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REASONING: SOURCE OF VARIABILITY IN THE BOOTHROYD AND DEWHURST ASSEMBLY TIME ESTIMATION METHOD

Essam Namouz
Research Assistant
Industrial Engineering
Clemson University
Clemson, SC, USA
enamouz@clemson.edu

Joshua D. Summers
Associate Professor
Mechanical Engineering
Clemson University
Clemson, SC 29634-0921
jsummer@clemson.edu

Gregory M. Mocko
Assistant Professor
Mechanical Engineering
Clemson University
Clemson, SC 29634-0921
gmocko@clemson.edu

ABSTRACT

This paper evaluates the effect of making a subjective decision in a design for assembly time analysis. An example is found in the first set of questions for estimating handling time of a part the user chose "parts are easy to grasp and manipulate" as opposed to "parts present handling difficulties". The subjectivity is explored through a study of assembly time estimates generated by a class of mechanical engineering students in the time analysis of a clicker pen based on the Boothroyd and Dewhurst estimation method. The assembly times calculated by the class ranged from a minimum of 23.64 seconds to a maximum of 44.89 seconds (range of 21.25 seconds). This large range in results serves as motivation in determining the effect that answering a subjective decision has on the resulting assembly time estimate. Initial results indicate that not answering the first level of subjective questions will result in assembly time estimate within 15% of the time had the subjective question been answered. The probability density plots of the time estimates also indicates that 63% of the time, the estimated assembly time without making the subjective decision will fall within the normal distribution had the subjective decision been made. This provides evidence that there is an opportunity to reduce the amount of subjective questions that a user must answer to estimate the assembly time of a product.

Keywords: Design for Assembly, Information Subjectivity, DFA, Assembly Time, DFM, DFMA

1.ASSEMBLY TIME ESTIMATION

Design for assembly (DFA) is a well-accepted technique that is based on empirical studies, and is used for analyzing products with the goal of reducing the assembly time. One method within the larger set of DFA approaches is an assembly time estimation method developed by Boothroyd and Dewhurst. This paper explores the subjectivity that is inherent within the method.

Assembly time reduction has become a common focal point in an effort to reduce manufacturing costs[1–16] . Design for Assembly is an approach for improving parts and systems as well as providing guidelines to assist designers in creating more assembly friendly components [17]. Use of the design for manufacturing and design for assembly approaches can help reduce the cost of manufacturing, reduce component count, and increase quality, while increasing yield manufacturing output [12].

One method developed by Boothroyd and Dewhurst estimates the assembly time of a product by focusing on estimating a handling time and an insertion time. A user implements the assembly time estimation method by navigating a set of hierarchical charts in which each level requires additional information about the part to be input by the user [18]. The information provided by the user about the part determines the route that will be travelled down the chart, and results in a handling code and insertion code, from which the user can directly retrieve the associated assembly times. The handling time and insertion time are then summed to determine the overall assembly time of a part. While a number of other assembly time estimation methods exist, such as motion-time method (MTM), this research will focus specifically on the Boothroyd and Dewhurst manual assembly time estimate method.

Boothroyd and Dewhurst empirically developed a set of charts that are used to estimate the assembly time of different products [12]. The charts are used to estimate the assembly time of a product based on two categories: handling and insertion. The user would determine a two-digit handling code based on part information such as number of hands needed to handle, the size of the part, and whether the parts nested or tangled together. The two-digit code can then be used to determine the estimated handing time of the part. The same procedure would be followed to determine the insertion time of the part. The two times would then be summed to determine the total assembly time for that part. This would be repeated for all the parts of a system to determine the assembly time of the complete system. Typically the best values of the charts, i.e. the lowest assembly times, are found in the upper left corner while the assembly time increases towards the lower right corner, but this is not always the case [19].

The tables are a collection of historical time data for assembly of different components. A portion of the handling table is shown below in a decision tree type of representation (Figure 1), and based on a choice the user makes reveals more possible decisions until the user arrives at the associated handling or insertion code.

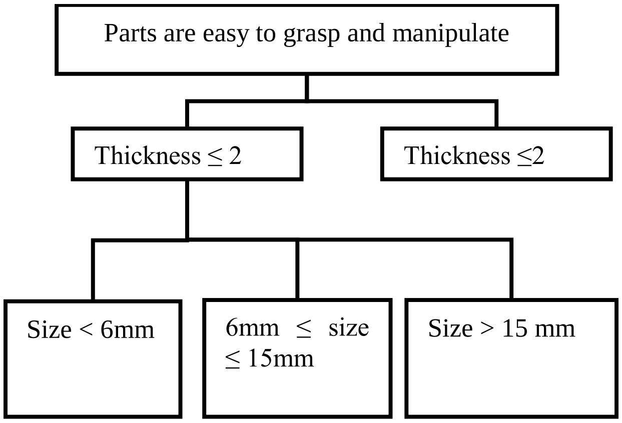

Figure 1: Partial Handling Code Decision Tree (Adapted from [12]**)**

The time estimate charts are a manual method to estimate the assembly time of different parts. Boothroyd and Dewhurst Inc. have implemented the time estimate method into a computer tool that can assist designers in estimating assembly time[1].

2.RESEARCH PURPOSE

The overall goal of this research is to automate the Boothroyd and Dewhurst assembly time estimation method by retrieving information from CAD software. While previous research has shown the benefits of implementing DFA approaches in industry [15], often DFA approaches are not used due to the amount of time required to train engineers in the use of DFA and the time required to conduct the analysis [12]. In an effort to decrease the amount of time and effort needed to implement the assembly time estimation portion of DFA, a tool is desired to retrieve information from CAD and reduce the amount of information required from the designer.

Computer software can be used to retrieve, interpret, and analyze quantitative parameters such as product size, weight, and symmetry. However, the Boothroyd and Dewhurst charts include a number of questions that are subjective, and require input from the designer conducting the analysis. To minimize the amount of information required from the designer, this paper will focus on the subject questions in the Boothroyd and Dewhurst assembly time estimate method, and the effect that these questions have on the variability and repeatability of the results. The results of an initial pilot study in which senior level mechanical engineering students conducted a DFA analysis to predict the assembly time of a pen will be discussed. To preface the discussion of the results of an assembly time estimation pilot study, a discussion on subjectivity is needed.

A subjective question is any question in which if given to multiple users, does not result in the same answer commonly based on an individual’s feelings or thoughts [20]. The question “Parts are easy to grasp and manipulate” or “Parts present handling difficulties” is an example of a subjective question. An objective question on the other hand can be answered by multiple users and arrive at an identical answer [20]. For example, in the handling charts one of the questions asks if the part thickness is greater than two or less than or equal to two. The thickness is a parameter of the part and if given a part all users would be able to identically answer this question. To analyze the sensitivity of the B&D time estimate charts, the charts are divided into levels based on the subjective questions in the chart. For example, the “ONE HAND” handling chart displays only one level of subjectivity (see Table 1). The only subjective question that needs to be answered by the user is the choice between “parts are easy to grasp and manipulate” and “parts present handling difficulties”. The bold numbers in the chart (1-9) are one of the digits of the handling code, and the estimated time for that handling code is seen below it. The times in the chart are based on empirical data in manufacturing [12]

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[1] http://dfma.com/ , accessed on 2/19/2012

Table 1: Level 1 Subjectivity for Handling Chart [12]

Easy to grasp and manipulate					Present handling difficulties				
T > 2			T <= 2		T > 2			T<=2	
S> 15	15>=S >=6	6> S	S>6	S <= 6	S > 15	15>=S >=6	S<6	S>6	6>=S
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
** T: Thickness (mm), S: Size (mm)									
**All times in seconds									

■	**Level 1 Subjectivity**

The insertion chart (Table 2) requires that three subjective questions be answered in order to determine an insertion time, resulting in three levels of subjectivity.

Table 2: Subjectivity Levels for Insertion Chart [12]

After assembly, no holding down required to maintain orientation and location				Holding down required during subsequent processes to maintain orientation or location			
Easy to align and position during assembly		Not easy to align or position during assembly		Easy to align and position during assembly		Not easy to align or position during assembly	
No resistance	Resistance	No resistance	Resistance	No resistance	Resistance	No resistance	Resistance
0	**1**	**2**	**3**	**6**	**7**	**8**	**9**
1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
**All times in seconds							

■	**Level 1 Subjectivity**
▨	**Level 2 Subjectivity**
□	**Level 3 Subjectivity**

The subjectivity levels are defined from the bottom to the top of the charts. The latest subjection question that must be answered to determine the insertion/handling time would be Level 1, the next question subjective question while traveling back up the chart would be Level 2, and the final set of questions would be Level 1.

This research will focus on the results of a pilot study to measure the effect of subjective questions on the estimated assembly time. Specifically this initial study will focus on Level 1 subjectivity for handling and insertion.

3.PILOT STUDY

A senior level mechanical engineering class was trained on the Boothroyd and Dewhurst method and assembly time estimate charts as part of a senior level manufacturing course. The students in the course were asked to complete an assembly analysis and estimate assembly time of a Pilot G-2 clicker pen (Figure 2) using the manual assembly time estimation charts .

Figure 2 Fully Assembled Clicker Pen[2]

3.1.Participants

The participants for the pilot study consisted of students from a senior level mechanical engineering manufacturing course. The students were allowed to divide amongst themselves into groups of two. The students' were trained in the two previous lectures, each lasting one hour and fifteen minutes, on the use and application of the assembly time estimate method. The students were all equally trained with the method, and considered to be comparable in experience to an entry level manufacturing engineer. Training for application of the method for an engineer may be conducted in a similar fashion, based on books or passed on from another engineer. One option that Boothroyd and Dewhurst offer is a special course in assembly time estimation. The course should improve the accuracy and use of the method by the engineer, but also has a number of drawbacks including cost and time required for training[3]. The instructor applied the method during a lecture to a pneumatic piston for demonstration purposes. The pen is the first assembly that the students would analyze independently, although the instructor was available to answer general questions on application of the method, but not any specifics on how to analyze the assembly or on the handling or insertion codes to choose for the different parts of the pen. The students conducted the time estimate in-class, and the assignment would count as an "In-class Activity", which as a category is worth 20% of the students' overall grade. This was not the first or last in-class activity that the students were given, so this particular assignment was not out of the ordinary A total of twenty groups were formed for the in-class assignment.

3.2.Process

In the Spring 2011 semester at Clemson University students in a Design for Manufacturing course (ME455) were asked to apply the Boothroyd and Dewhurst manual assembly estimation method to a Pilot G-2 Clicker Pen (Figure 2). The students were allowed a time limit of one class period (75 minutes) to complete the analysis. Each student had a pen that they were allowed to disassemble and reassemble to complete the assembly time estimate. Each individual group would

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[2] http://www.officespecialties.com/pilot_31277_g2_ultra_fine_retractable_pen_42038_prd1.htm, accessed on 2/19/2012

[3] http://www.dfma.com/services/dfmacore.htm

discuss the assembly time estimate, and once a consensus was reached, the group would turn in one results sheet. The students were provided a basic template to record the handling and insertion codes, as well as the handling and insertion times for each part, and additional cells to show the sum of the handling and insertion times for each of the individual parts resulting in a total assembly time. An example of a completed results table is shown in Table 3.

Table 3: Example Student Clicker Pen Time Estimate

Task	Description	Handling Code	Handling Time (s)	Insertion Code	Insertion Time (s)	Total Time (s)
1.1	Top	30	1.95	00	1.5	3.45
1.2	Bottom	10	1.5	00	1.5	3
1.3	Button	11	1.8	00	1.5	3.3
1.4	Cartridge	10	1.5	00	1.5	3
1.5	Spring	83	5.6	00	1.5	7.1
1.6	Base	10	1.5	38	6	7.5
1.7	Grip	10	1.5	31	5	6.5
Total Assembly Time						33.85

3.3.Results

A summary of the results of the pilot study, including the handling time, insertion time, and total assembly time of the pen from the different groups is summarized in Table 4.

Table 4 Pen Data from In-Class Activity

Group	Handling Time (s)	Insertion Time (s)	Total Assembly Time (s)
1	11.77	25.50	37.27
2	15.69	16.00	31.69
3	8.58	25.35	33.93
4	14.03	16.50	30.53
5	15.83	18.00	33.83
6	17.10	24.50	41.60
7	17.10	24.50	41.60
8	13.03	24.00	37.03
9	11.77	25.50	37.27
10	11.92	29.10	41.02
11	12.60	26.00	38.60
12	12.51	19.50	32.01
13	14.14	23.50	37.64
14	7.45	16.50	23.95
15	11.14	12.50	23.64
16	13.40	18.00	31.40
17	13.70	26.50	40.20
18	10.05	17.00	27.05
19	13.39	31.50	44.89
20	15.35	18.50	33.85

The results of three of the groups (groups 3, 10, 18), shaded in Table 4 were eliminated due to incorrectly identifying a handling code for an insertion code or vice versa leaving a total of seventeen groups. For example, group 3 provided an insertion code of “87” with an associated insertion time of 5.85 s. The insertion charts do not include a value for a insertion code of “87”, and to ensure the students did not flip the designation of “row * column”, the value of insertion code “78” is also not a value included in the insertion charts. However, a handling code of “87” does exist, and is associated with a time of 5.85 s. Each part requires a separate handling code and insertion code, and the two cannot be interchanged. While this is an error in the application of the method, this is not specifically the focus of this research and those values would influence the results.

A statistical analysis of the results of the data shown above, excluding the three cases which were eliminated due to circumstances discussed earlier is summarized in (Table 5).

Table 5 Clicker Pen Assembly Statistics

	Handling Time	Insertion Time	Total Time
Average	13.53	21.59	35.12
St. Deviation	2.38	5.03	5.88
Max	17.10	31.50	44.89
Min	7.45	12.50	23.64
Range	9.65	19.00	21.25

The assembly time estimation for the clicker pen resulted in an average of 35.12 seconds and a range of 21.25 seconds. This suggests that multiple users that are equally trained and provided with the same product did not arrive at the same estimated assembly time. Initial observations of the data suggest that the decisions that the user makes to the Level 1 subjective questions for handling and insertion, contributes to the variation in assembly time estimates.

To determine the influence of answering the subjective question on the assembly time estimate, the alternate possible handling and insertion times assuming that Level 1 subjective question was answered alternatively was retrieved. The average of the two values was then used as the time estimate. This serves to simulate the user not having to answer the subjective question, but instead using the average value that could result. The maximum and minimum values of the alternate decision were also investigated, but resulted in values that exaggerated the variability of the method. The average value is used as a middle value to represent the user not making the decision and as a baseline time for this subjective question to add into the time analysis.

This process is repeated for each handling time and insertion time for each group to determine the effect of estimating the assembly time of the pen, while replacing the Level 1 subjective values with the average of the two values. The results of each group's initial assembly time estimate, and the derived estimate using the average of the two subjective values is shown in Table 6.

Table 6: Total Assembly Time Comparisons

Group	Total Assembly Time (s)	Total Assembly Time using average of Level 1 Subjective Question	Percent Difference
1	37.27	38.67	3.8
2	31.69	35.95	13.4
4	30.53	43.60	42.8
5	33.83	50.78	50.1
6	41.60	45.00	8.2
7	41.60	45.00	8.2
8	37.03	41.72	12.7
9	37.27	38.67	3.8
11	38.60	46.62	20.8
12	32.01	35.40	10.6
13	37.64	45.30	20.3
14	23.95	28.62	19.5
15	23.64	27.05	14.4
16	31.40	35.11	11.8
17	40.20	41.42	3.0
19	44.89	49.43	10.1
20	33.85	38.50	13.7

The basic statistics of the total assembly time using the average of Level 1 subjective questions indicates a mean of 40.4 seconds, with a standard deviation of 6.65 seconds which is slightly larger than the student assembly time standard deviation Table 7.

Table 7: Statistical Comparison of Data Sets

	Student Assembly Time	Assembly Time using Average of Level 1 Subjectivity
Average	35.12	40.40
St. Deviation	5.88	6.65
Max	44.89	50.78
Min	23.64	27.05
Range	21.25	23.74

A statistical normality test (Anderson-Darling) was conducted on each set of data to ensure that each data set was normally distributed. The resulting p-values of the student estimates and the average of Level 1 subjectivity estimates are $p = 0.49$ and $p = 0.67$ respectively. This is required to justify the use a probability distribution plot to represent the data. A curve is fit to both sets of data and the resulting density plot is shown in Figure 3.

The mean of the estimates derived without the Level 1 subjective questions results in a conservative time estimate that is 5 seconds or 15% greater than the mean of time estimates from the in-class activity. This indicates that had the students not made a subjective decision on Level 1, the difference in means of the results would still be within 15%. A variation of 15% is a reasonable range considering Boothroyd and Dewhurst state that a variation of up to 50% can be seen when conducting the assembly time estimate [12]. In this specific case the time estimates without Level 1 subjectivity resulted in a value that was greater than the student estimate. If the students had selected a handling or insertion code with a higher time estimate, then the average may have resulted in a time that was less than the student estimated time. The range of values should also be considered to ensure that a lower estimate does not influence the designer to overlook a part with assembly difficulties.

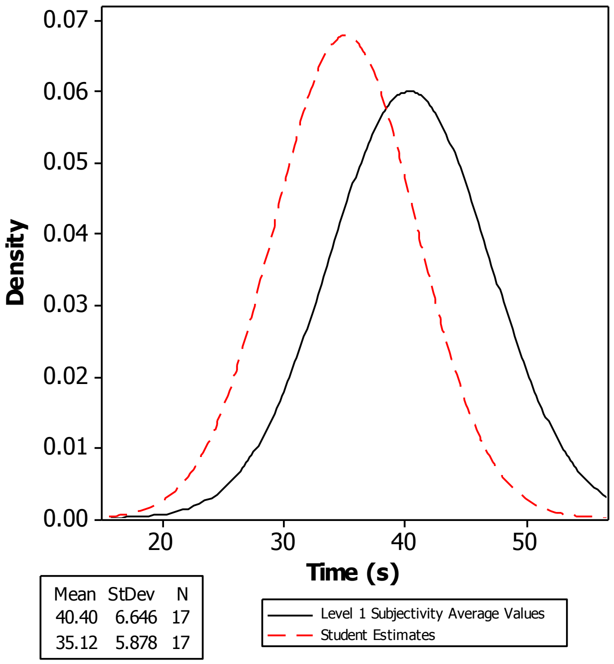

Figure 3: Density Plot of Student Time Estimates and Level 1 Subjective Questions Average

Furthermore the area underneath the average subjectivity curve (Figure 4), which is shared by the student estimate curve is approximately 63%. The range of times that were considered is from the student minimum time estimate of 23.64 s to the student maximum estimate of 44.89 s. This indicates that using the average value of the Level 1 subjective questions would result in an estimated assembly time estimate which falls within the normal distribution of the student estimates 63% of the time.

4.CONCLUSIONS AND FUTURE WORK

The current assembly time estimation method requires subjective input from the individual conducting the analysis such as: “is the part easy to grasp and manipulate”, “is the part easy to align and position during assembly”, “does the part present handling difficulties”, and “will the part nest or tangle”. Initial results from the in-class activity suggest that the subjective questions in the Boothroyd and Dewhurst manual assembly time estimate charts has an effect on the estimated assembly time of part. However, the results from the pilot study indicate that even if the user does not make the Level 1 subjective decision, an assembly time estimate within approximately 15% can be predicted relative to if the subjective decision had been made.

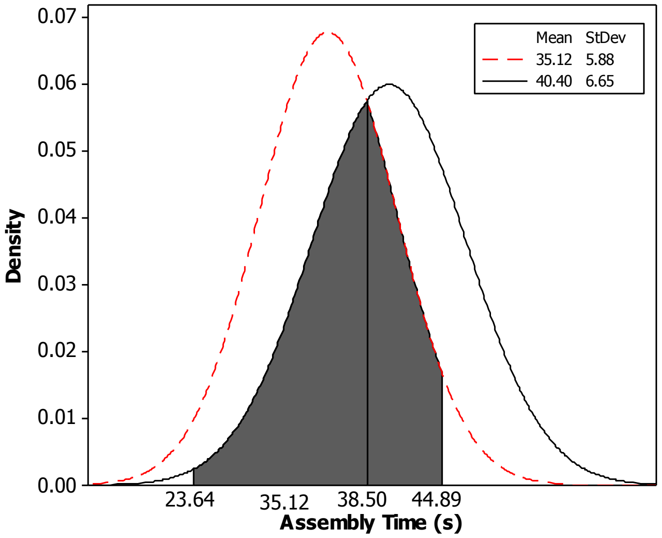

Figure 4: Area Overlap Under Data Curves

While the sample size used in the current pilot study is not large enough to generalize the conclusions, it does provide anecdotal evidence that there is an opportunity to reduce or eliminate the subjective questions in the Boothroyd and Dewhurst manual assembly time method. Reducing or eliminating can allow the user to estimate the assembly time with a certain confidence, such as providing a range of estimated assembly time as opposed to a single assembly time with a false sense of confidence. The assembly time estimate charts may be organized such that if the user is not confident in the answer of any of the questions, they may choose to not answer it, and lack of additional information will just results in a larger range of estimated assembly time with a certain confidence that the actual assembly time falls within this range. In order to accomplish this, further research is required to determine the specific effect of each subjective question on the overall assembly time estimate.

If an assembly time interval can be derived based on the questions that a user has answered (as discussed above), an opportunity exists to support assembly time estimation throughout the design process. For example, if a part is being studied during the conceptual phase for feasibility, an assembly time estimate within 50% may be sufficient, and if that is the case then less information may be needed about the part to provide the designer a rough estimate of the assembly time. The user may be able to estimate an assembly time of a product by providing the answer to only one question of the assembly chart, but this will decrease the confidence in the assembly time estimate. This will reduce the amount of time and information needed to implement the assembly time estimation method. Early product design stages dictate between 70-80% of the cost of product development and manufacturing, therefore an opportunity to estimate the assembly cost of a product at the conceptual stage, even with a large confidence interval may be beneficial in reducing manufacturing costs[12,21–24].

The outcome of this paper is motivation for further investigation into the effect of subjective questions on the estimated assembly times predicted from the Boothroyd and Dewhurst method. For example, one research question reserved for future work is: Does increasing product complexity increase the variation in assembly times? The results of this paper also serve as further as the basis for the overall objective of this research to implement the Boothroyd and Dewhurst assembly time estimate method as tool that would communicate with CAD software to retrieve required information. The tool would retrieve information from CAD such as dimensions, weight, material, and symmetry to provide an initial assembly time estimate range. The estimated assembly time range would be based on the statistical variation attributed to the subjective questions. As the user gains additional information about the product and is able to answer some of the subjective questions, the range of the estimate assembly time would decrease and the confidence of the assembly time estimate would increase.

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