Assembly Time Modeling Through Connective Complexity Metrics

James L. Mathieson, Bradley A. Wallace, Joshua D. Summers
Clemson Engineering Design Applications & Research
Mechanical Engineering, Clemson University
Clemson, SC USA
[jmathie, bwallac, jsummer]@clemson.edu

***Abstract*— This paper presents the development of a model for predicting the assembly time of a system based on complexity metrics of the system architecture. A convention for modeling architecture is presented, followed by ten analyzed systems. These systems are subjected to complexity metrics developed for other applications. A model is developed based on a recognizable trend and a regression of that trend. The regression is then further refined based on its similarities to additional metrics other than that used in regression. The final model uses average path length, part count, and path length density to predict assembly time to within ±16% of that predicted by the Boothroyd and Dewhurst design for assembly analysis method.**

Keywords— Manufacturing; Assembly; Complexity Measures

I. Complexity in Assembly

Complexity in design is often addressed indirectly through various analysis techniques which have been specially developed for a single purpose. Examples of this include design for X (DFX) analysis, where a procedure has been developed for determining a particular property of the design. One such procedure is design for assembly analysis. The purpose for design for assembly (DFA) is to create a design solution for a particular product which will ease the assembly process for the product.

In the 1960's many companies developed handbooks which guided designers in creating parts for manufacturing ease [1]. The emphasis of these design manuals was to produce and assemble many simple parts, an idea which was thought to be the cheapest method of manufacturing. However, this was before experimental and theoretical analyses were performed on the effects that part features had on the assembly time of the parts [2].

From such studies, Boothroyd and Dewhurst [3,4,5] developed a DFA methodology which accurately quantifies and rates the producability of designs for comparison [6]. The Boothroyd and Dewhurst DFA method aimed at minimizing assembly times and costs by minimizing the number of individual parts [4], as well as optimizing individual part design for ease of handling and joining [7].

Other DFA methods include the Hitachi Assembly Evaluation Method (AEM), the Lucas method [8] as well as Sony's design for assembly cost-effectiveness (DAC) [9]. The Hitachi AEM decomposes each operation of an assembly into its basic operations. Each operation is then assigned a penalty score which is proportional to the operation's average time compared to the basic operation, a downward attachment. The score is then calculated by determining the average score of each of the individual parts and the total number of parts. The assembly time and cost for the product are then estimated from the product's AEM score [10].

The Lucas method uses functional, handling, and fitting analyses [11]. The functional analysis ensures that the ratio of parts demanded by the design specification, *A* parts, to parts required by the particular design, *B* parts, is greater than 60% through the elimination of *B* parts [1,12]. The handling analysis introduces penalties based on each part's size, weight, and handling difficulties. The fitting analysis adds penalties due to difficulties in the joining the individual parts [13,8,12].

In the Sony DAC methodology, each operation of assembly is given a score out of 100 points. Simple operations have a lower score and higher operations have a higher score [9].

Since the development of formalized DFA methods such as these, companies that have utilized them, such as Texas Instruments, Ford Motor Company, General Motors, and Motorola [2] have achieved significant cost savings by producing, on average, 50% fewer parts which are more complex but result in simpler product architecture [14,4].

However, all of the DFA methods discussed here require the designer to correctly answer to questions related to each individual part in an assembly. Many of the questions have subjective, rather than objective, answers. Therefore, the process can be extremely time consuming and the results will differ from one execution to another [1]. As such, many DFA analyses tend to be used towards the end of the design process and not used iteratively through the design cycle [15].

This paper seeks to counter this deficiency by exploring the possibility that complexity metrics may be used to develop a model for assembly time based on the architecture of the system without the need for exhaustive designs by the designer. By applying a model based on a consistent definition of system architecture, it may be possible in the future to incorporate real-time assembly time analysis in CAD systems as assemblies and parts are developed. This will allow designers to consider the impacts of their decisions on assembly time early in the design process using concrete numbers rather than anecdotal experience. The first step to this goal is to establish the basis for modeling the connections in the system architecture.

II. Connectivity Modeling

The modeling of system complexity for assembly requires that a representation of the system's architecture be developed.

This is done by tracking the connections between the system's constituent elements in a bi-partite graph. In this graph, connections are drawn between two independent sets.

The first independent set is system elements or physical parts. This includes both major system components to be assembled as well as fastener components. These are drawn on the left side of the bi-partite graph.

The right side of the graph and the second independent set consists of relationships. As we are interested in system architecture, relationships tracked here are instances of connection and contact. For example, two parts may contact each other in one relationship, but also be fastened together using a nut and bolt in a different relationship.

A. *Surface Contact*

Contact between parts can involve multiple instances due to the geometry of parts. For example, two parts may contact each other through a flat surface on each part, a series of posts, or interfacing contours. However, these contact conditions do not need to be fully defined in the connective model. Rather, it is sufficient to acknowledge that two parts contact each other outside of any given fastening instances. As such, there should be no more than one contact relationship between any two primary parts. Additionally, surface contact relationships should only be noted if this contact occurs outside of any fastening region. Future extensions may be explored with feature contacts, but they are currently deemed out of scope for this paper.

B. *Fasteners*

Fasteners are a type of relationship which can have a significant impact on the assembly time of the system. This is due to the introduction of additional system elements in the form of nuts, bolts, rivets, and screws as well as the interaction of these fastening elements with the parts they are joining. To illustrate this, take the bolting diagram in Figure 1.

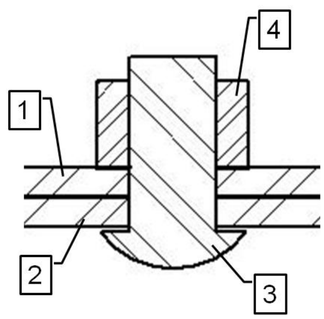

Figure 1: Bolting Diagram

Here, we have two fastening elements, a nut (4) and a bolt (3), clamping together two parts (1 and 2). As this clamping interaction applies load through all of the elements and would not function in the absence of any given element, both of the parts as well as the nut and bolt are considered to be connected to a single relationship for the bolting as shown in Figure 2.

It should be noted that a unique system element is required for each physical element used. For example, a given item may be assembled using several identical screws. Rather than modeling these screws as a single element, each screw must exist as an independent element as it is in the physical system.

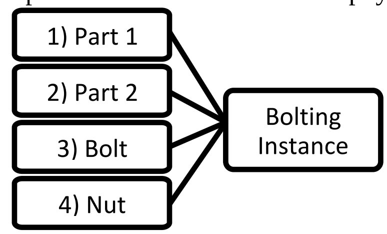

Figure 2: Bi-partite Connectivity Graph for Bolting Instance

C. *Snap, Press, and Interference Fits*

Snap, press, and interference fits are similar to fasteners in that they are a unique connection between parts separate from that of traditional surface contact. These features are more determinant than simple surface contacts and can impart the same clamping loads as fasteners. However, the major difference in snapped connections is that there are no additional minor parts used in forming the connection while still being a unique relationship. This unique relationship captures the fact that the each snap must still be aligned and engaged in assembly. Therefore, the connective relationship for a snap fit would be arranged as in Figure 3.

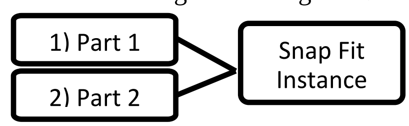

Figure 3: Bi-partite Connectivity Graph for Snap-fit

D. *Other Connections*

There are other forms of connections which require specific rules regarding how they are to be modeled in the graph. These include shafts, springs, and electrical connections, each of which raise unique questions regarding the proper arrangement of elements and relationships. The guideline applied here is that these elements are, in effect, fasteners of one form or another.

This implies that, while each of these is a physical element, they are also related through a single relationship instance. As such, a shaft would be modeled as a shaft element connected to all of the elements attached along its length through a single shaft relationship. Similarly, a spring will be connected to the elements contacting it through a spring relationship.

Electrical connections pose a larger challenge as the form of connection to be made in assembly must be considered. If the connection is of a pre-made cord and plug, this may be modeled as a press or snap fit instance as that is exactly what this relationship is. However, if bare wires are to be joined, fastening elements such as crimps, twists, and solder must be modeled individually as fasteners.

III. Example Systems

In order to identify a model which will approximate the results of design for assembly analysis, several systems with previously established DFA results are needed. Five systems, automotive shifter, cylindrical Tweel™, electric knife, electric hand mixer, and electric chopper, and their redesigns based on traditional DFA principles are introduced here. Four of these systems were analyzed and redesigned as part of an undergraduate/graduate design for manufacturing course. One of the systems and redesign, the automotive shifter, is from an industry sponsored research and development project. The authors were only directly involved in the DFA analysis of two of these systems, the Tweel™ and the electric knife. It is important to note that each DFA analysis was done by ten different individuals. The analyses were taken as correct and not re-evaluated by the authors for this paper. These systems are then subjected to complexity analysis for use in the development of a predictive model.

A. *Automotive Shifter*

The first system addressed is an automotive shifter unit. This is a relatively small item with only five primary parts and is used to represent a lower order of assembled systems.

1) *Original*

The original design of the shifter is heavily dependent on screw fasteners and multiple stages of assembly. Some parts are joined by as many as five screws. Only the connection between Parts 4 and 5 is done through a snap-fit clip. Figure 4 illustrates the assembly of the shifter in detail. In Boothroyd DFA analysis, the shifter was estimated to require 104.56 seconds to assemble. However, it should be noted that in practice the manufacturer observed an average assembly time of 105.24 seconds, highlighting the approximate nature of traditional DFA analysis.

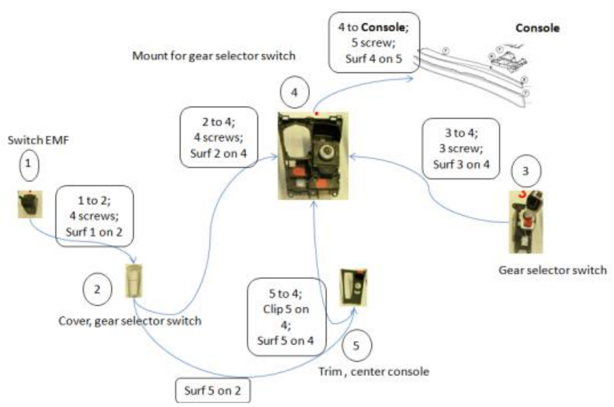

Figure 4: Original Shifter

2) *Redesign*

The shifter was redesigned based on established DFA principles with an eye toward lazy parts. A lazy part is one that does not serve any unique functional purpose in the final assembly. In the shifter, Part 2 is a trim cover which attaches onto another piece of trim. As this cover and trim combination does not perform separate function in the final assembly, these parts can be combined to a single part. This allows the switch to attach directly to the central mount with a clip. These changes are reflected by the conceptual redesign assembly diagram in Figure 5. The estimated assembly time for this design by Boothroyd DFA is 42.60 seconds.

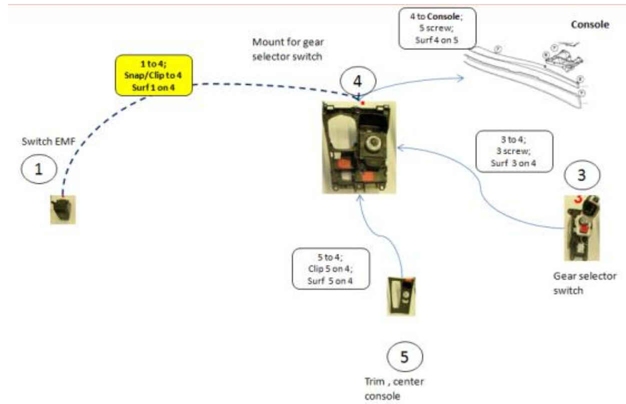

Figure 5: Redesigned Shifter

B. *Cylinder Tweel™*

The second system is a meta-material lunar Tweel™ prototype. This system includes 225 metallic cylinders attached to inner and outer hoops to mimic the shear properties of polyurethane in a standard terrestrial Tweel™. As a result, this system contains a high number of parts and connections and thus represents an upper order of assembled systems.

1) *Original*

The original cylinder Tweel™ prototype makes heavy use of bolted connections. For each of the 225 cylinders, there is a bolted connection on both top and bottom. In addition to this, the fifteen spoke-hub bars are attached by three bolted connections each. This makes for 495 bolted connections and twice that number in fastening parts. An illustration of this design is shown in Figure 6. The assembly time for this design is estimated by Boothroyd DFA to be 13,561.34 seconds, or just over 3 hours and 45 minutes.

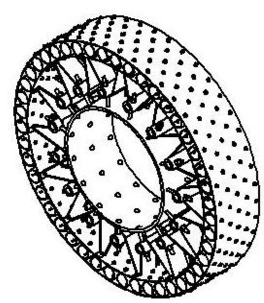

Figure 6: Original Cylinder Tweel™

2) *Redesign*

The redesign of the cylinder Tweel™ prototype focuses on reducing the number of fasteners and particularly on eliminated bolted connections. As a result, the shear cylinders are held in place by snap-fit fasteners which affix one row of cylinders at a time, rather than individually as with bolted connections. The spoke-hub bars are held in place by rings integrated into the hub and a cap plate on either side of the hub. These plates are affixed to the hub by three bolted connections. This is illustrated in Figure 7. The assembly time is estimated by Boothroyd DFA to be 4925 seconds, or an hour and 22 minutes.

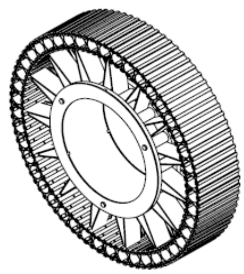

Figure 7: Redesigned Cylinder Tweel™

C. Electric Knife

The third system is a consumer electric knife typically used for carving meats and slicing bread. This cutting action is achieved by a pair of adjacent reciprocating blades. These blades also can be ejected from the unit for washing. This ejection functionality and the linear motion of the reciprocating blades make this system relatively more complicated than similar consumer appliances.

1) Original

The original electric knife design contains a large number of fasteners for its size. The majority of these fasteners are screws used to join the major internal components to the base of the unit. However, most notable is the large number of springs used. There is one spring for each exterior button as well as two springs on each blade mount for a tensioning plunger and the blade clip. Figure 8 shows the numerous screw holes in the base as well as the two spring fasteners on the blade mounting arm. The estimated assembly time for this design by Boothroyd DFA is 325 seconds.

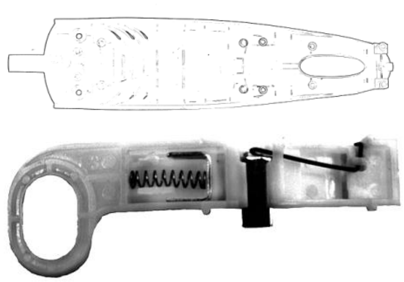

Figure 8: Original Electric Knife Housing and Blade Mount

2) Redesign

The redesign of the electric knife addresses the issue of fasteners. Specifically, this is done by eliminating fasteners which are unnecessary to fully restrain the joined parts as well as joining as many primary parts as possible with each fastener. Additionally, the spring used to tension the blades in each blade mount is replaced with a compliant mechanism integrated into the polymer blade mount. These alterations can be seen in Figure 9. The estimated assembly time for this design by Boothroyd DFA is 240 seconds.

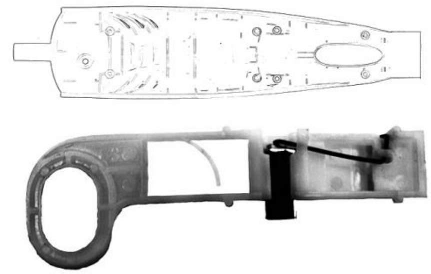

Figure 9: Redesigned Electric Knife Housing and Blade Mount

D. Electric Hand Mixer

The fourth system is a consumer electric hand mixer. This system is composed of fifteen primary parts. These parts are joined using snap fits, slide fits, and traditional hardware fasteners.

1) Original

The original mixer design, shown in Figure 10, is composed of three cover sections attached with a total of six screws. The motor was mounted in the casing with four screws. The power cord was connected to the mixers wiring system via a clamp and two screws. The rest of the parts are assembled via slide fits. Three parts, the two beaters and the speed control, are also spring loaded, which increases their assembly times. The estimated assembly time for this design by Boothroyd DFA is 130.45 seconds.

Figure 10: Original Electric Hand Mixer

2) Redesign

The hand mixer was redesigned with an emphasis on eliminating unnecessary fasteners, which would eliminate the total number of parts in the assembly. All but one of the screws previously used to attach the cover pieces were removed and replaced with snap fits. The number of screws used to attach the motor to the inside of the cover pieces was reduced from four to two. The screws used to hold the power cord were replaced as they were deemed unnecessary to hold the cord within the mixers enclosure. The estimated assembly time for this design by Boothroyd DFA is 74.7 seconds.

E. Electric Chopper

The fifth and final system is a small consumer electric blender, representing another product on the same scale as the hand mixer. The blender was made of mostly injection molded parts connected using fasteners and snap fits.

1) Original

The original design, shown in Figure 11, contained three main subsystems: the container, the housing and the drive system. The housing system contained the majority of the fasteners in the system, with a total of eleven screws. The drive system also contained two screws. The container subsystem was attached to the housing using a twisting motion. The rest of the assembly process consisted of snap and slide fits. The estimated assembly time for this design by Boothroyd DFA is 228.5 seconds.

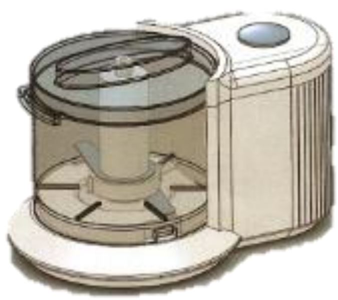

Figure 11: Original Electric Chopper

2) Redesign

A redesign was completed by determining which parts had the lowest design process efficiencies. The container subsystem was redesigned so that the twisting operation was no longer necessary. The inside of the housing case was redesigned to remove and reshape ribs to decrease resistance and increase the visibility during assembly. The bracket used to attach the motor was redesigned to allow unobstructed access to the motor mount. It should be noted that these design changed did not eliminate any of the parts, but only eliminated the difficulties in assembling the current parts, and thus did not change the connectivity graph. The estimated assembly time for this design by Boothroyd DFA is 201 seconds.

IV. Complexity Metrics

With sample systems established, a complexity analysis is be performed. This analysis addresses nine different metrics in three different classes. These classes are size metrics, path length metrics, and decomposition metrics developed in [16,17].

A. Size

Size metrics are the most common in complexity analysis [18,19,20]. These metrics address counts of elements within the system. Here, we address both dimensional and connective size properties.

Dimensional size addresses physical counts, particularly the elements and relationships in the system. The elements addressed in these systems are parts, including primary parts as well as any fastening parts. Relationships here are the connection instances which have been addressed in Section II.

Connective size addresses the number of connections which have been made in the system. In simplest terms, connective size represents the number of lines which are drawn between elements and relationships in the bi-partite graph. Each of these connections represents an interface which must be established in assembly. However, also of interest is the number of properties which are available for change in the system. This is otherwise known as the system’s parametric degree of freedom. This metric tracks the number of times each element is connected directly to another element. When these metrics are applied to the example systems, the results are those shown in Table 1.

Table 1: Size Metrics for Example Systems

	Elements	Rel.	Conn.	DOF
Shifter Original	22	23	62	55
Shifter Redesign	13	19	46	35
Mixer Original	24	23	59	52
Mixer Redesign	15	17	40	29
Chopper Original	36	37	93	81
Chopper Redesign	36	35	79	79
Knife Original	49	64	160	132
Knife Redesign	38	51	126	105
Tweel™ Original	1190	524	2023	3029
Tweel™ Redesign	613	531	1971	2802

B. Path Length

Path length metrics are derived from an algorithmic treatment of the connective layout of the system. The result of this algorithm is a matrix of the number of connections which must be traversed in order to go from any given element to any other given element. This can then be used in conjunction with the established size metrics to produce general properties of the system’s path lengths.

The first metric is total path length. This is the sum of the path length matrix and represents the number of connections traversed if every possible flow of system information were to be considered. Derived from this is the average path length. This is determined by dividing the total path length by the size of the path length matrix minus the empty identity. This will represent the average number of connections which must be traversed to go from any point in the system to any other point.

Additional metrics include path length density and maximum path length. The latter of these, maximum path length, is self-explanatory as it is simply the greatest number of connections which must be traversed to go between any two elements. Path length density is derived from average path length by again dividing this number by the number of relationships in the system, providing the average path length generated by any given relationship. The results of these complexity measures applied to the systems are those shown in Table 2.

C. Decomposition

The final metric applied addresses the decomposability of the system. This is measured by the Amer-Summers decomposability algorithm [18]. This is done by systematically breaking the least-connected relationships as so to isolate elements. The algorithm develops a score for the system based on how many steps are required to isolate the elements, how many elements can be isolated in each step, and the number of relationships which must be broken to isolate the elements in each step. When this is applied to the example systems, the results are those shown in Table 3.

Table 2: Path Length Metrics for Example Systems

	Total	Max	Average	Density
Shifter Original	948	3	2.05	0.0892
Shifter Redesign	272	2	1.74	0.0918
Mixer Original	1118	4	2.22	0.1010
Mixer Redesign	490	5	2.33	0.1373
Chopper Original	3226	5	2.56	0.0692
Chopper Redesign	3226	5	2.56	0.0732
Knife Original	6110	4	2.60	0.0406
Knife Redesign	3450	4	2.45	0.0481
Tweel™ Original	3544532	6	2.51	0.0048
Tweel™ Redesign	892240	7	2.38	0.0045

Table 3: Decomposability Metric for Example Systems

	Ameri-Summers
Shifter Original	36
Shifter Redesign	44
Mixer Original	21
Mixer Redesign	29
Chopper Original	74
Chopper Redesign	61
Knife Original	273
Knife Redesign	218
Tweel™ Original	641
Tweel™ Redesign	1869

V. MODEL DEVELOPMENT

To develop a model for prediction of assembly time, a pattern must be identified between complexity metric results and DFA results. Rigorous model development protocols require numerous data points which are not available at this time. As such, a more rudimentary pattern recognition approach is applied.

A. *Metric-Assembly Relationship*

This first step in this process is to visualize the relationship between the various metrics and the Boothroyd DFA analysis results. This is done by plotting the DFA results for each system against each metric. Figure 12 shows this for size metrics for all systems other than the Tweel™ variations. This is due to the significantly higher order of the Tweel™ metrics and DFA results. From this plot it can be observed that the general trend is for assembly time to increase dramatically with increasing size. The plots for path length and decomposition metrics are not shown here for brevity. It should be noted, however, that among those metrics only total and average path length produced consistent trends.

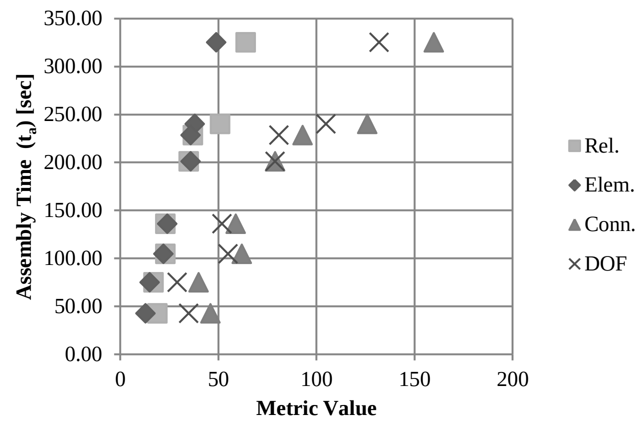

Figure 12: Size Metric Plot

To better visualize the size trends (Figure 12) such that the Tweel™ results may be considered, a log-log plot of the same data was created. This is shown in

Figure 13. Here, it can be seen how the size metrics for the consumer products align with those from the Tweel™. The assembly time values for most of these measurements still reflect a dramatically higher slope for the Tweel™ than the other systems, despise the log-log format. However, there is one notable exception. Elements, representing the count of primary and fastening parts, appear as a nearly straight line for all systems including both variations of the Tweel™. Such a consistent trend with regards to part count is not entirely surprising as the positioning of each individual physical element is a significant driving force in assembly time.

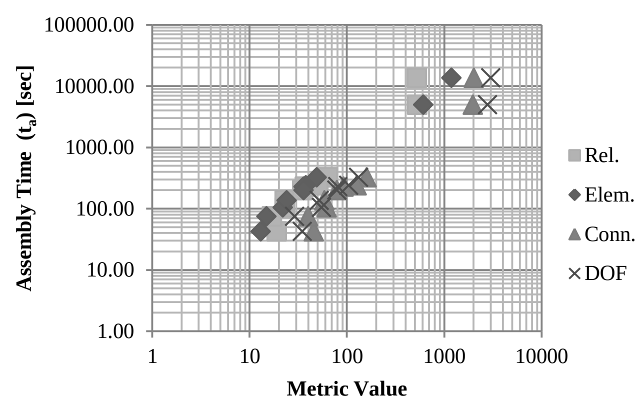

Figure 13: Log-Log Size Metric Plot

B. *Regression*

The next step is to establish a rough model through regression. As the relationship between part count and assembly time appears linear in a log-log plot, it follows that the appropriate model for this trend is that of a power regression. This is computed automatically by software and results in the line and equation shown in Figure 14. The high R-squared value quoted here is the result of the large range over which the model is applied with limited intermediate values.

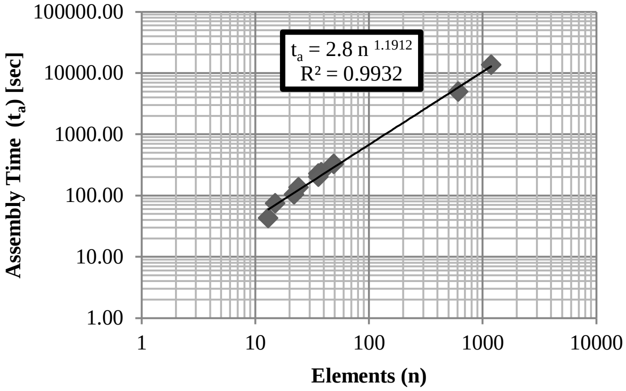

Figure 14: Power Regression of Part Count – Assembly Time Trend

C. *Refinement*

The accuracy of the regression, while exhibiting strong correlation, is far from perfect. To better understand the accuracy of this model, Table 4 was created. This shows how the percent error in the regression model varies between -1% and +77%. This shows significant over estimation in the regression model, particularly with small systems.

Table 4: Error in Regression Model

	DFA Time [sec]	Reg. Time [sec.]	% Error
Shifter Original	104.56	146.70	40%
Shifter Redesign	42.60	75.29	77%
Mixer Original	104.56	170.25	25%
Mixer Redesign	42.60	102.33	37%
Chopper Original	136	256.53	12%
Chopper Redesign	74.7	260.23	29%
Knife Original	228.5	338.49	4%
Knife Redesign	201	254.34	6%
Tweel™ Original	13561.35	13362.01	-1%
Tweel™ Redesign	4925.00	6032.32	22%

To correct for this large discrepancy, additional metrics may be used to supplement the model by replacing in whole or in part the constants derived by the regression. To this end, it is observed that the coefficient of the regression, 2.80, is similar to the average path length of the systems, which range between 1.74 and 2.51. The value of average path length was also observed to be roughly proportional to estimated assembly time. Thus, the constant coefficient of the equation is replaced with average path length to introduce the proportional trend.

This brings the values closer to the DFA estimates with some values now underestimated with an error range of -28% to +1%. To correct for this, the exponent of the regression, 1.1912 is supplemented through the use of path length density. The value for path length density is never greater than one, is typically on the order of hundredths or less, and decreases with increasing system size. Thus, it is proposed that the path length density be added to provide a slight increase to and a finely granular step down of the exponent as the system size increases.

The final step in refinement was to tune the resulting model to the available DFA estimates to minimize the average absolute percent error. This is done by adjusting the constant in the exponent to the third decimal place. Tuning to higher significant digits does not produce appreciable change in results. These alterations to the model result in Equation 1 where t_a is assembly time, APL is average path length, n is the number of elements, and PLD is path length density.

$$t_a = [APL] \times n^{(1.185+[PLD])} \quad (1)$$

When this refined model is applied to the example systems, the results are those shown in Table 5 and illustrated in Figure 15. The percent error is reduced to ±16%, within the error range which may result from different designers conducting DFA analyses for all systems. Additionally, it can be seen that the ordinal change between the original and redesigned version of each system is correctly predicted for all but the chopper. This discrepancy is due to the fact that the redesign of the chopper primarily addressed geometric changes for ease of access in assembly operations and included the removal of some assembly feature symmetry for manufacturing savings. As this model is driven by system architecture and not geometry, it is to be expected that only the increase in assembly due to the loss of feature symmetry would be captured.

Table 5: Error in Refined Model

	DFA Time [sec]	Model Time [sec.]	% Error
Shifter Original	104.56	105.37	1%
Shifter Redesign	42.60	46.10	8%
Mixer Original	136	132.28	-3%
Mixer Redesign	74.7	83.76	12%
Chopper Original	228.5	229.20	0%
Chopper Redesign	201	232.50	16%
Knife Original	325.00	306.26	-6%
Knife Redesign	240.00	217.71	-9%
Tweel™ Original	13561.35	11430.28	-16%
Tweel™ Redesign	4925.00	4919.21	0%

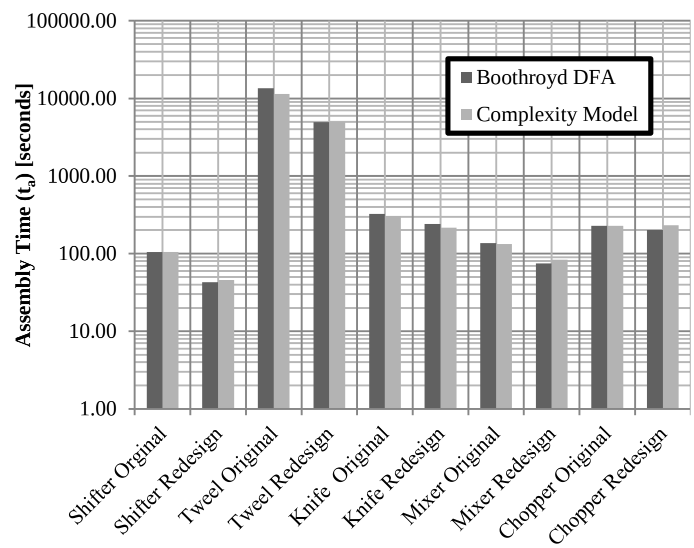

Figure 15: Refined Model Results

VI. CONCLUSIONS & FUTURE WORK

The model developed here has shown a capability to predict the assembly time of a system based on the architecture of that system. The variability of the model with respect to the results of a traditional Boothroyd DFA analysis are within the range one may observe between different designers conducting the DFA analysis. This is highlighted even more by the fact that the analysis on the five different systems and their redesigns were in fact conducted by different designers.

This demonstrates the ability of complexity metrics to be used to predict properties of the final design. While the method applied to the development of this model lacks the rigor of a formalized model development method, the level of correlation and accuracy which can be achieved through these means is suggestive of the power of complexity modeling.

Further research should establish confidence in this model through its application to additional systems without further tuning. This will validate the model as a tool which may be used in practice and may reveal the underlying mechanisms which cause the model to behave as it does. Of particular interest is the origin of the tuned exponent value of 1.185.

An additional point of interest is the extension of complexity modeling methods to other measures of interest. These may include any number of design for X analysis, design performance, and product performance measures. For example, the model here is independent of geometry but it may be possible to produce a model, based on CAD representations, which is an analog for design for manufacturing analysis or as a complete prediction of system production cost.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the funding provided by NASA and SC EPSCOR.

REFERENCES

[1] G. Boothroyd and L. Alting, "Design for Assembly and Disassembly," *CIRP Annuls 1992 Manufacturing Tecnology*, vol. 41, no. 2, pp. 625-636, August 1992.

[2] Geoffrey Boothroyd, *Assembly Automation and Product Design*, Second Edition ed. Boca Raton, FL, USA: Taylor & Francis, 2005.

[3] G. Boothroyd and J. Walker, "Design for Assembly," in *Handbook of Manufacturing Engineering*, Jack Walker, Ed. New York, NY, USA: Marcel Dekker, 1996, ch. 1, pp. 1-50.

[4] G Boothroyd and P. Dewhurst, "Product Design for Manufacture and Assembly," *Manufacturing Engineering*, pp. 42-46, April 1988.

[5] G. Boothroyd and P. Dewhurst, *Product Design for Assembly*. Wakefield, RI, USA: Boothroyd and Dewhurst, Inc., 1980.

[6] John Priest and Jose Sanchez, *Product Development and Design for Manufacturing*. New York, NY, USA: Marcel Dekker, 2001.

[7] H.J. Warnecke and R. Babler, "Design for Assembly - Part of the Design Process," *CIRP Annuls 1988 Manufacturing Technology*, vol. 37, no. 1, pp. 1-4, August 1988.

[8] P.G. Leaney, "Case Experience with Design for Assembly Methods," in *Design for X: Concurrent Engineering Imperatives*, G.Q. Huang, Ed. London, UK: Chapman & Hall, 1996, ch. 2, pp. 41-71.

[9] Y. Yamigiwa, T. Negishi, and K. Takeda, "Life Cycle Design Achieving a Balance Between Economic Considerations and Enviromental Impact with Assembly-Disassembly Evaluation/Design DAC (Design for Assembly/Disassembly Cost-effectiveness)," *First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, pp. 760-765, 1999.

[10] T. Ohashi, M. Iwata, S. Arimoto, and S. Miyakawa, "Extended Assemblability Evaluation Method (AEM)," *JSME International Journal*, vol. 45, no. 2, pp. 567-574, 2002.

[11] C. Mascle, "Decision Support System in a Design for Assembly and Disassembly Methodology," *Proceedings of the 5th IEEE*, pp. 216-221, July 2003.

[12] A. Mital, A. Desai, A. Subramanian, and A. Mital, *Product Development: A Structured Approach to Consumer Product Development, Design, and Manufacture*. Oxford, UK: Butterworth-Heinemann, 2008.

[13] G. Boothroyd, "Product Design for Manufacture and Assembly," *Computer-Aided Design*, vol. 26, no. 7, pp. 505-510, July 1994.

[14] T. Welter, "Designing for Manufacture and Assembly," *Industry Week*, September 1989.

[15] G.F. Dalgleish, G.E. Jared, and K.G. Swift, "Design for Assembly: Influencing the Design Process," *Journal of Engineering Design*, vol. 11, no. 1, pp. 17-29, 2000.

[16] J.L. Mathieson and J.D. Summers, "Complexity Metrics for Directional Node-Link System Representations: Theory and Applications," in *Proceedings of the ASME IDETC/CIE 2010*, Montreal, Quebec, Canada, 2010, pp. IDETC2010-28561.

[17] J. Mathieson and J. Summers, "Relational DSMs in Connectivity Compexity Measurement," , Greenville, SC, 2009.

[18] F Ameri, J.D. Summers, G.M. Mocko, and M. Porter, "Engineering design complexity: an investigation of methods and measures," *Research in Engineering Design*, vol. 19, no. 2-3, pp. 161-179, November 2008.

[19] J.D. Summers and J.J. Shah, "Mechanical Engineering Design Complexity Metrics: Size, Coupling, and Solvability," *Journal of Mechanical Design*, vol. 132, no. 2, p. 021004 (11 Pages), February 2010.

[20] J.L. Mathieson, C. Sen, and J.D. Summers, "Information Generation in the Design Process," in *Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, San Diego, CA, USA, 2009, pp. 1-10.