, I_p , to describe a human performance rate in performing a particular task over a wide range of movement amplitudes and clearances. The formula was defined as:

$$I_p = \frac{Id}{MT} \quad (3)$$

Fitts’ Law has been confirmed and broadly applied by many investigators. Later, through a series of five experiments involving discrete movement tasks, Fitts and Peterson (1964) confirmed that moving time was highly correlated with Fitts’ Id . Kerr and Langolf (1977) found the logarithmic tradeoff to hold with tasks involving throwing in the sagittal plane. Drury (1975) obtained the tradeoff to predict foot movement times. Fitts’ Law has also been confirmed by Chukwu’s research (1990). Chukwu found that Fitts’ Law was applicable to movement tasks under different levels of visual guidance such as direct vision, limited vision, and screened vision. Not only was Fitts’ Law applied to measure human performance, but Shinar (1986) concluded that it can also be used to describe movement time for both directed hand movements and remotely controlled robot movements.

Fitts’ Law has been widely referred to as a movement time predictor for human aiming tasks; however, the true basis of this law may not be understood. Connelly (1984)

mathematically analyzed the law using first order model where movement velocity can be controlled and a second order where movement acceleration can be controlled. The results showed that Fitts' law could be represented by the first and second order models with a linear control law. In addition, Phillips and Repperger (1997) also derived the law by using basic control theory. However, Phillips suggested that the human movement system is more complex than that.

As Fitts' law presented a relationship between speed and accuracy for a one-dimensional translational motion, some researchers have adapted the law to measure an angular motion neuromuscular channel capacity as well (Kondraske, 1994; Wong, 1994). The term $(2A/W)$ was considered as a probability and replaced by $(2\theta_a/\theta_w)$. The index of difficulty for angular movement is defined as:

$$Id(\theta) = \log_2\left(\frac{2\theta_a}{\theta_w}\right), \theta_a > \frac{\theta_w}{2} \quad (4)$$

where θ_a is angular movement amplitude and θ_w is angular target width. From the experimental results, Kondraske (1994) concluded that Fitts' law is applicable to model human angular movement.

Even though many researches have indicated a substantial correlation between Fitts' Id and movement time in various kinds of point-to-point tasks, several investigators have proposed other formulas for some specific tasks. Welford (1968) discovered that Fitts' law acceptably fits all data except for very short and very long movement times. Welford proposed a number of alternatives to the Fitts' law such as:

$$MT = K \log \left(\frac{A}{W} + \frac{1}{2} \right), A \geq \frac{W}{2} \quad (5)$$

where K is a constant. In addition, Schmidt, Zelaznik, Hawkins, Franks, and Quinn (1979) found that the relationship between speed and accuracy was linear for a movement times ranging from 140 to 200 msec, while errors were unconstrained. Schmidt proposed speed-accuracy tradeoff as:

$$MT = K \left(\frac{D}{W_e} \right) \quad (6)$$

where K is a positive constant, D is the amplitude of movement, and W_e is the standard deviation of the errors in positioning accuracy. Another speed-accuracy tradeoff approach, stochastic optimized-submovement model, was proposed by Meyer et al (1988). Meyer described that the greater velocities reduced first submovement time but increased the probability for the second (correction) submovement. Meyer discovered that the expected movement time is an optimized tradeoff between the duration of each submovement and came up with a model as:

$$E[MT] \approx a + b \left(\frac{A}{W} \right)^{\frac{1}{2}} \quad (7)$$

where a and b are constant, A is a movement amplitude and W is a target width. This model has been validated by several sets of experiments (Meyer et al., 1988).

These studies indicated that each type of movement that occupies different sets of mechanisms might be appropriately described by different models. Since the concentration of this study is on heavy-part movement tasks, which requires dependent

two-handed human operation, it is necessary to study the speed-accuracy tradeoff relationship for such tasks.

2.2 Design for Assembly Method

In today's competitive world of manufacturing, it is critical to enhance the processes of product development since the design of products determines the methods of assembly, and consequently defines the assembly time and costs of the products. The design for assembly (DFA) method is one of the approaches that improves the Design/Manufacturing interface. The objectives of DFA are to simplify the manual assembly processes, improve quality, minimize lead-time, lower overhead, and most importantly reduce total assembly cost. During the past few decades, many DFA methods have been developed.

One of these methods was introduced by Boothroyd and Dewhurst in 1983. It is a systematized and quantified methodology to assess the simplicity of assembly, based on a large amount of empirical data gained from observations of people and machines performing assembly tasks. To consider a comparison among alternatives of designs, Manual Design Efficiency is derived by using the following equation:

$$\text{Manual_Design_Efficiency} = \frac{3 * \text{Theoretical_Minimum_Number_of_Parts}}{\text{Total_Manual_Assembly_Time}} \quad (8)$$

Theoretical Minimum Number of Parts is the number of parts that cannot be eliminated or combined with other parts. Boothroyd and Dewhurst Charts provide the estimated time of handling and insertion of each part, which is added up to be Manual Assembly Time. However, this method is merely used to compare among different choices of existing designs. It does not help in exploring new alternatives to compete with the existing ones.

Moreover, Boothroyd's DFA method is limited by the estimated time provided by the charts, which might not be enough to capture the actual assembly difficulty.

Later in 1989, Sturges developed an analysis system to evaluate the difficulty of handling and assembling of objects, considering the geometric features of a part and the assembly process, called "Design for Assembly Calculator". Based on Fitts' index of difficulty (ID), the system quantifies the dexterity and assembly time. The indices of difficulty of various assembly tasks are compared and the manual assembly time can be obtained by multiplying them by the human motor capacity. The Design for Assembly Calculator provides an index of difficulty for the tasks and, practically, gives immediate comparative evaluations and analysis of designs and methods.

The methods mentioned apply well to parts that are relatively light and small. However, in heavy part assembly tasks, there are additional difficulties due to its weight, mass, size and inertia, which is yet to be adequately treated. Wong and Sturges (1994) conducted experiments similar to Fitts (1954) to find the relationship between the parts' weight, Index of performance and assembly time. The results indicated that the parts' weight and mass affect index of performance in the same way. In other words, the assembly time will not vary by being changed to a weightless environment. A formula to calculate movement time with the effect of weight was proposed as:

$$MT = Id (100 + m * Weight) \quad (9)$$

where m is the slope value taken from the graph plotted between $1/I_p$ and the parts' mass. In addition, the results also showed that there was a linear relationship between moment of inertia and index of performance. Wong suggested that only small changes of the

moment of inertia of a part might greatly increase the assembly time. An assembly time predicting equation is proposed as:

$$MT = Id(100 + n * Inertia) \quad (10)$$

where n is the slope value taken from the graph plotted between $1/I_p$ and the parts' moment of inertia.

2.3 Ergonomics in Heavy Parts Manufacturing and Assembly Operations

Poor ergonomics, especially in heavy-part manufacturing, is a major factor in impeding productivities and increasing worker injuries. To improve the ergonomics of manufacturing and assembly environments, most companies implement several kinds of material handling systems, both automatic and manual in their production. Examples are industrial manipulators, workstation cranes, lift tables, positioners and balancers, pallet stackers, specially designed conveyers and tilt tables. However, in many situations, workers still have to lift and carry parts with their hands. For this reason, it is necessary to understand the ergonomics of heavy-part manufacturing.

Lifting Technique

Lower back pain is one of the most leading injuries in heavy-part manufacturing industry (Bonica, 1980; Rosomoff, 1985). Most of the causes attributed to lifting, bending and other body motions due to excessive weight and incorrect positioning. Over the past several years, various investigators proposed different techniques in manual lifting; however, there is no scientific approach to effectively reduce the risk of lower back pain injuries.

Several investigators proposed straight-back, bent-knee lift as a preferred posture because a person could squat down with the feet beside the object allowing the load to be held close to the torso while lifting to minimize the bending moment and compressive force on the back (Anderson, 1970; Davis, 1959; Floyd, 1958; Himbury, 1967; Munchinger, 1962; Nachemson, 1971). However, when an object is too large to straddle, one must lift the object around the knees, resulting in excessive stresses on one's back

and knees. Furthermore, during the squatting, the feet may not be flat on the floor and the knees are acutely flexed. These result in insufficient thrust to lift the load smoothly (Davis et al., 1965; Owen, 1985).

Over the past decades, there were many other lifting techniques proposed such as kinetic method of lifting (Anderson, 1970; Davies, 1978; International Labor Office, 1967), squat position with flexed back (Adams et al., 1985; Williams, 1974), squat posture, straddle foot stance and flat back (Anderson et al., 1986), and Back flexed and knees slightly flexed (Cailliet, 1981). Unfortunately, there is no proof to indicate which method is safer than the others.

Lifting Capacity

A psychophysical approach proposed by Snook and Irvine (1967) served as an influential framework for the scientific investigation of human capacities in manual handling tasks. It has been used to determine the maximum acceptable weight of lift (MAWL) for almost three decades. MAWL is the weight chosen by the participant on his/her own preference to lift under given task conditions, according to his/her feelings of exertion or fatigue. Based on the assumption that workers are capable of determining the highest acceptable workload they could sustain over an 8-hour shift, the psychophysical approach points to quantify human lifting capacity based on perception of workers' exertion level. However, there is no evidence that this technique can eliminate back pain and musculoskeletal injuries of the workers. Later, Karwowski (1996) introduced a new set of instructions to determine the maximum safe weights of lift (MSWL). In this instruction set, the participants are asked to picture working safely over an eight-hour

workday, and to determine the weight they could safely lift without raising the risk of lower back pain or muscular overexertion.

Many research efforts have focused primarily on task variables that affect the preferred weight, such as, symmetrical/asymmetrical lifting, frequency of lift, heights at the bottom and top of a lift, horizontal distance, configuration of the container handled, age, body weight and other task variables (Ayoub et al., 1980; Kassab et al., 1976). It is claimed that asymmetrical lifting is more physically stressful due to significant lateral torsional strain, and the workers are able to lift heavier weights symmetrically (Bhattacharya et al., 1982; Sanchez et al., 1992; Mital et al., 1983). Moreover, substantial differences also exist in the effects of frequency on the maximum acceptable weight of lift between students and experienced workers (Mital et al., 1983). The acceptable weights of the experienced workers are higher than that of the student population, however, the trends for both populations are almost the same.

In 1981, the National Institute for Occupational Safety and Health (NIOSH) published the Work Practices Guide for Manual Lifting (NIOSH WPG, 1981) due to the growing problem of work-related back injuries. It contained a summary of the lifting-related literature, including analytical procedures and a lifting equation for calculating a recommended weight for specified two-handed, symmetrical lifting tasks. This Manual was revised in 1991 to provide a modified equation that can be applied to various lifting tasks.

The equation principally provides the recommended weight limit (RWL), which is a specific set of task conditions as the weight of the load that nearly all healthy workers

could perform over a substantial period of time without a greater risk of developing lifting-related low back pain (LBP) (Walter et al., 1993). The following is the revised equation that defines RWL.

$$\text{RWL} = \text{LC} \times \text{HM} \times \text{VM} \times \text{DM} \times \text{AM} \times \text{FM} \times \text{CM} \quad (11)$$

The equation consists of the load constant (LC), which is 51 pounds, and various multipliers referring to the reduction coefficients (i.e. HM, VM, DM, AM, FM, and CM). The values of these variables vary from zero to one, indicating that in the ideal situation where all of the multipliers are equal to one the maximum recommended weight would be equal to 51 Lbs. The recommended weight decreases as the task becomes more stressful. The following are the descriptions of the multipliers applied in the equation.

Horizontal multiplier (HM) takes into account the horizontal location of hands away from the midpoint between the ankles.

Vertical multiplier (VM) expresses the effect of vertical location of the hands from the floor.

Distance multiplier (DM) represents the differences caused by absolute value of vertical travel distance between the origin and the destination of the lift.

Asymmetric multiplier (AM) stands for the reduction of RWL caused by angle of asymmetry or how far the object is displaced from the front of the worker's body at the beginning or end of the lift.

Frequency multiplier (FM) refers to reduction coefficient from frequency rate of lifting measured in lift/minute over a 15-minute period.

Coupling multiplier (CM) takes into account the quality of hand-to-object coupling, which is categorized as good, fair, or poor, depending on the type and location of the coupling, the physical characteristic of the load, and the vertical height of the lift.

Team Lifting

Separate from automated or motored material handling, team lifting is a common alternative for handling material when the heaviness of the part exceeds the capacity of one person. A number of researchers reported that the lifting capacity of a team is less than that of the sum of individual isometric lifts. For a two-person team, Karwowski and Pongpatanasuegsa (1988) found that the percentage of the sum of individual lifting strengths represented by the team lifting strength are 90%. Sharp, Rice, Nindl, and Williamson (1993) reported 85% for three-person team and 86% for four-person team as a percentage of the sum of individual lifts. Other investigators reported that the lifting capacity of the team is indicated by the weakest of the members (Rice et al., 1995).

2.4 Predetermined Time Standard Systems

Determining the amount of time required to finish a job is an important task, assisting in determining the costs of manufacturing. Thus, Predetermined Time Standard Systems (PTS) is used as a field of work measurement to estimate the time needed by qualified workers to perform a particular task at a specified level of performance. The systems set the standard time based on the motion used, their nature, the condition under which they occur, and their previously determined performance time. There exist three currently renowned computerized PTSs: Methods-Time Measurement (MTM), MODular Arrangement of Predetermined Time Standard (MODAPTS), and Maynard Operation Sequence Technique (MOST).

One of the most well known PTSs is MTM, which divides any operation into a set of single basic motions. MTM-1, the most detailed PTS, has 7 categories of actions (Obtain, Locate, Rotate, Force, Recoil, Visual and Body) consisting of 26 single motions used to explain manual activities (MTMA, MTM-1 User Manual, 1978). Later on, MTM-2 was developed to make use of a simpler application of MTM-1. Similar to the concepts of DFA, PTSs takes into account the movement distance, clearance, and weight of the part to determine the standard time of a particular task. In MTM-1, the distance of movement directly affects the time required in Reach and Move motions. Clearance considered in MTM-1 does not go deep down in much detail, instead, it is classified into 3 levels, i.e. place against stop, place to approximate location, and place to exact location. Weight also has effects on time needed in that the weight held adds an initial time delay, plus a proportional delay, as defined as follows;

Total Movement Time = Constant + Factor * (Movement Time without Weight)

Additionally, MTM-2 considers weight of load as the factor that increases time required. That is, each of two pounds would add 1 TMU (0.00001 hour) for Get Weight motion.

MOST is a simplified outgrowth of MTM originally developed in Sweden in 1967 (Zandin, 1980). It allows a 5 times faster determination of standard time than MTM-1 while sacrifices only an insignificant accuracy. MOST utilizes even fewer time fragments than MTM-2, based on the principle of combining simple small motions together to form sequenced models. It identifies three basic sequence models: general move, controlled move, and tool use. In addition to the mentioned three basic models, an equipment-handling sequence is also available to analyze the movement of heavy objects that require a manually operated or powered crane.

In 1966, MODAPTS was first introduced in Australia for manual factory work. Afterward, a version for office work, called OFFICE MODAPTS, was developed followed by TRANSIT MODAPTS, which is for heavy work (Heyde, 1983). The principle of MODAPTS is that the time taken for any movement can be specified in terms of a multiple of the time taken for a single finger movement. It assumes that normal finger, normal hand, forearm, full arm and shoulder movements need $1/7$, $2/7$, $3/7$, $4/7$ and $5/7$ of a second to perform respectively. In addition, RECOVERY is a special feature of MODAPTS to compensate the standard time for heavy physical work. Based on energy expenditure, it determines how long each rest period should be and how frequently the rest periods should occur.