HAND-CALCULATED SAVINGS:

CASE STUDIES IN THE APPLICATION OF A SIMPLIFIED BOOTHROYD-DEWHURST METHODOLOGY IN THE DESIGN AND MANUFACTURE OF COMPLEX ASSEMBLIES

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ABSTRACT

The part and assembly cost of electro-mechanical assemblies is often an important design criterion, yet it is often easier to estimate part manufacturing costs than the cost of assembly time. This paper recounts two case studies of companies for whom cost reduction analyses of complex assemblies were performed. A theoretical model was constructed to predict assembly time based on the Boothroyd-Dewhurst methodology. Model-predicted assembly times at the sub-assembly level were within 5% of empirical assembly times, despite several simplifying assumptions made at the assembly-step level. Using design-for-manufacture (DFM) best practices and predictions from the theoretical model, design changes were made which reduced assembly times (and corresponding labor costs) by more than 50%. Overall return on investment is maximized when assembly time modeling is completed early in the design process.

INTRODUCTION

Acorn Product Development is a design consultancy that focuses exclusively on the mechanical engineering design and analysis aspects of new product design and development. Our company culture is analysis-driven, which means that we strive to understand how a product will function prior to building our first prototype. With this strategy, we enable our clients to achieve revenue-ready products in the most efficient way possible by leveraging design-for-manufacture (DFM) and design-for-assembly (DFA) best-practices. First-order analysis is a critical tool early in our design process – whether structural, thermal, mechanistic, or tolerance analyses. We focus our development expertise primarily in the following four industries: telecom/server, industrial equipment/defense, medical, and consumer products. With offices in Silicon Valley, Boston, and Dongguan, China, we support our clients' manufacturing activities both in the US and abroad.

In an effort to deliver solutions that allow our clients to meet their demanding production cost targets, we employ a Boothroyd-Dewhurst methodology for assembly time estimation [1]. This methodology allows us to accurately estimate the time and cost required to assemble a product, and it allows us to make this estimation early enough in the design cycle that our findings can be leveraged to achieve an easier-to-assemble, more manufacturable product design. This paper focuses on two case studies of tactical implementations of the Boothroyd-Dewhurst method for estimating assembly time.

We will look at the theory and methodology employed, the specific problems presented by each client, and the results achieved by implementing the Boothroyd-Dewhurst model to estimate assembly time.

COST ESTIMATION

The cost required to manufacture an electro-mechanical assembly is a critical design criterion which both industrial and consumer product companies track throughout their product design cycle. However, this can be a difficult metric to track, especially early in the design process when many of the cost elements must be estimated.

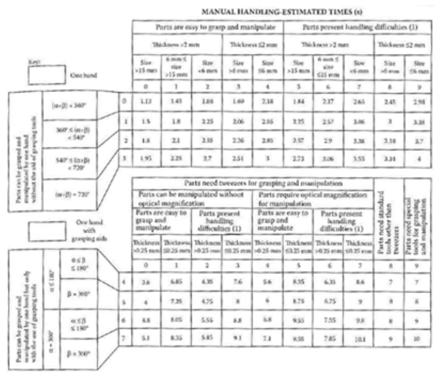
Generally the costs of an electro-mechanical assembly are grouped into two broad categories. First, part-level cost or Cost of Goods Sold (COGS) is an estimate of the cost required to manufacture each of the components in the assembly, part by part. Usually this is tracked in the form of a Bill of Materials (BOM), and can include mechanical elements (e.g. CNC machined parts, sheetmetal parts, molded plastics, etc.), electrical components (e.g. PCBAs and wire harnesses), as well as part-level finishing and handling costs.

Second, assembly cost is an estimate of the cost required to assemble the constituent parts into a finished assembly. This can include mechanical assembly (e.g. snaps, screws, etc.), wire routing, and other assembly-level finishing operations (e.g. adhesive application, painting, etc). The assembly cost is usually estimated as the product of the time required to assemble the unit and the fully-burdened labor rate of the assembly technician. The fully-burdened labor rate takes into account shop-level overhead and inefficiencies, and it varies dramatically depending on the location where the product is being manufactured (i.e. Far East vs. the Americas). The assembly time (and resulting assembly cost) is more difficult to estimate than the COGS, especially early in the design cycle, and as a result it is often made a lower-priority design consideration by the design team. However, ignoring assembly cost early in the design cycle often results in increased frustration on the part of the manufacturing team later, as we will see in the case studies below.

It should be noted that there are other areas of cost to be considered in addition to COGS and assembly costs when undertaking a comprehensive cost-reduction effort for a finished product. Some of these areas include finished material handling, shipping, supply chain operation, and other inventory and warehousing considerations. For the purposes of most product design efforts, however, the above simplification into part costs and assembly costs is sufficient to adequately capture cost as a design metric.

ASSEMBLY TIME ESTIMATION

In both case studies detailed below, we estimate manual assembly time using heuristic data given by Boothroyd and Dewhurst [1]. Component assembly times can be broken into the time required to handle a part to prepare it for assembly (e.g. picking up and positioning a screw), and the time required to insert the part into the assembly (e.g. driving the screw into position). The chart shown in **Figure 1** is a representative portion of the Manual Handling-Estimated Time chart [ibid, 83], which is used to estimate the time in seconds required to manipulate a part into assembly position. The chart takes into account several part characteristics to arrive at this estimate, including the symmetry of the part, whether grasping tools are required, the overall size of the part, and qualitative factors like how difficult the part is to handle. There is a similar chart used to estimate insertion times for parts, which takes into account whether the part is temporarily placed or permanently affixed to the assembly in the operation and also takes into account the nature of the fastening operation (e.g. screw, press, weld, bond, etc.).


MANUAL HANDLING-ESTIMATED TIMES (s)

		Parts are easy to grasp and manipulate					Parts present handling difficulties (1)				
		Thickness >2 mm			Thickness ≤2 mm		Thickness >2 mm			Thickness ≤2 mm	
		Size >15 mm	6 mm ≤ size >15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
		0	1	2	3	4	5	6	7	8	9
$(\alpha+\beta) < 360°$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
$360° \le (\alpha+\beta) < 540°$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
$540° \le (\alpha+\beta) < 720°$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
$(\alpha+\beta) = 720°$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

(Key: One hand. Parts can be grasped and manipulated by one hand without the aid of grasping tools.)

		Parts need tweezers for grasping and manipulation								Parts need standard tools other than tweezers	Parts need special tools for grasping and manipulation
		Parts can be manipulated without optical magnification				Parts require optical magnification for manipulation					
		Parts are easy to grasp and manipulate		Parts present handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present handling difficulties (1)			
		Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm		
		0	1	2	3	4	5	6	7	8	9
$\alpha \le 180°$, $0 \le \beta \le 180°$	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
$\alpha \le 180°$, $\beta = 360°$	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
$\alpha = 360°$, $\alpha \le \beta \le 180°$	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
$\alpha = 360°$, $\beta = 360°$	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

(Key: One hand with grasping aids. Parts can be grasped and manipulated by one hand but only with the use of grasping tools.)

Figure 1 – Representative Portion of Boothroyd-Dewhurst Manual Handling Time Chart

Another calculated factor used in the Boothroyd-Dewhurst methodology is the dimensionless assembly efficiency. Given in **Equation 1**, assembly efficiency (E) is calculated as a theoretical minimum assembly time divided by the actual assembly time (t). The theoretical minimum efficiency time is the minimum number of parts in the assembly (N) multiplied by the average assembly time for those parts (t_0, usually taken to be 3 seconds). N is counted by adding only the functionally essential parts in an assembly (i.e. fasteners removed). This quantity is calculated in the case studies below as a relative metric that provides a measure for how much "better" one assembly design is over another.

$$E = \frac{N \cdot t_0}{t} \qquad (1)$$

There are many additional factors that can be included in the Boothroyd-Dewhurst methodology to take into account part handling and insertion complications. Some of these include additive factors for part weight, fastener type & length of engagement, difficulty of part insertion, and other geometric handling constraints. An underlying assumption throughout our analyses of assembly times is that these factors are secondary considerations to the part characteristics explicitly listed in the Boothroyd-Dewhurst handling and insertion time charts. In general we've seen this assumption to be valid with about 10% accuracy. An assembly with some unusual characteristics might require the inclusion of one or more of these excluded factors to maintain sufficient accuracy.

In a pure Boothroyd-Dewhurst analysis the total assembly time for a specific operation is simply the handling time for the component added to the insertion time for the component. We modify this method slightly to take into account inherent inefficiencies present in the case of a single assembly technician executing the assembly as a multi-step process, instead of looking at each step in a vacuum. **Equation 2** gives the form of our assembly time (T) function, which includes three modifying coefficients. These three coefficients were identified as significant contributors to the case studies in question by using a sensitivity analysis. C_1 is the setup penalty, a universal penalty assigned to the overhead required to reconfigure the assembly workspace for the next operation. C_2 is the number of setups required for a specific operation. This might be utilized in the case where the same screw is installed on opposing sides of an assembly, requiring repositioning of the assembly. C_3 is the number of passes, which is used in the case where the part insertion operation must be repeated multiple times (e.g. if a pattern of screws must all be inserted then a second pass is required to tighten them). I and H are the traditionally calculated Boothroyd-Dewhurst insertion and handling times, respectively. C_1 and C_2 modify the handling time H, while C_3 modifies the insertion time I. Most of these considerations could be captured as separate operations, but the coefficients allow them to be combined for simplicity.

$$T = (1 + C_1)C_2H + C_3I \tag{2}$$

In general our process for investigating assembly time optimality is to first build a baseline model by inputting all process steps required to construct the assembly into a single list. Then, coefficients are assigned based on our understanding of the assembly process and workspace. Boothroyd-Dewhurst handling and insertion times are calculated either with a manual lookup table or via an automated tool. These factors are summed according to **Equation 2**. Assuming good model correlation with actual build data, the model can then be used to explore the assembly time impact of various design alternatives.

CASE STUDY 1 - COST REDUCTION OF A PROTOTYPE DESIGN

The first case study we will consider is a cost reduction and DFM program we completed for a company which manufactures electro-optical assemblies for use in lab-based laser focusing applications. We conducted a comprehensive DFM audit and cost optimization on a multi-channel subassembly of moving optical components. The positioning and tolerance requirements were strict, the material choices were limited to survive a harsh environment, and they desired at least a 30% reduction in BOM and assembly cost. The client had one working prototype, and desired a re-design that would enable them to ramp to production quantities of several hundred units per month. **Figure 2** shows a CAD model of the original client prototype of the multi-channel optical focusing assembly.

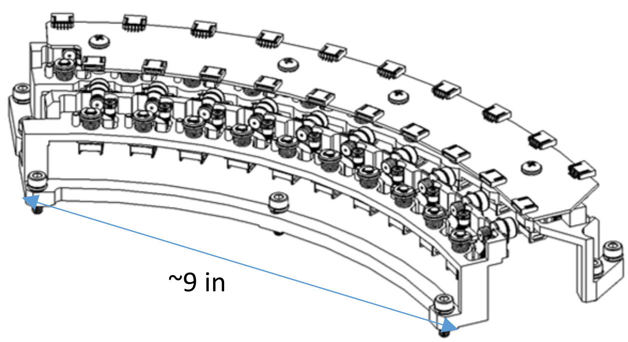


Figure 2 – Original Client Prototype Model

In order to estimate and optimize the time required to assemble the subassembly, we first built a predictive model based on the client's existing prototype using the Boothroyd-Dewhurst methodology outlined above. As we made changes to the baseline design, we could immediately see what impact those changes had on predicted assembly time. Our baseline model also allowed us to target and optimize the steps which most significantly contributed to assembly time. **Figure 3** below shows the Pareto chart for the baseline assembly model; 50% of assembly time is localized in 20% of the parts, and the longest single contributing operation is 28% of the total assembly time. We used this model throughout the design as input to our design tradeoffs and select design concepts that reduced assembly time as well as part cost. Our assembly time model of the baseline design (the client's prototype) was correct within 8% to the actual time it took the client to assemble the prototype. The client's prototype required an hour for a technician to assemble; our model predicted .925 man-hours required with an assembly efficiency of 16.6%. This translated to a cost burden of under $50 per assembly for US manufacturing, or $10 per assembly in the Far East. In either manufacturing locale, it was a significant cost component with respect to the COGS for the prototype. Previous to the implementation of our Boothroyd-Dewhurst assembly time model, the client had not known how to estimate assembly cost or which areas of the assembly to target for cost optimization.

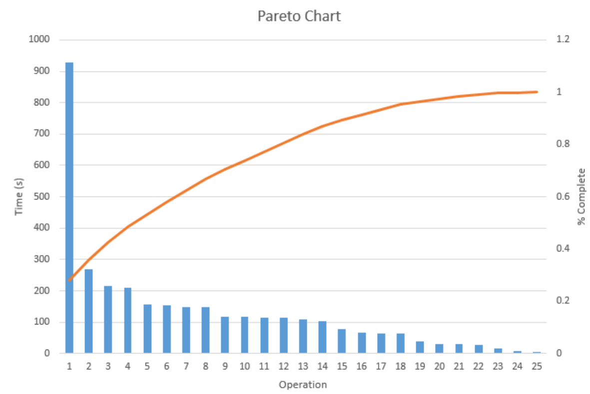


Figure 3 – Baseline Assembly Model Pareto Chart

At the conclusion of our cost reduction and DFM process, the predicted assembly time was decreased from .92 man hours to .43 man hours, and the assembly efficiency increased from 16.6% to 20.7%. The original assembly contained 374 parts, which was reduced to 148 parts. This represents a significant cost savings per assembly in the US, or a total yearly savings that well exceeds $100,000, depending on the final manufacturing venue. **Table 1** contains a representative portion of our assembly time model for this subassembly, where each line is an assembly operation in the original client prototype. Lines highlighted in blue are parts or operations removed from the baseline, while green blocks and lines are modifications in process or additional process steps added to the baseline to create the DFM-optimized design. For this relatively small implementation of the assembly time model, we manually entered insertion and handling times for various operations from the corresponding Boothroyd-Dewhurst charts. We assigned corresponding coefficients (see **Equation 2**) based on our knowledge of the anticipated assembly plan. As mentioned above, we ignored all refining considerations like screw type & engagement, extra part alignment penalties, and part weight penalties, since we were able to achieve model accuracy within 8% without these additional considerations.

Table 1 –Assembly Time Model, Optimized Design

Focusing Module DFM
Touch Labor Rollup

Burdened Labor Rate $/hr		
US:	$50.00	1.39 cents/sec
China:	$11.50	0.32 cents/sec

Setup Penalty
25 %

	Description	Operation	Qty	Min Qty	# Pass	# Setup	Handling (s)	Insertion (s)	Total Time (s)	Operation Cost
1	Base	Manipulate	1	1	1	1	3	0	3.75	5.208333333
2	Mounting Bar	Snap	2	2	1	1	1.95	5.5	15.3875	21.37152778
2.1	Spring Pin	Press	0	0	0	0	2.18	3.5	0	0
2.2	Rocker Gear	Place	20	20	1	2	1.8	5.5	146.9	204.0277778
2.2.1	Optical Element	Bond	20	20	1	1	1.43	4	108.9575	151.3298611
2.2.2	Shaft	Bond	0	0	0	0	1.8	4	0	0
2.3	Bushing	Place/Press	20	20	1	1	2.35	5	147.5875	204.9826389
2.4	Bushing	Place	0	0	0	0	2.35	1.5	0	0
2.5	Spring	Snap	1	1	1	1	5.1	9	15.375	21.35416667
2.6	Washer	Hold	20	0	1	1	1.69	1.5	64.2225	89.19791667
2.7	Washer	Hold	0	0	0	0	1.69	1.5	0	0
2.8	Snap Ring	Snap	0	0	0	0	2.18	3.5	0	0
2.9	Pinion Shaft	Press	0	0	0	0	1.69	3.5	0	0
2.10	Pinion	Place	20	20	1	1	1.88	3	98.07	136.2083333
2.11	Snap Ring	Snap	0	0	0	0	6.85	3.5	0	0
2.12	Stepper Motor	Snap	20	20	1	4	2.25	4.5	137.25	190.625
2.12.1	Worm Gear	Bond	0	0	0	0	1.88	4	0	0
2.12.2	Motor Plate	N/A	20	0	1	1	0	0	0	0
2.13	Phillips Screw	Screw	0	0	0	0	2.35	11	0	0
3	Washer	Hold	0	0	0	0	2.18	1.5	0	0
4	Lock Washer	Hold	0	0	0	0	2.18	1.5	0	0
5	Hex Screw	Screw	0	0	0	0	2.35	11	0	0
6	Stepper Board	Snap	1	1	1	1	1.95	5.5	7.9375	11.02430556
7	Standoff	Screw	0	0	0	0	2.35	7	0	0
8	Phillips Screw	Screw	0	0	0	0	1.8	11	0	0
9	Motor Cables	Solder	80	0	1	1	3.6	3.5	568.9	790.1388889
10	Top Cover	Snap	1	1	1	1	1.95	4.5	6.9375	9.635416667
11	Shoulder Screw	Screw	20	0	1	1	2.35	8.5	217.5875	302.2048611
								Totals:	**0.427461806 (man-hours)**	**21.37309028 (dollars)**
								Asm Eff:	**20.66461428 %**	

In order to accomplish these assembly time savings, there were several DFM best practices that we implemented in the design of the optical assembly. We consolidated the support structure from two aluminum mounting bars to one glass-filled plastic mounting assembly. We eliminated screws and snap rings from each of the optical channels and replaced them with drop-in crush rib locating features and snap fastening features. We eliminated an idler gear from the positioning gear train, and changed the gear material from machined aluminum to molded plastic. **Figure 4** shows a comparison of just the optical channel components in the client prototype (left) and in our recommended design (right).

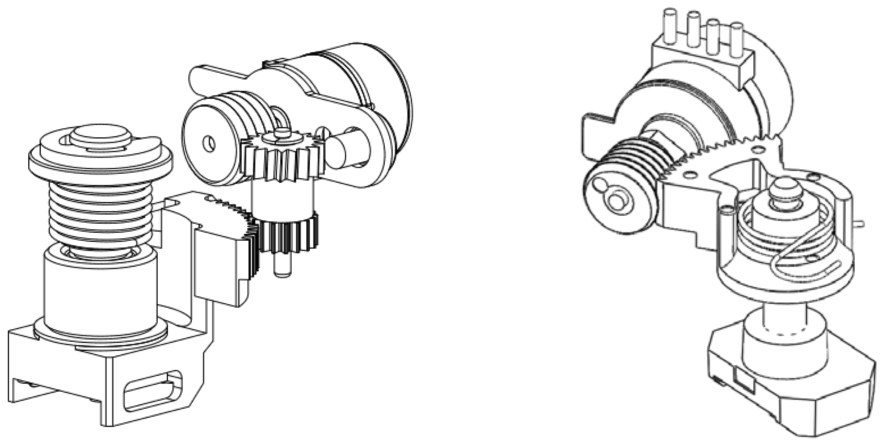


Figure 4 – Optical Channel Components, Before and After Assembly Optimization

The optical element mount was simplified and combined with the rotational shaft in a co-molded part for installation simplicity. The overall strategy employed in re-designing the assembly was to move to a paradigm where each component of the optical channels simply dropped in to a lower mounting bar, then a single compressive retention part would be added to retain all the motors and drive trains simultaneously. This strategy was informed at a conceptual level by the Boothroyd-Dewhurst distinction between "handling" and "insertion" time, and by the time saved by just "placing" a part in the assembly vs. "securing" it in the same operation. In our optimized design we achieved a method for more than 80 parts to be placed into the assembly and secured in place in one operation, minimizing required assembly time. Our design also allowed us to do this in a way that met the very strict positioning and tolerance requirements inherent in the application. **Figure 5** shows this assembly concept both in the preliminary CAD model and accomplished in practice with our re-designed prototype. Compare this to the client's initial design in **Figure 2**, and it's easy to see qualitatively how much more rapidly the optimized design can be assembled.

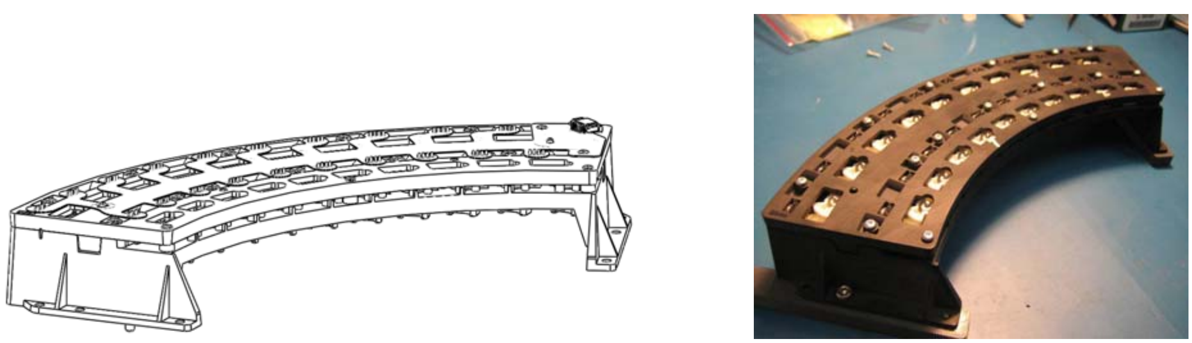


Figure 5 – Optimized Assembly Concept, in CAD and First Prototype

It is worth noting that because the client engaged in assembly time optimization early in the product design cycle during a planned design spin, "return on investment" is synonymous with "cost savings" in this case study. In addition to the assembly time savings outlined above, we were able to reduce just the COGS by 35% using the part consolidations and material and process changes discussed above. Including both assembly cost and COGS, we achieved a gross savings of around $50 per assembly, or around 35%, which translates to about half a million dollars saved annually in production. Our first prototype of the optimized assembly took 30 minutes to assemble, which closely matches the 26 minutes predicted by the optimized Boothroyd-Dewhurst model (especially when taking into account the first-time assembly learning curve).

CASE STUDY 2 – COST REDUCTION OF A TOOLED ASSEMBLY

The second case study we will consider is a cost reduction and DFM optimization we completed for a company that manufactures large-scale industrial test equipment. They had a test apparatus already in pre-production which they were planning to manufacture in a quantity of 14,000 units. Their desired assembly time target was for a technician to be able to assemble a unit in less than three hours, but presently it was taking about 6.5 hours. Spread over the entire manufacturing run, this over-2x assembly time delta represented a huge area of increased costs for our client.

We were tasked with brainstorming and feasibility analysis for methods to reduce the assembly time. This was made more challenging by the fact that the client had hard tooling in place for most molded plastic parts in the assembly, so our goal was to minimize any changes to part tooling. This constraint, along with the focus solely on assembly time and not on COGS, are the main differentiating factors between this and the previous case study. **Figure 6** shows a CAD representation of the client's test apparatus. It consists of several repeated sub-assemblies, including ten unit-testers and five fan assemblies which are all assembled into the top level pictured here.

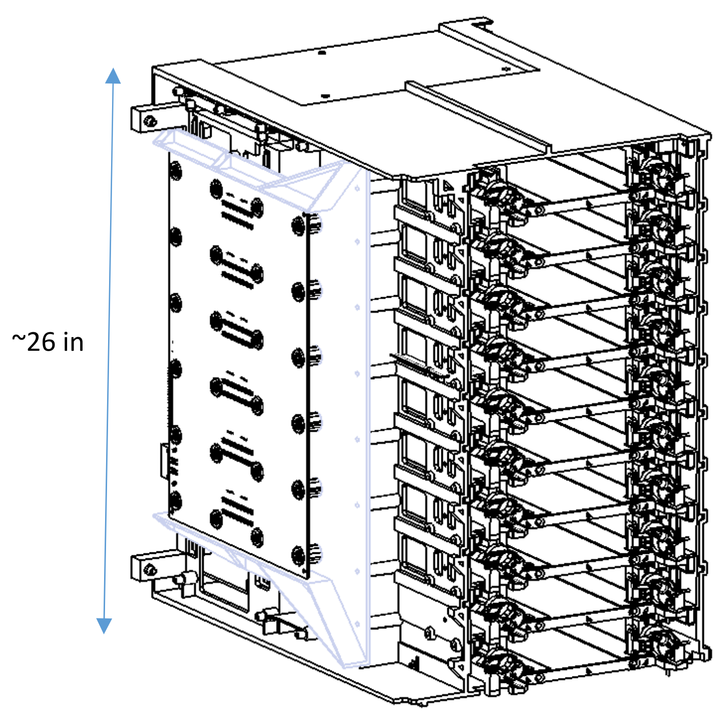
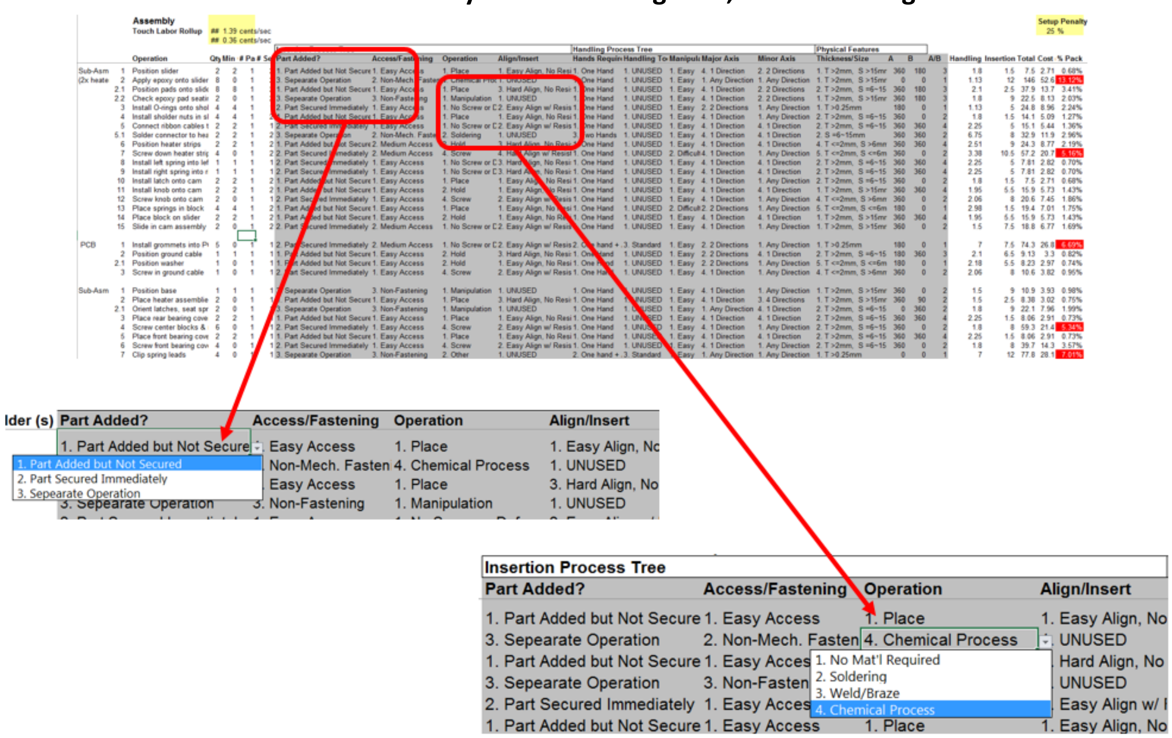


Figure 6 – Test Assembly to be Optimized

As in the previous case, we began our analysis by building a theoretical assembly time model which we could then use to predict the effect of proposed design changes. We carried through the same assumptions, ignoring secondary time modifiers and extra penalties. Unlike the previous case, we refined the implementation of our model to eliminate the need to hunt and peck across the handling and insertion operation time charts. Instead, we used a tool which maps the nested operation characterization statements from the charts into Excel drop-down menus and converted the Boothroyd-Dewhurst chart to a lookup table. The baseline model was significant, containing over 1700 individual parts. This tool allowed us to easily track an assembly of that size since it is functionally halfway between the manually-operated charts and the DFMA software offered by Boothroyd-Dewhurst, Inc. In terms of overall accuracy the tool still suffers from the +/- 10% limit inherent in the previous case, which is an advantage of the DFMA software. For a first-pass order-of-magnitude tool that can be easily used to rapidly evaluate tradeoffs between various design concepts, we found our tool to work very well.

Table 2 shows a representative portion of the baseline assembly time model prior to any attempted optimizing design changes. The white portions on the sides contain data similar to the columns in **Table 1** (operations, quantities, coefficients, calculated insertion and handling times, and resulting costs), but the center greyed-out block contains all the multi-selection drop-down menus corresponding to the process of reading a Boothroyd-Dewhurst chart. The selections from these menus drives the insertion and handling time calculations on the right. The final thing to note in this table is that any operation that contributes more than 5% of the total assembly time is highlighted in red on the far right. This, along with a Pareto chart similar to the one shown in **Figure 3**, gave us a good idea of the operations to target first for potential design changes and optimization.

Table 2 – Assembly Time Modeling Tool, Baseline Design

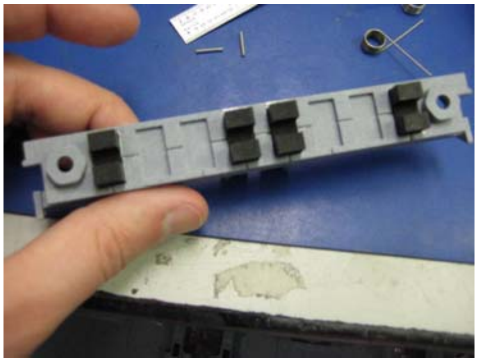


Since the design was already in pre-production, we had much higher-resolution data available to us here than in the previous case. We compared our predictive model against actual assembly time study data at the top assembly level, the sub-assembly level, and at the individual operation level. At the individual operation level we found errors as much as 20% to be common between the model and empirical data, and in some cases we found errors as much as ~200%. This is primarily a result of the previously-discussed assumptions we made in both cases to ignore modifying factors. However, on the sub-assembly level we found these discrepancies tended to cancel out and across three sub-assemblies investigated, the largest discrepancy between the model and empirical data was only 5%. At the top level, the accuracy discrepancy was only 2%. This gave us great confidence that changes we made to the predictive model to investigate potential design changes would be reflected in reality. **Table 3** shows a representative sub-assembly-level comparison between measured assembly times and those predicted by our Boothroyd-Dewhurst model.

Table 3 – Model-Predicted Assembly Times vs. Empirical Data

Step	Actual Time	Model Time	Notes
BLOWERS:			
apply epoxy to flap base	15	13.5	without epoxy mixing time
position flap base onto fan	13	15	Clean up operation not in model
backfill gaps	17	26	
place PSA onto jig	20	26	
press fan onto PSA	20	29	
orient blower weldment	5	10.8	
install first blower	24	4.4	Include PSA mask removal?
re-orient blower weldment	5	12.7	
install second blower	21	4.4	
route cables	16	23	
route ribbon cables	17	24	
place blower assembly into duct cover	12	12.7	
screw assembly	93	55	manual driver, check cables
flip assembly over	3	13	
screw assembly	31	23	
check cable movement	7	22	
snap on blower flaps	15	14	
check blower flap movement	4	11	
Totals	**338**	**339.5**	

For each of the significant time-contributing operations identified in our baseline assembly time model, we brainstormed 3-4 potential modifications we could make to reduce the assembly time. These brainstormed solutions ran the gamut from fixture and process changes that wouldn't require changes to the tooled plastics, to potential solutions that would require tooling changes. Because of these diverse options, return on investment (ROI) became a significantly more important consideration here than in the previous case. **Figure 7** shows a representative example of an area we identified for improvement along with one of several potential solutions. One of the subassemblies in the unit required rubber bumpers to be epoxied to a plastic slider. This epoxy operation was very time consuming since it required mixing and dispensing of the epoxy, placement of the bumpers, and checking the finished part in a fixture to assure the bumpers were seated correctly. This operation in total was a 10% contributor to the unit tester sub-assembly, and since the unit tester sub-assembly is repeated multiple times in the top level assembly, this single operation took 8% (24 minutes) of total build time at the top assembly level. Our proposal involved changing the epoxy application in four places to a single bumper with a pressure-sensitive adhesive backing. This would require minor changes to the existing plastic slider tooling, and a new rubber bumper part with a PSA backing. The gross savings of this change would be around $100,000 in Malaysian labor across the entire product build, but when factoring in the cost to make the design modification late in the product cycle and change the existing tooling, the ROI is reduced to around $75,000. This is still a worthwhile change to make, but not as attractive as it could have been if DFM and ease of assembly had been taken into account earlier in the original product design.



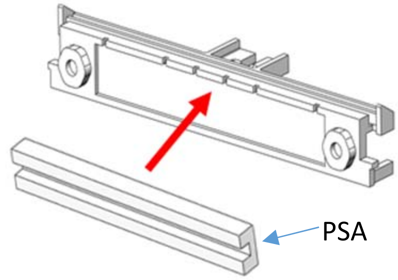


Figure 7 – Original Epoxied Rubber Bumpers and Proposed Change

This process of problem identification and solution evaluation was repeated 30 times across all three subassemblies in the product. In the end we compiled a matrix of potential design changes along with their associated development risk and ROI. By selecting the brainstormed design options with the highest ROI, we developed a comprehensive strategy across the assembly for modifying the existing design and assembly plan to decrease the assembly cost. A chart of our recommended mitigation plans in all the problem areas of the assembly is presented in **Table 4**. We selected options with low associated development risk and the best ROI, which yielded an assembly time savings of 3.6 man-hours. Subtracted from the 6.5 man-hours expended to assemble the original design, this optimized design can now be assembled in 2.9 hours, below the 3 hour goal. The assembly efficiency at the top level increased from 7.6% to 14.9%, with corresponding increases in each of the sub-assemblies.

Table 4 – Selected Design Changes to Reduce Assembly Time

Selected Option	Description	Est. Time Savings (s)	% Total	Est. Assembly Cost Savings	Est. Tooling	Est. NRE	Part Cost Delta	Est. ROI	Risk	Part cost notes
1.2	Single bumper, simplified attachment	1860	9.3%		$8,000	$10,000	$0.00		Low	
2.1	PSA heater to bumper	740	3.71%		$2,000	$10,000	-$1.00		Low	-screws&shoulder nuts
3.s	Modify spring to cut length	780	3.91%		$1,000	$0	$0.00		Low	
3.1	Snap-in cam assembly covers	1110	5.6%		$30,000	$10,000	$0.00		Med	-screws +slot plastics
pm	One-way snap to retain pusher	485	2.4%		$10,000	$5,000	$0.00		Low	-screws +pusher plastics
4.1	Isolation washers, snap-on wireform	1530	7.7%		$10,000	$10,000	$0.00		Low	-screws&washers + wireframe
5.1	Customize blowers	520	2.6%		$8,000	$5,000	$0.00		Low	
6.1	PSA strips	95	0.5%		$0	$2,000	-$0.50		Low	-diecut psa
7.1	Snap-on covers to blowers	560	2.8%		$5,000	$10,000	$0.00		Low	
7.2	Custom install of blowers into weldment	1220	6.1%		$30,000	$15,000	-$1.00		Med	-duplicate blower shroud
8	Frame tool change	900	4.5%		$20,000	$0	$0.00		Low	
cr.1	Change PCBA layout & mounting	972	4.9%		$20,000	$10,000	$1.00		Low	+sheetmetal hinged frame
cr.3	Route slot cables out side of pack	1155	5.8%		$30,000	$15,000	$0.20		Med	+slot cable retainer
si.2	Slot divider tray modifications	1014	5.1%		$10,000	$10,000	$0.00		Low	-screws, +wireframe
	Totals	12941.00			184000.00	112000.00	-1.30			
		3.59472222 hours								

The ROI over the 14,000 unit build is well over $300,000 in labor cost. It is worth noting that if we selected design options based on the best assembly time savings instead of best ROI we arrive at a total time savings of 4 hours instead of 3.6, but the ROI is reduced to below $200,000. This indicates that if this Boothroyd-Dewhurst model had been implemented earlier in the design process to optimize assembly time (i.e. before hard-tooling all the plastic parts), with our suggested design changes a total assembly time of 2.5 hours would have been possible.

SUMMARY AND CONCLUSIONS

As has been noted previously, one of the biggest juxtapositions between the two anecdotal cases presented here is the point in the design cycle at which the need for assembly time optimization was addressed. In the first case, 100% of our client's cost savings were realized because the assembly optimization occurred as part of a planned design spin. In the second case, a significant portion of our client's cost savings were re-absorbed by the cost to change tooling and make late-stage design changes. The lesson which can be inferred is that the earlier in the design process one considers assembly cost, the easier it is to realize meaningful cost savings in that area (and the more your manufacturing department will love you). **Table 5** summarizes the results from each case study in terms of overall assembly time savings discovered and overall model accuracy.

Table 5 – Summary of Case Studies

	Case 1 - Optical Assembly	Case 2 - Test Assembly
Initial Assembly Time (hrs)	0.92	6.5
Optimized Assembly Time (hrs)	0.43	3.6
Assembly Time Reduction	29.4 min	2.9 hrs
Assembly Cost Savings (per unit)	~$5	~$50
COGS Cost Savings	$40 (35%)	N/A
Build Quantity	12,000/yr	14,000/yr
Total Client ROI	~500K	>$300K
Model Correlation	10-14%	2-5%

There are a few caveats that should be noted when extrapolating lessons from these two case studies. Both designs were intended to be assembled manually by a single technician. Other Boothroyd-Dewhurst models apply for cases where parts are assembled by automation, or in the case of more complex manufacturing schemes (e.g. production lines). Both electro-mechanical assemblies considered here were composed at least in part of many duplicated sub-assemblies. Thus when a time savings was achieved at the sub-assembly level, significant savings was achieved at the top level due to a factor of ten multiplication. Flatter assemblies without as many duplicated sub-assemblies might be harder to optimize. Finally, it is worth stating again the assumptions we made in not including additional modifying factors like screw type, thread engagement, part weight, and a myriad of other part characteristics for which a complete treatment of the Boothroyd-Dewhurst methodology fully takes account. In these two cases the exclusion of these details still got us within 10% of the true assembly time (which is accurate enough for a first-order-of-magnitude analysis); however, it may be possible in fringe cases to exacerbate these errors (e.g. if the assembly included only safety screws or other difficult-to-install fasteners).

Even with these qualifications, these case studies demonstrate that the Boothroyd-Dewhurst method for assembly time estimation is an accurate, useful design tool, and is an essential component of a comprehensive DFMA strategy.

REFERENCES

[1] Boothroyd, Dewhurst, Knight, 2011, Product Design for Manufacture and Assembly, CRC Press