AGILE ANALYSIS OF MANUFACTURING CELL COSTS FOR MOLDING OF SMALL COMPOSITE PARTS

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ABSTRACT

In 2016, RApid High Performance Molding (RAPM) for Small Parts was initiated by a Boeing-led team and the U.S. Government (DARPA) under the guidance of the United States Army Research Office to revolutionize the cost paradigm for small composites parts enabling pervasive use in defense applications that are insensitive to part mix and rate fluctuation. This paper discusses the cost modeling effort to predict the cost implications for the technology development efforts pursued in the program and their appropriateness in various production environments, the value proposition for reconfigurable tooling concepts, selected trade study results, and potential applications and implications of the technologies evaluated in RAPM.

1. INTRODUCTION

The RAPM program is actively developing manufacturing methods of small composite parts for three processes: resin infusion, thermoset prepreg forming, and thermoplastic forming [1]. Each process employs different feedstock materials, some being produced in large quantities for active aerospace production, while others are currently developmental candidates designed for the RAPM use-cases. An array of different part geometries are also used to highlight improvements over the state-of-the-art composite limitations. To physically measure the manufacturing costs of each geometry, material, and process combination would require tremendous engineering and manufacturing resources. Therefore, the observed actual or expected processing time data, capital expenditure estimates, and tooling costs provided by the RAPM tracks have been compiled into various predictive cost models.

The scope of RAPM cost analysis work can be separated into three main categories. First, each process was individually modeled with the available information to reflect the absolute cost of representative small parts with geometric features of interest. This was used to predict the major cost drivers for each manufacturing track and focus the subsequent technical development work.

Second, and to a lesser extent, reconfigurable tooling concepts were investigated as possible rate-enablers. By assessing the change in non-recurring costs for generic part families, and accounting for expected changes in tool changeover times, the overall value of new tooling approaches can be understood.

Lastly, a systematic scenario-based model was built to estimate the value of a marginal increases in capital on overall cell performance. Each of these three analyses methods, and the associated conclusions impacting RAPM, are described here.

1.1 Cost Data Limitations

The cost analysis presented here was performed alongside development activities with the intent to steer priorities and actively inform part selection. Therefore, the accuracy and completeness of cost model inputs have improved as connected data becomes available or the processes are more fully understood. Whenever possible, motion studies (a.k.a. time studies, timed trials, etc.) were performed by Boeing personnel on-site with the processor while manufacturing representative parts. This is the preferred data collection methodology, as it ensures the collection of all necessary data in a complete and unbiased way. However, due to the nature of the program being supported across several sites and companies, many process times could not be observed and were provided by the appropriate engineers and returned as a worksheet. For non-recurring costs like tooling and equipment, a combination of actual procurement costs (when available) were used, along with quoted estimates or engineering estimates if necessary.

"Actual" cost information is typically sensitive and proprietary, so it is carefully treated during analysis and public distribution. A common practice in corporate manufacturing cost estimates is to describe the material weight, labor hours, cycle time, and non-recurring costs individually in units of mass, time, and dollars. While that approach does offer some advantages in transparency, it fails to highlight the comparative advantage of recurring or non-recurring elements of various processes, since the units and assumptions cannot be translated into a standard cost unit without revealing sensitive information. Therefore, the calculations used for this work were internally communicated in United States Dollars (USD) but will be reported as either a percentage of the baseline calculated costs or USD when representing a range of values. The constituent costs and assumptions, like actual procurement values and overhead burdened labor rates, are strictly proprietary information.

1.2 Software Tools

Commercial-off-the-shelf (COTS) software tools available today are well-suited for leveraging historical data and capturing extended effects of complex fabrication flows. However, a significant amount of detailed work is necessary to aggregate and "calibrate" data into the necessary formats before using COTS tools. Given the new design and processing space under consideration for RAPM, the cost-analysis for this program will be comprised of bottom-up calculations, as well as some analogous estimation. Currently, all models and charts were developed in Microsoft Excel, although additional tools are actively under consideration for future optimization and visualization.

2. INDIVIDUAL PARTS COST ANALYSIS

2.1 Objective

The part-to-part cost investigation centered on the original set of parts being manufactured in the RAPM technology tracks. Using the original understanding of each process, along with expected procurement costs, this analysis sought to estimate the cost of deliverable parts through inspection. Furthermore, it aimed to identify which aspects of the production contributed most significantly to the overall cost, and how sensitive those cost drivers were to various assumptions. Finally, improved data was used to predict program cost savings for specific "challenge" parts with customer insight regarding demand requirements. In all cases, the cost of composite parts was compared to that of a baseline machined-aluminum geometry.

2.2 Assumptions

For all of the individual part cost analysis, a set of global assumptions was unchanged. These included variables like direct labor rates, overhead burdens (by category), and available shifts. The precise values used for full-scale production estimating are highly sensitive and distribution is tightly controlled. However, the approximations drawn from general experience, literature, and typical assumptions used within Boeing will have minimal effect on final results for the analysis, provided they are applied equally to all scenarios.

Normally, an aluminum to composite part trade would involve re-sizing the structure based on material allowables. For initial simplification purposes, the part volume and features were assumed constant. This assumption, therefore, affects the flyaway part weight and ply count. Therefore, the calculated composite costs are typically conservatively high compared to what may be expected from a structurally designed equivalent.

Material costs were defined in units of dollars-per-mass. In some cases, the specific negotiated values are sensitive so the approximate values for comparable materials from the same family are instead. When the material in question is developmental or non-qualified within Boeing, material suppliers provided engineering estimate tables that can be used for basic estimates. A curve, showing dollars-per-mass as a function of annual procurement volumes, was produced. To simplify the trade-space and use conservative assumption, the material rates corresponding to the smallest quantities provided were used. In future iterations of the model, this assumption may be removed or generalized. In all cases, a “buy-to-fly” (BTF) ratio was applied on top of the solid volume for a given part. This represents the wasted raw materials associated with nesting unique plies within rectangular rolls, as well as the trim excess included in the manufacturing. Based on literature and estimation, the BTF for most composite parts is typically between 1.20 and 1.35. The BTF ratio typically get worse, or larger, for smaller parts.

Raw aluminum costs vary significantly by alloy and grade. In this program, a typical value was provided by subject matter experts that represents an aerospace-grade aluminum purchased by Boeing in large stock quantities. Future iterations of “green field” manufacturing factories may consider less-leveraged purchasing rates. As the aluminum designs considered by RAPM are complex and machined, the BTF ratio is often in excess of 1.8 times the original billet quantity.

Equipment, like mills and presses, were applied to the part cost only for the duration in which the machine was being utilized. In other words, the machinery utilized for these parts was not dedicated to solely producing the parts in question. The total cost of the capital would be divided by its overall functional time to assess the impact of that operation. For example, a $1MM piece of capital may be assumed to support 1-shift operation for 10 years, resulting in a functional amortization rate of 50 dollars per hour of utilization. If a given part fully utilized the press for thirty minutes, its per-part cost would increase by $25.00. If, however, that same cycle produced a batch of 10 similar parts, then its per-part cost impact would be just $2.50 per part. In most manufacturing environments, besides extremely high-rate purpose-built facilities, capital is purchased with the intention of supporting a large variety of parts and this approach is appropriate. On top of the equipment utilization costs, a floor space cost would be applied to the time occupying manufacturing equipment. Based on industry values, clean-room floor space (for equipment like ply cutters) would be more expensive per-area than factory space (for equipment like presses). All machinery was assumed to have approximately a one meter wide perimeter of empty space beyond its footprint for accessibility.

Tooling is treated even more simply than equipment. For this model, the cost of the tool would be divided by either the cycle-life of the tool or the total units of the part being delivered to the program, whichever is smaller. In almost every case, the cycle-life of the tool (e.g. 100,000 cycles) is larger than the number of parts required for a fictional aerospace program (e.g. 5000 shipsets). If, however, less durable tooling materials were used in a high-rate environment, the program would be required to purchase replicate non-recurring costs to support a long production run. In the initial part-to-part estimates, the production run was assumed to be a multi-year program with a total of 100 shipsets being produced. Most small, specific composite parts in question would be represented only once or twice per shipset. This effect typically presents itself as a high amortized tooling cost.

A variety of other, smaller assumptions were also included in the calculations. The part scrap rate ranged from 2% to 10%, depending on the expected process and material robustness. As the processes mature and have added controls, the model values can be improved to better represent actual production. Consumable materials, like bagging materials and mold releases, were also included in the per-part material costs but typically played a minor role overall. Batch sizes for various processes/parts were typically assumed based on the current equipment being used by the manufacturing tracks. In general, the values used in these models represent the best-case performance that can be demonstrated today or reasonably expected outcomes in production environments. The effects of learning curves and further negotiated material rates were not incorporated.

2.3 Approach

Each process was modeled into is subsequent steps. Starting with the work done in RAPM Track 2 Resin Infusion [2], Track 3 Thermoset Forming [3], and Track 4 Thermoplastic Consolidation [4], their respective process steps were organized as either fixed times independent of the part (e.g. setting up a machine) or variable times that get multiplied by part properties (e.g. layup time as a function of the number of plies). A simplified example of the processing time form is shown in Figure 2. Key considerations for processing data are the steps, individual step times, affected batch size, and labor full-time equivalent (FTE). The FTE represents the "attention" required by a full-time worker to complete the step. For example, processes like post-cures may take several hours, but only require a few minutes of dedicated worker attention to complete, and would therefore have a small FTE. Combining those properties with the assumed labor rate provides an estimate for the associated labor cost of a given step.

Process	Process Step	Rate	[units]	Batch	[units]2	Cycle Time per Part [min]	Labor FTE	Direct Labor Cost	Equipment type	Tooling	Consumables [$/part]
Task 1	step 1	10	min/job	5	parts	2.0	1	[redacted]	Ply Cutter		
	step 2	2	min/job	1	parts	2.0	1	[redacted]	Ply Cutter		
	step 3	2	min/job	1	parts	2.0	0.5	[redacted]	Ply Cutter		
Task 2	step 4	5	min/part	1	parts	5.0	1	[redacted]			$ 1.00

Figure 2. Sample of process model raw data format.

The final part cost, similar to a "should-cost" or "cost of goods sold" (COGS), the labor, material, equipment, tooling, and other cost impacts must be calculated together. Figure 3 illustrates the scope of variables in consideration.

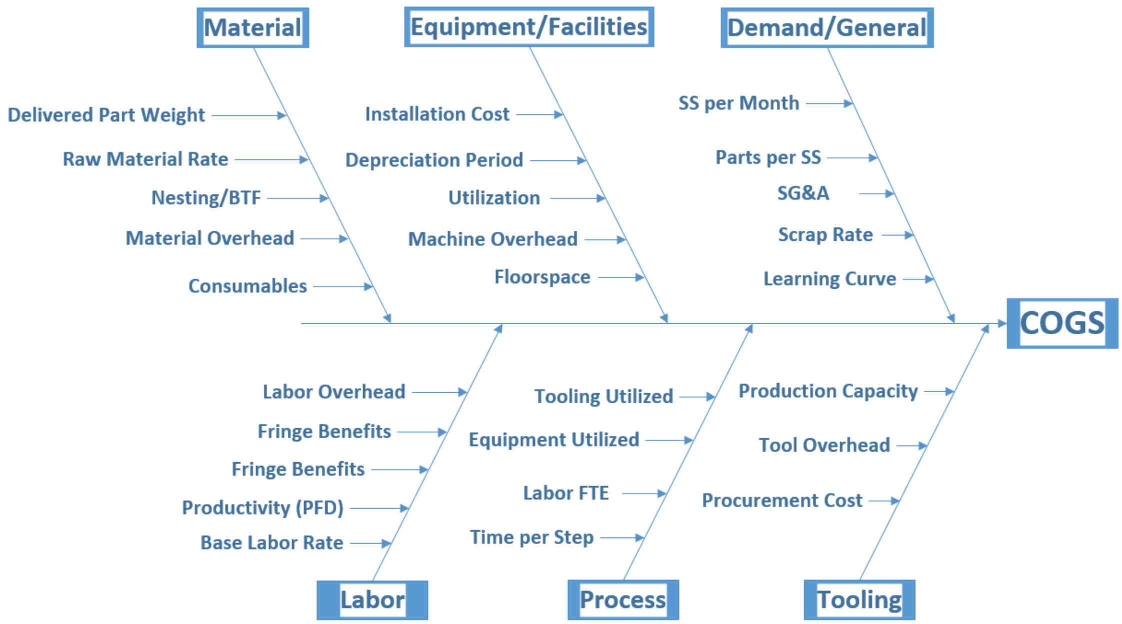


Figure 3. Factors incorporated into final part cost.

2.4 Results

The results for a given part, process, and material are typically displayed as a decomposed bar chart, as represented in Figure 4. Also, the individual process steps would be plotted sequentially to suggest which individual ones may be unduly adding to the labor cost of a part.

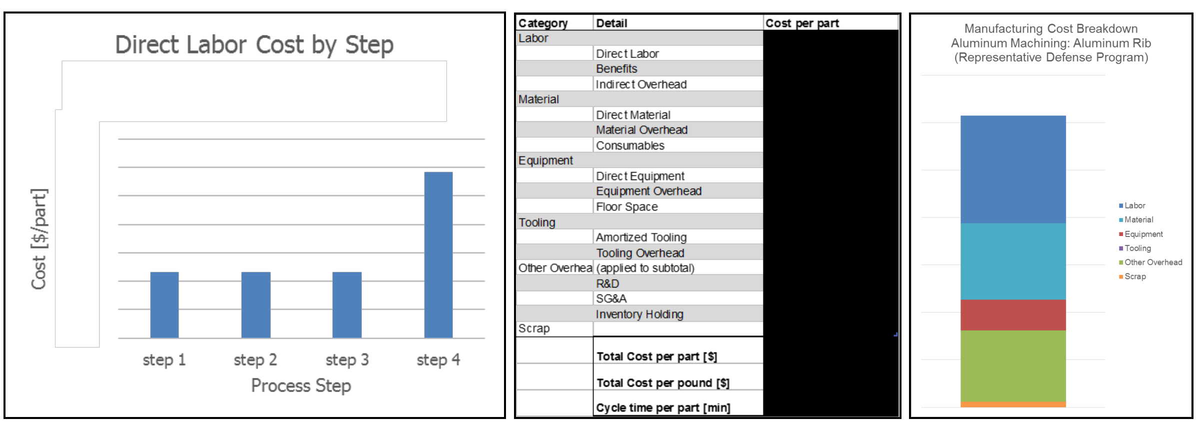


Figure 4. Sample of part-to-part analysis outputs.

At the time of performing this analysis, there was insufficient demonstrated data with RAPM thermoplastic forming to include in the part-to-part analysis. The parts of interest were the c-channel, rib, and both variants of the beaded panel. There was also interest in comparing a stamped aluminum beaded panel to a machined aluminum beaded panel, since the geometry (unlike others) was constant thickness and feasibly could be formed from aluminum stock sheet. For public distribution, the values have been normalized against a comparable machined aluminum baseline part.

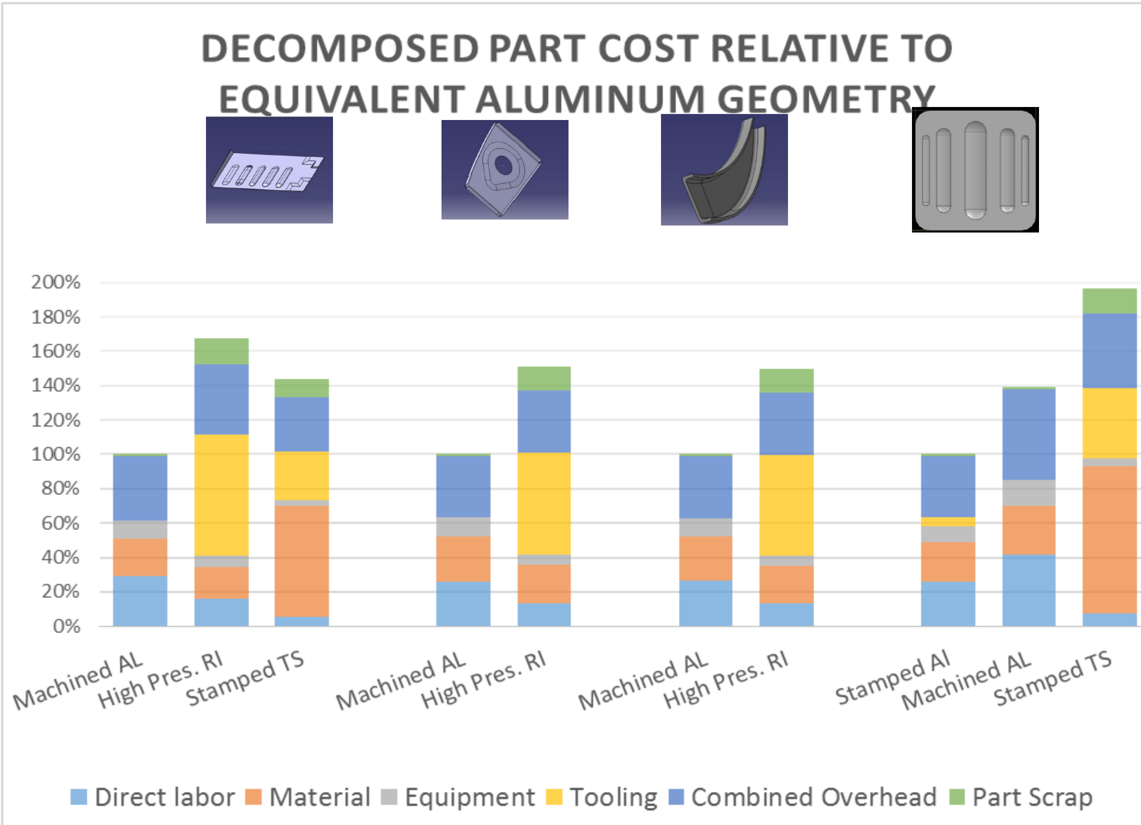


Figure 5. Initial part-cost outome.

For the early development of these processes targeting small parts, the decomposed cost data suggested areas of focus for the subsequent development. For infusion, the tooling cost was a large opportunity for further cost reduction. In thermoset forming, there is substantial value to be had by beginning with cheaper materials and decreasing waste in the process. Although not shown in Figure 5, structural thermoplastic carbon composite materials are currently expensive and the cycle time required a significant ramp-up and ramp-down time. In RAPM Thermoplastic Forming, those technical gaps are addressed via integration of the Surface Generation Performance to Functional Specification (PtFS®) system (specifically CF-OaO-RAPM-001 for Boeing) for configurations amenable to compression molding.

Basic sensitivity analysis was performed for key performance indicators of Track 2 Resin Infusion and Track 3 Thermoset Forming. A single assumption or variable would be modified within a large range and compared to the baseline machined aluminum cost, all as a function of production quantity of parts. By testing multiple variables in this way and observing the cross-over locations, it becomes clear which variables are worth individually targeting for further development. In Figure 6, for example, it is clear that changes in the material rate will drastically advance the break point of the specific part, compared to improvements in labor time, which would require drastic improvements in order to win the trade against aluminum. An important note, however, is that each of these curves represents changing one variable independently from all other variables. Practically speaking, the maturation of the technology will involve improvements on many fronts simultaneously and interactively.

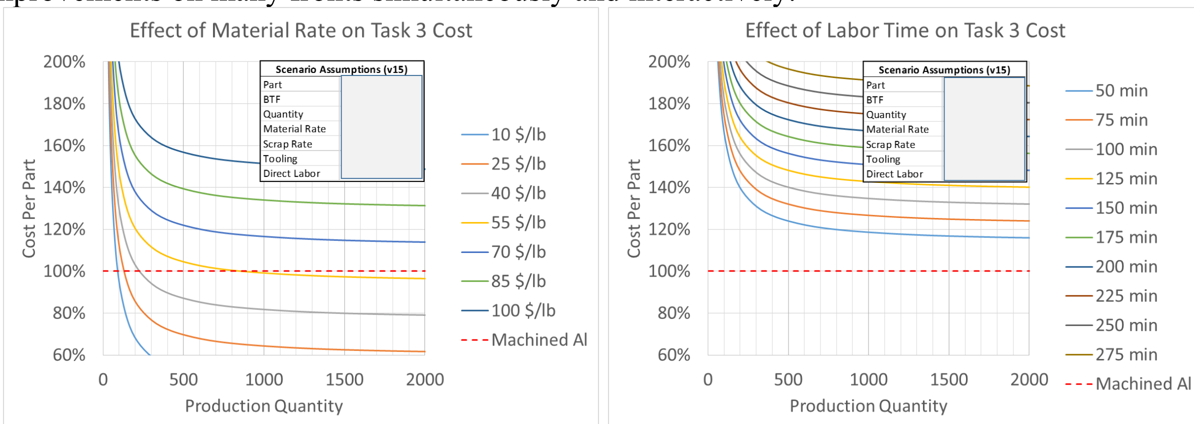
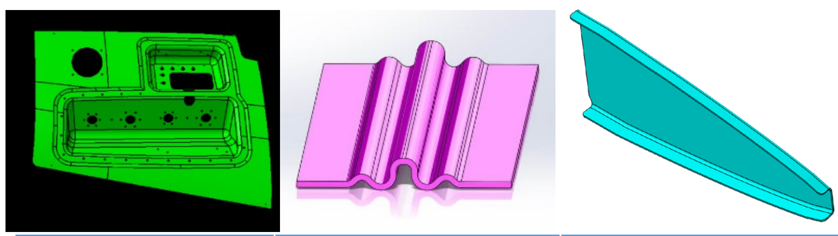


Figure 6. Sensitivity analysis during part-to-part.

The final component of individual part cost analysis specifically involved the three challenge parts, as seen in Figure 7. Each geometry is related to existing programs for reference, which enabled simple extrapolations of impacts to the program. As this analysis occurred much later than the initial part cost analysis, the processes being modeled were better understood and the baseline assumptions were also more robust.

The recurring manufacturing costs (plus tool amortization) of select challenge part families were compared to machined aluminum



	RI-RAPM-004 Deep Draw	TS-RAPM-012 Wave	TP-RAPM-013 Rib
Related Part Family	5 per SS	4 per SS	18 per SS
Weight Savings Per SS	5.6 kg (12.4 lbs)	1.8 kg (4.1 lbs)*	3.4 kg (7.4 lbs)
Recurring Cost Savings	67%	- 7%	12%
Potential Savings Over Life of Program	~ $3M	NA	~ $900K

* Opportunity exists to reduce weight additional 0.5 kg (1.1 lbs).

Figure 7. Challenge part cost analysis, with impact on program.

3. RECONFIGURABLE TOOLING COST ESTIMATES

3.1 Objective

For the purposes of this work, tooling is considered reconfigurable by either facilitating a rapid change from one mold face to another or minimizing the majority of the non-recurring costs associated with procuring custom mold faces. Reconfigurable tooling may have especially important implications in small part manufacturing cell environments. The three main types in consideration for RAPM are Surface Generation pixelated heating [5], Building Blocks (also known as "Lego Block"), and Tooling Inserts, as summarized in Figure 8. While there are potentially some improvements in part quality, the purpose of this cost assessment is strictly focused on the justification of tooling investments via cycle-time reduction.

Tooling Concept	Description	Advantages	Disadvantages
Baseline (Steel/Invar)	Traditional steel/invar, one-sided for autoclave and two-sided for press	Well-known design principles	One-part, one-tool; High fabrication costs
Surface Gen Pixelated Heating	Active/customizable heating and cooling system; actively controls thermal load across a mold-face via an array of pixels	Faster cycle-times (especially during cooldown); can be configured to prevent exotherms, cold-crystallization, and part distortion; Pixels can be rearranged to accommodate various geometries, decreasing fixed-cost associated with large design space.	Complex process design and setup-card verification
Lego-Blocks	Cast a thin mold face and support platen-side with standardized blocks to fill volume	Reusability of majority of tool volume for all geometries; reduced recurring cost for new geometries	Assembly required for each geometry; capital expense of reusable blocks
Similar Stackable Mold Faces, Inserts, and "Beer Crate" base	One part-family being produced by a base tool and a variety of pad-up mold-lines or swappable inserts for variable features	Reusability of majority of tool area for family; reduced recurring cost for new inserts; can be designed to accommodate Surface Gen	More details and fit requirements add procurement cost to the base tool

Figure 8. Three classes of reconfigurable tooling under consideration.

3.2 Assumptions

All Capital costs were based on representative or analogous procurements of tooling and machinery in the past. Of the concepts being estimated, only the Surface Generation Pixelated Heating system was procured and tested by Boeing for RAPM. Therefore, the cycle time impacts for Building Blocks and Tool Inserts were based off of available data and engineering judgment.

Surface Generation Pixelated Heating, as will be explained, is especially well suited for cycle-time reduction of high-rate thermoplastic fabrication, which demand a controlled cool-down during crystallization and reach higher temperatures than traditional epoxy. Therefore, thermoplastic fabrication was used for analysis purposes. Tool inserts, were simple to model for a family of small parts. However, the limited available data and understanding regarding Building Blocks prevented the tooling concept from being included in this analysis.

During the work described below, the CF-OaO-RAPM-001 work cell scenario will assume five procured tools on hand, and a varying number of replicates produced per tool. The Tool Insert analysis, however, will assume 20 replicate parts per too and vary the number of tools. Both have the effect of increasing total parts produced.

3.3 Approach

The Surface Generation pixelated heating system enables use of highly engineered heating and cooling cycles [5]. To benefit from the modular tool cells that control individual zones, each geometry requires a new mold face with specialized features as seen in Figure 9. Mold faces with precision machining on both faces (part-side and platen-side) require extra analysis and are approximately twice the cost to procure a comparable mold face. In addition, the control units required to run the system are a significant cost beyond that of a comparable platen-heated presses.

To approximate the break-even point for Surface Generation Pixelated Heating applied to thermoplastic fabrication, the improvement in cycle time over a large number of parts had to justify additional up-front costs. An imaginary scenario involving G geometries and R replicates, was used to represent production. The number of geometries, G, was fixed at five. Therefore, five unique mold faces plus the Surface Generation capital would be purchased and installed. Then, R replicates of each geometry were produced. The resulting per-part cost was plotted with other baseline thermoplastic processes as a function of total parts produced (G times R).

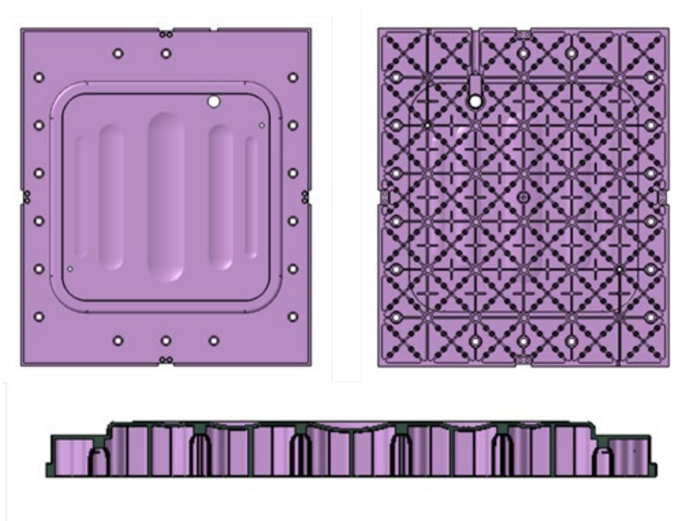


Figure 9. Representation of machined mold face. Courtesy of Surface Generation.

Tool Inserts will have the largest impact over traditional tooling for part families with many minor variants. The common features can be built into base tool while unique ones can be a part of modular sections of the tool assembly. Full tool changes and each tool-insert change is assumed to take the same amount of time as a traditional tool change.

For the analysis of Tool Inserts, as seen in Figure 10, a similar approach was taken to that described for the PtFS system. However, it was instead compared to Track 3 Thermoset Forming, from which the challenge part may be a strong candidate for Tool Inserts, and varied the total number of parts by increasing geometries, G, not replicates per geometry, R.

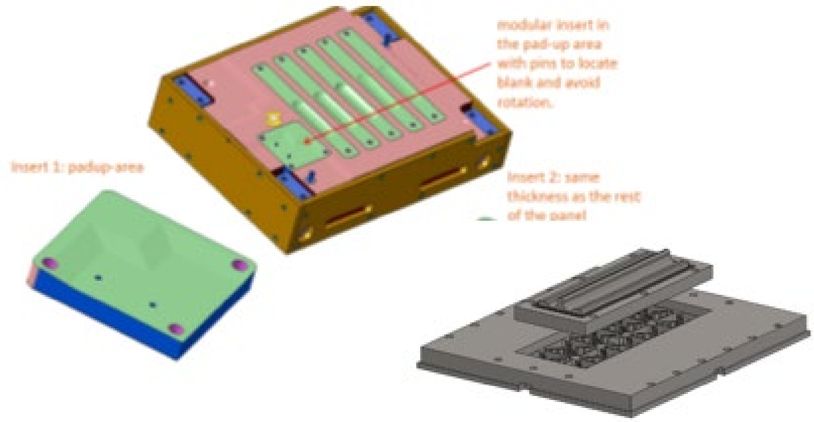


Figure 10. Representation of Tool Inserts. Courtesy of Solvay and Surface Generation.

Standardized building blocks allow majority of a tool volume to be comprised of reusable material. Figure 11 and Figure 12 provide an example of a Building Block tool without and with the mold-face cover. The part-specific mold faces may be cast to near-net-shape then machined. This can offer significant tool cost advantages for geometries with significant out-of-plane curvature, which would normally use very deep tools. Also these tools can be incorporated into the CF-OaO-RAPM-001 work cell for PtFS process controls. The tool-change times may be significant, however, and detract from business case for small runs. Additional investigation of the value proposition is needed once procurement costs and processing times are understood.

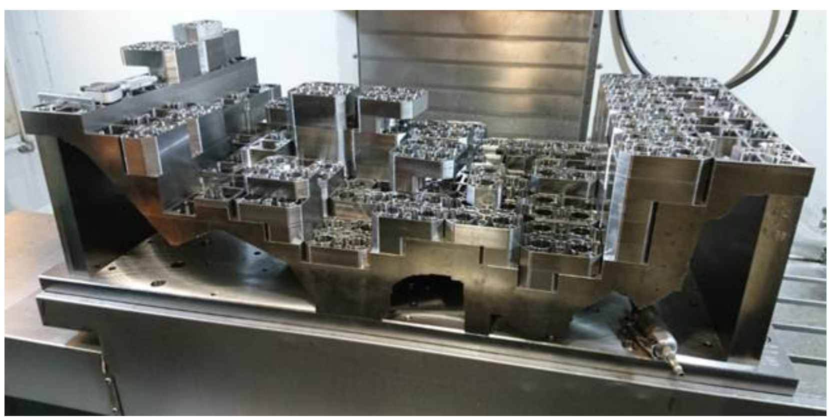


Figure 11. Representation of Building Blocks. Courtesy of Surface Generation.

Figure 12. Representation of Building Block and machined mold face. Courtesy of Surface Generation.

3.4 Results

Of the RAPM tracks, the best business case for using cycle-time savings to overcome capital cost is for mid-size thermoplastics, where cool-down time can be decreased significantly. See Figure 13, which shows the relative per-part cost as a multiplier of the baseline thermoplastic part cost. Note the logarithmic x-axis. When compared to baseline processes for a variety of run-sizes, it requires approximately 7000 parts of improved cycle time savings to justify the added capital and tooling cost for producing a set of five distinct geometries.

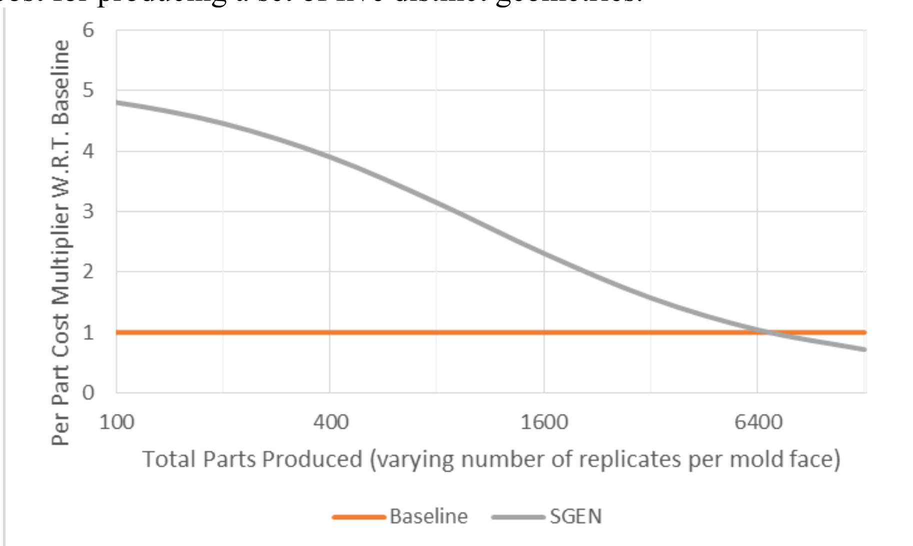


Figure 13. Break-even point for Surface Generation use with thermoplastic small parts.

For tool inserts, by contrast, the cost advantage is strongest when the number of applicable geometries to one base tool is highest. When compared to the baseline part cost for a variety of run-sizes, it takes approximately 100 parts to justify the carrier plate, as shown in Figure 14. To study the value of inserts in a highly utilized cell, the number of parts produced was varied by increasing the number of geometries per base-plate, not the number of replicates.

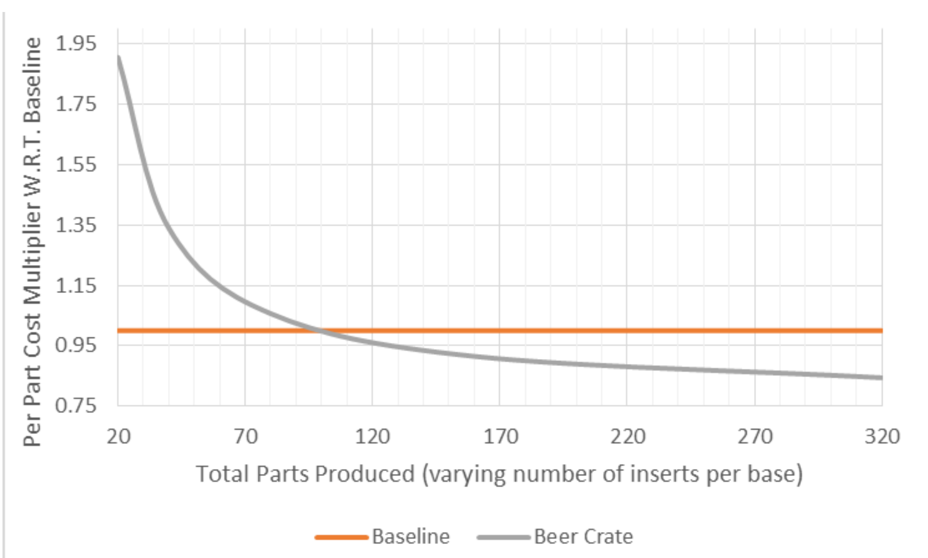


Figure 14. Break-even point for Tool Inserts use with thermoset formed small parts.

4. MANUFACTURING CELL ANALYSIS

4.1 Objective

In single-track cells, a program may be tasked with determining the level of investment needed to efficiently produce parts in a new facility. With limited foresight into specific part demand, making well-balanced capital investment decisions for long-run production is extremely challenging. The purpose of this analysis is to illustrate, specifically for composite small parts leveraging RAPM processes, the effect on part cost by adding automated capability and sophisticated capital into single-track work streams.

4.2 Assumptions

The demand, or required delivery rate, of a program typically is not a critical driver in the individual cost of a part. For the purposes of these estimates, numerous "scenarios" are used to represent that variability in demand. The most common scenario utilized in the preceding discussions was that of a generic defense production program, with approximately 100 shipsets produced over a 10 year contract. In this case, small wing sub-structure components would have a total of roughly 100 parts over which to amortize all of the combined tooling costs. A cell tasked with supporting this program will likely plan to make a small batch to deliver at a time, versus making all 100 sequentially and storing them for 10 years. By investing in specialized equipment, the times associated with changing tools and completing parts can be improved, thus changing the efficiency and agility of that cell to meet unpredictable program demands.

In collaboration with the RAPM manufacturing track subject matter experts, three "levels" of capitalization were designed to represent different version of independent cells. In total, there were nine track/level combinations being considered. The technical assets of each are described in Figure 15. The capital costs of each were aggregated, and the per-part cycle time was estimated based on prior work.

Several capital expenses were estimated to facilitate the analysis. When available, procurement costs for comparable machines were used. More often, however, estimates were provided by subject matter experts within Boeing. The final results would be minimally sensitive to the specific value assigned to a piece of equipment.

As explained below, the program is assumed to treat inventory costs of all small parts the same. This represents realistic delivery priorities for both commercial and defense programs. The analysis also assumes totally unique geometries, not similar tool faces. Also, the cells and operators downtime is not considered, nor are labor supply shortages. All parts are roughly 2.3 kgs (5 lbs) with flanges and radii that require NDI.

4.3 Approach

Each scenario was a totally independent demand environment from the others. For this analysis, a scenario is defined by three variables: the geometries being produced ("G"), the replicates of each geometry to meet program needs ("R"), and the lot size fraction ("L"). Lot-size fraction simply represents the tolerance of the program for holding inventory. These three variables drive the number of tools and tool changes being used in high-rate production.

	Level 1 Lowest Capital Cost	Level 2	Level 3 Highest Capital Cost
Resin Infusion	▪ Mid-size press ▪ Ply cutting table ▪ Post-cure oven ▪ Computer Numerical Control (CNC) Mill ▪ 2.4m (8ft) x 2.4m (8ft) NonDestructive Inspection (NDI) tank ▪ NDI standards, fixtures, and porosity coupons	▪ Mid-size press ▪ Tool mounted mixing ▪ Auto resin delivery ▪ Ply cutting table ▪ Post-cure oven ▪ CNC Mill ▪ 2.4m x 2.4m NDI tank with software control of tooling ▪ NDI standards, fixtures, and porosity coupons	▪ Larger press ▪ 2x tool mounted mixing ▪ Auto resin delivery ▪ Pick-and-place preforms ▪ Post-cure oven ▪ CNC Mill ▪ 2.4m x 2.4m NDI tank with software control of tooling ▪ NDI standards, fixtures, porosity coupons, and custom transducer arrays
Thermoset Forming	▪ Material freezer ▪ Mid-size press ▪ CNC Mill ▪ 2.4m x 2.4m NDI tank ▪ NDI standards, fixtures, and porosity coupons	▪ Material freezer ▪ Large press ▪ Post-cure oven ▪ CNC Mill ▪ 2.4m x 2.4m NDI tank with software control of tooling ▪ NDI standards, fixtures, and porosity coupons	▪ Material freezer ▪ Pick-and-place ▪ Large press ▪ Post-cure oven ▪ CNC Mill ▪ 2.4m x 2.4m NDI tank with digital control ▪ NDI standards, fixtures, porosity coupons, and custom transducer arrays
Thermoplastic Forming	▪ Ply cutting table ▪ Mid-size press ▪ CNC Mill ▪ 2.4m x 2.4m NDI tank ▪ NDI standards, fixtures, and porosity coupons	▪ Pick-and-Place ▪ Mid-size press ▪ Stamp form press ▪ CNC Mill ▪ 2.4m x 2.4m thermography system ▪ NDI standards and fixtures ▪ *only treating porosity over 1%	▪ Pick-and-Place ▪ PtFS® + press ▪ Automated shuttle system ▪ Stamp form press ▪ CNC Mill ▪ 2.4m x 2.4, thermography system with robotic control of tooling ▪ NDI standards and fixtures ▪ *only treating porosity over 1%

Figure 15. Nine track/level combinations with unique capital investments.

An “L” value of 1 represents no tool changes once the part production has begun. A fractional “L” value represents delivery of small batches of parts. So-called “just in time” production lines would have small lot-size fractions for their production cells. The effect of these variables s represented in Figure 16. Each column represents a unique demand scenario, although both yield the same mix of production assets. The letters represent entirely unique part geometries (with independent tools) being produced by the cell.

G3-R4-L1	G3-R4-L0.25
A	A
A	TOOL CHANGE
A	B
A	TOOL CHANGE
TOOL CHANGE	C
B	DELIVER
B	A
B	TOOL CHANGE
B	B
TOOL CHANGE	TOOL CHANGE
C	C
C	DELIVER
C	A
C	TOOL CHANGE
DELIVER	B
	TOOL CHANGE
	C
	DELIVER
	A
	TOOL CHANGE
	B
	TOOL CHANGE
	C
	DELIVER

Figure 16. Two scenarios with similar output, but significantly different costs per part.

Over 200 unique demand scenarios were tested. The number of geometries being produced ranged from 4 to 104. The number of replicates per geometry ranged from 2 to 10000. The lot-fraction ranged from 0.25 to 1. Each scenario is coded in the format “G_-R_-L_”, as seen in the header row of Figure 16.

Each of the 200+ demand scenarios was modeled in the context of each of the nine track/level combinations. Two intermediate metrics were calculated. First, were the total non-recurring costs (equipment plus tooling) corresponding to the given scenario/cell combination. The next step was to calculate production efficiency. The two valid approaches of measuring production efficiency were either parts per labor hour, or parts per cell hour. The labor-hour approach would ultimately reflect part costs, while the cell-hour approach is important for rate-driven programs. The basic trends observed in both are comparable, as seen below in Figure 17.

Finally, the two were combined into a cell efficiency index, as shown below:

$$Cell\ Efficiency\ Index = \left(\frac{Production\ Efficiency}{Total\ Non - Recurring\ Cost}\right) = \left(\frac{Parts\ Per\ Labor\ Hour}{Equipment + Tooling}\right)$$

Higher index scores represent low recurring labor costs and little initial expenditure towards capital and tooling. In general, this corresponds to lower per-part costs (assuming full utilization of the cell). Conversely, low index scores represent slow production rates and high non-recurring costs. This is to be expected in some scenarios, where there may be a significant number of geometries and tool changes. The indices also represent the overall uncertainty associated with various levels of cell capitalization and may be compared across levels of capitalization.

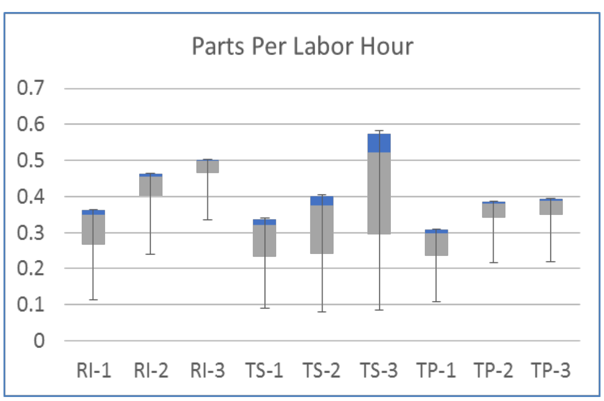
To anchor specific scenarios into the context of the overall 200+ scenarios being used, two were specifically created and labeled in the final charts. They are G25-R4-L1, and G8-R10000-L0.05, which correspond to a prototyping facility and a high-rate production environment.

4.4 Results

The following results represent each capitalization level of all three tracks. Because the cell concepts were individually constructed (rather than calibrated across tracks), it is not recommended to compare values between tracks. Instead, the most valuable information can be garnered be found within the trends between levels of a given track. Each column is indicated by two letters and a number (e.g. "RI-2"). These labels represent the track (RI = resin infusion, TS = Thermoset Forming, TP = thermoplastic forming) and the capitalization level (see Figure 15).

All values calculated in the 200+ scenarios are portrayed in box-and-whisker charts. The full range of values is contained within the shown "whiskers." The blue rectangles represent the third quartile values (between median and 75th percentile of results), while the grey rectangles represent the second quartile (between the 25th percentile and median). The median is at the border of the blue and grey regions.

Both interpretations of production efficiency are displayed below, and indicated in the chart titles. As expected by the design of the cell concepts, additional capital positively impacts the speed with which parts are produced, regardless of track. Between the Level 1 and Level 3 cells, the effect of extra automation/capitalization can be as much as 40% added efficiency.



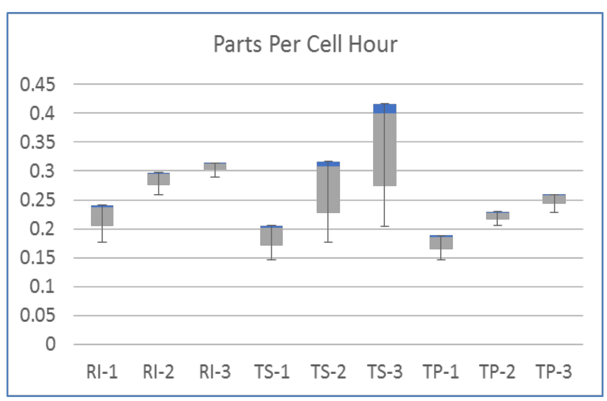


Figure 17. Intermediate metrics for production efficiency; two approaches.

The total non-recurring costs associated with each scenario and cell design were also calculated below. The widely varying cost is a function of high tooling costs exacerbating scenarios with a high number of geometries.

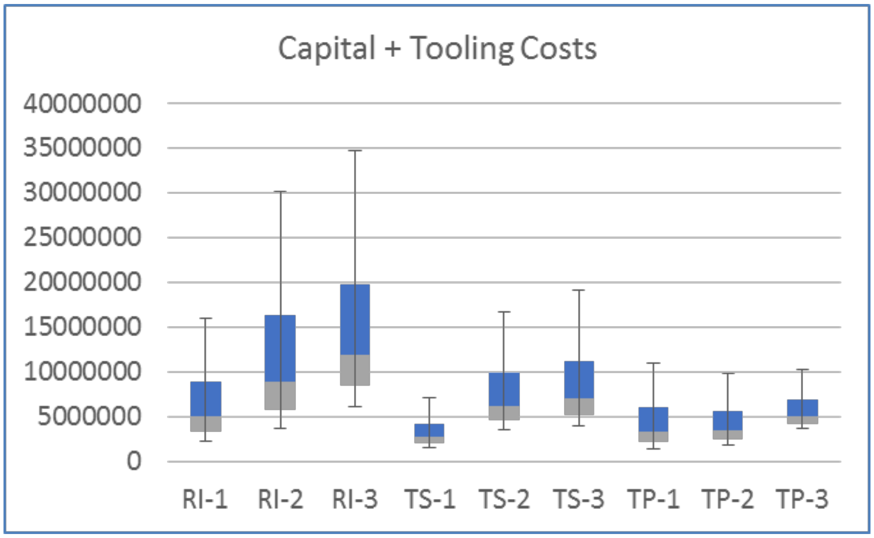


Figure 18. Non-recurring costs associated with each cell/scenario.

The final index was calculated by dividing the labor-based production efficiency by the total non-recurring costs associated with standing up a dedicated cell with necessary tooling. The combination of trends observed in production efficiency and non-recurring costs between levels 1, 2, and 3 present interesting results. Furthermore, the “prototype” and “high-rate” test cases are shown within each bar chart as blue and white circles, respectively.

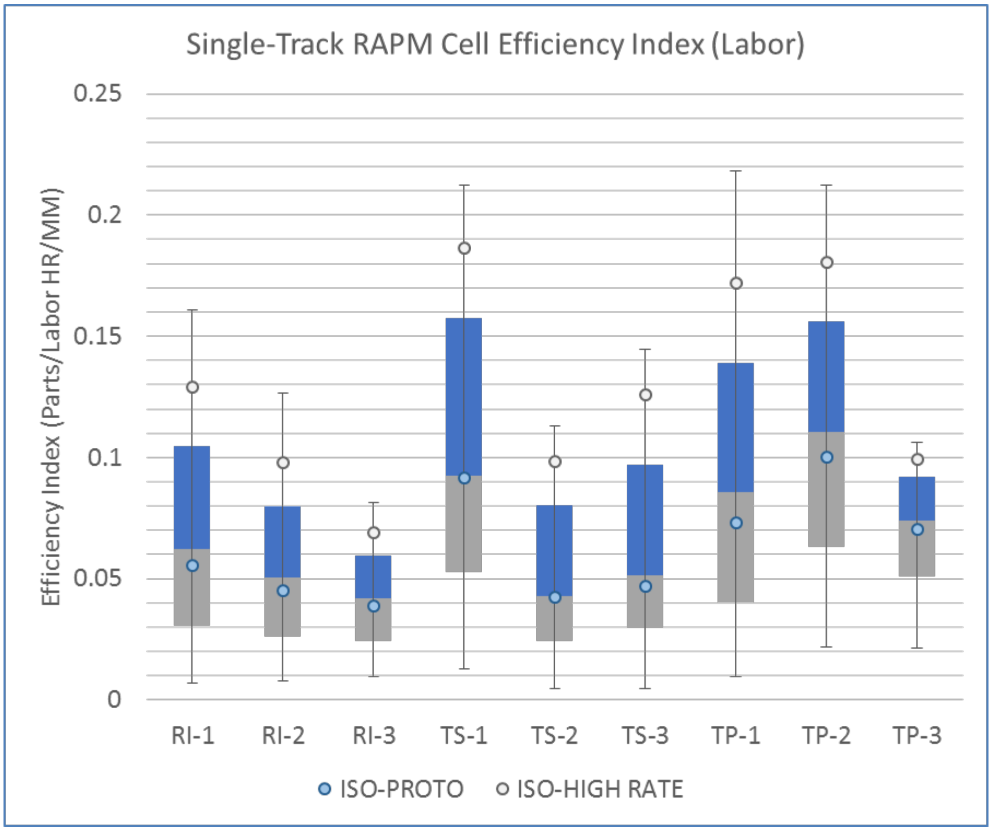


Figure 19. Calculated Cell Efficiency Index by Track/Level.

Several trends are apparent within each track. Resin infusion suffers from high combined tooling costs for each geometry. The downward trend of the index represents a less than 1:1 tradeoff between added capital costs and rate multipliers. However, there will be many production environments that would benefit from significant invest in capital to meet program rates. Although it may not have an out-sized effect on production efficiency, it is still increasing production rates and offering more predictability in the time required to build a given part, not to mention ergonomic and quality advantages.

Level 1 of the thermoset forming cells utilize minimal capital. The addition of a post-cure process and large press in Level 2, like in resin infusion, had a much larger effect on combined capital cost than its improvement on rate. In Level 3, however, there was a minor addition of capital that had a significant effect on the cell efficiency index.

Like thermoset forming, the Level 1 capitalization involves simple manual layup and one press with a bladder. More importantly, though, is the use of traditional ultrasonic NDI. In Levels 2 and 3, thermography was used to rapidly decrease flow time per part. Similarly, the incorporation of the CF-OaO-RAPM-001 work cell and pick-and-place also had significant effects on the production.

With respect to the index used for this study, the number of geometries, G, was clearly the most important cost driver in part decisions, followed by replicates and finally lot-size fraction. When analyzing the index, the spread of data can be used to represent predictability. The two narrowest index bands correspond to RI-3 and TP-3, which both utilize significant automation. Another clear observation during the course of this work is that individual pieces of capital to improve a single step in particularly complex multi-step manufacturing processes will have a minimal impact on the overall part cost. Instead, programs should consider shifting design methods or inspection criteria to have large sweeping impacts on platform costs. For example, NDI represented as much as 30% of the total part manufacturing costs in some instances. This explains some of the drastic improvement between TP-1 and TP-2 by switching to thermographic inspection methods. However, the implementation would also require a major criteria change program. Of course, it is also important to reiterate that predictive models are fundamentally speculative, especially with such significant amounts of information relating to non-existent cells.

5. CONCLUSIONS

The part-to-part analysis was originally used to inform the manufacturing tracks about the largest technical opportunities for cost improvement. Sensitivity analysis supplemented that information with quantifiable targets to meet, which could improve the break-even point for composite small parts.

Reconfigurable tooling was briefly investigated in two customized demand scenarios. In specific circumstances, the cycle-time reduction for thermoplastics enabled by Surface Generation PtFS makes the system and tools a worthwhile investment. Even more simply to justify, however, were tool inserts. For new programs, there is significant value in standardizing enough features from part-to-part to enable tooling inserts.

In general terms for reconfigurable tooling, the most valuable niche lies in highly "utilized" environment with fewer number of parts per tool, as illustrated in Figure 20. If the press (or tool-loading equipment) is a bottleneck for production, then there is significant opportunity cost associated with waiting for tool changes. If the press is not being fully utilized during a given shift, then investing capital to expedite tool changes will never be justified.

	Low Utilization	High Utilization
Low # of Parts Per Tool	Low-cost tooling	Reconfigurable tooling (and low-cost if possible)
High # of Parts Per Tool	Traditional tooling	Traditional tooling (and reconfigurable if possible)

Figure 20. Manufacturing space that benefits from reconfigurable tooling.

The final element of this work, investigated the effect of advanced capital on overall cell efficiency. The spread of cell efficiency indexes underscores the importance of understanding incoming work statement as completely as possible before designing a cell. In nearly every track/level combination, the middle 50th percentile (ranging from the top of the 25th percentile to the bottom of the 75th percentile) would approximately double in index score, based on the type of work statement provided to the cell.

Ultimately, configuring work cells is complex and highly dependent on available information. When planning for automated equipment, several other decision factors like delivery rate, safety, and quality controls must be considered as well. Other factors to weigh are the availability of nearby cells to complete similar steps, as well as the typical sizes and classes of materials to be ordered.

In order to make a material/process decision for a specific part, it is first necessary to understand the required interfaces, environmental/service conditions, and loading. Next, it is important to know the program schedule, cost/weight sensitivity ratio, production demand rate, and other program objectives. Finally, and least importantly, one should try to understand the existing equipment and personnel availability and program risk tolerance.

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