Are Printed Patterns Viable for Production?

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Abstract

It has been more than 25 years since the first printed patterns were used to create investment castings and have been one of the most successful applications of additive manufacturing. Since then, several technologies for printing investment casting patterns have been developed and commercialized and the use of printed patterns to create prototype castings has become standard practice in the industry. It has also become commonplace to use printed patterns for very low volume production castings, design iterations for high volume tooling and for bridge production: creating low volumes of production castings while waiting for pattern tooling to be completed.

While the use of printed patterns is not uncommon, there has been little to no usage of printed patterns to create production castings of any volume. Printed patterns are generally considered too expensive and too slow to be viable for production use on jobs of a hundred castings or more. In addition, most printing technologies required significant changes to the casting process that add time and expense.

The wax printer used in this study has improved printing speed and lowered cost to the point that printed patterns can be competitive with molded wax patterns both in pattern cost and the time required to deliver quantities of a few hundred patterns or less. A printer that uses wax to create patterns will naturally be advantaged over other technologies due to the drop-in nature of the wax patterns created.

Figure 1. ProJet MJP 2500 IC printer

In this model presented in this paper, the cost and time required to print patterns is compared to the time and cost of molded wax patterns for dozens of actual parts based on

foundry data to determine under what conditions it will be cheaper and/or faster to printer patterns than to mold them.

Introduction

Figure 2. Printed Wax Patterns

Following the successful introduction of the ProJet® MJP 2500W wax printer for the jewelry market, a natural extension into industrial casting was pursued. The product strategy for this new printer, the ProJet® MJP 2500 IC, is to leverage the ease of use benefits of a RealWax™ 100% wax pattern and the time benefit of immediate production of printed patterns to provide customers with a solution that would be competitive to injection molding patterns for medium production runs.

During product development, a project to validate of the production market target space was initiated with one of the authors: Tom Mueller at AMS. The model work began by gathering actual pattern cost data from various foundries. Data for fifteen parts from 4 foundries were obtained. These same parts were used to estimate cost and completion time of printed wax patterns and a comparison of both injection molded and printed patterns cost and completion time could thus be made. This model was used to understand and fine-tune the market opportunity.

Model Description

The model starts with benchmark foundry data. The foundries provided specific information on pattern creation: envelope dimensions of the pattern, volume of the pattern, surface area of the pattern, tooling cost and lead time and cycle time per mold. Material cost, a waste factor and typical shop rate for the cycle time is applied to determine cost per molded pattern. The total cost is the product of per pattern cost and number of patterns produced plus the cost of the tool.

The printed pattern cost takes into account the number of patterns printed in a build, printer depreciation and maintenance per build, material costs and the post processing costs. This per pattern cost is multiplied by the number of patterns to come up with total cost. No tooling cost is incurred with printed patterns.

The output of the model calculates the total cost of patterns as a function of the number of patterns required. Typical cost output is shown in Figure 3.

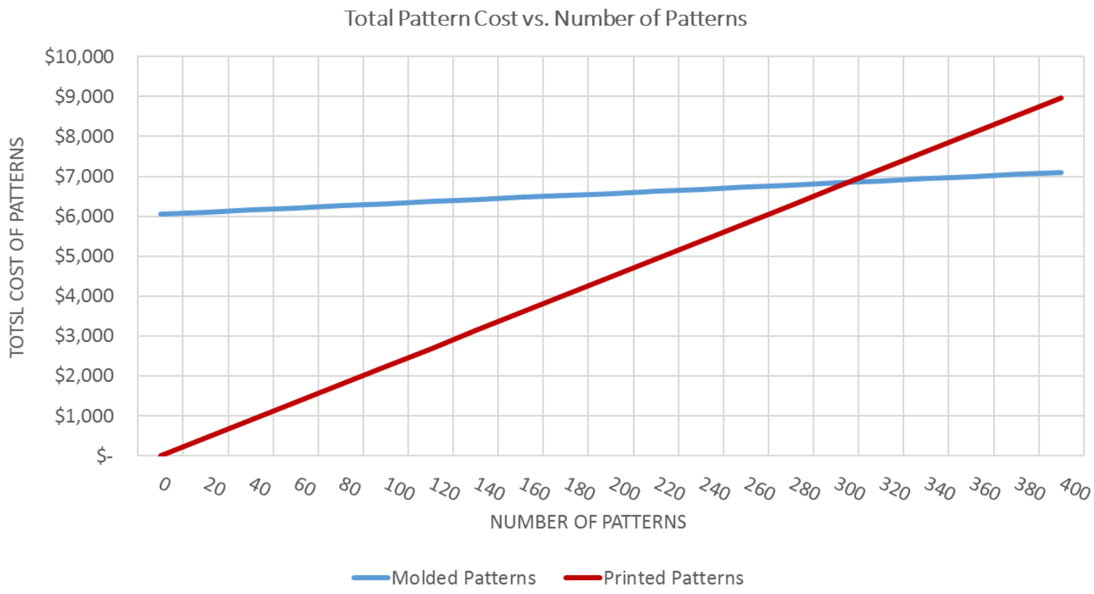


Figure 3. Model Cost Output

In Figure 3, the blue line represents the total cost of molded patterns. The line does not start at zero because a tool must be purchased before molding can begin. The slope of the line is the incremental molding cost: a few minutes of molding time plus the cost of materials. The red line represents the cost of printed patterns. It starts at zero because no tooling is required, but the incremental cost per pattern is higher so the slope is steeper. The point at which the two lines cross is called the cost break-even point. **Cost Break-Even (CBE) is the quantity at which total cost of printed patterns equals the total cost of molded wax patterns.** For quantities of patterns less than CBE, printed patterns will be cheaper. For quantities higher than CBE, molded wax patterns will be cheaper. In Figure 3, the total cost of printed patterns is less than molded patterns until more than 300 patterns are needed.

The data obtained from the foundries is used to look at another important consideration for foundry production: time to create patterns. The molding time includes tooling lead time and then cycle time per pattern. The results presented in this paper assumed that the molds are run 2 shifts and 7 days a week. The printed pattern time includes patterns per build based on the build envelope provided, build time and time to swap the build plates. It is assumed that the machine can run 24 hr a day, 7 days a week. The swap time used is 6 hours. Although the time to swap one plate is nearer to 5 or 10 minutes, a longer swap time is used to account for builds that may finish at times when no operators are available to start the next build. The time to post process patterns is much shorter than the print times and it is assumed that post processing occurs in parallel with printing and thus not added to completion time.

In Figure 4, the blue line is the time in days to deliver the different pattern quantities and is dominated by the tooling lead time. Multiple lines are shown for printed patterns. The point at which the blue molded pattern line crosses a red printed pattern line is called the time break-even. **The time break-even (TBE) is the quantity at which the total time required to print patterns is the same as for molded wax patterns.** For quantities of patterns less than TBE, printed patterns will be faster.

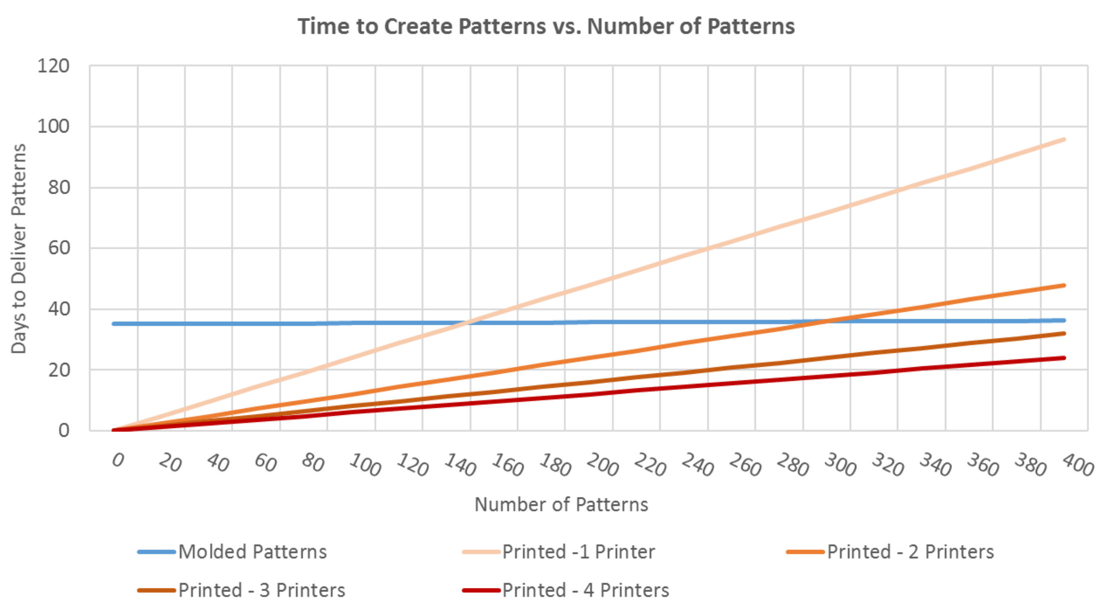
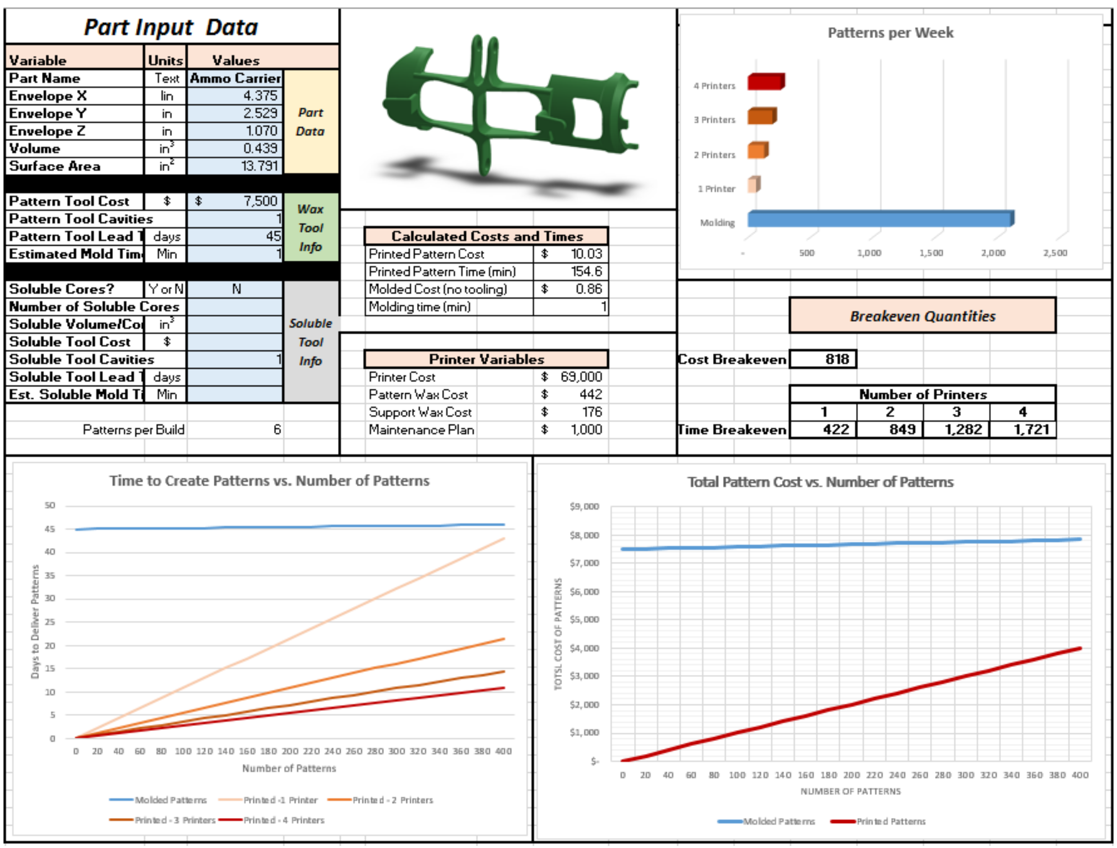


Figure 4. Model Time Output

The red lines show the impact of adding multiple printers building in parallel, which significantly increases the time break-even. A foundry with multiple printers can leverage them immediately to begin printing patterns once the digital file is available. Since the molding time is insignificant compared to the tooling lead time, having multiple injection mold tools doesn't have the same benefit in time and then would significantly increase the cost of producing parts and was not considered in this study.

Individual Model Results

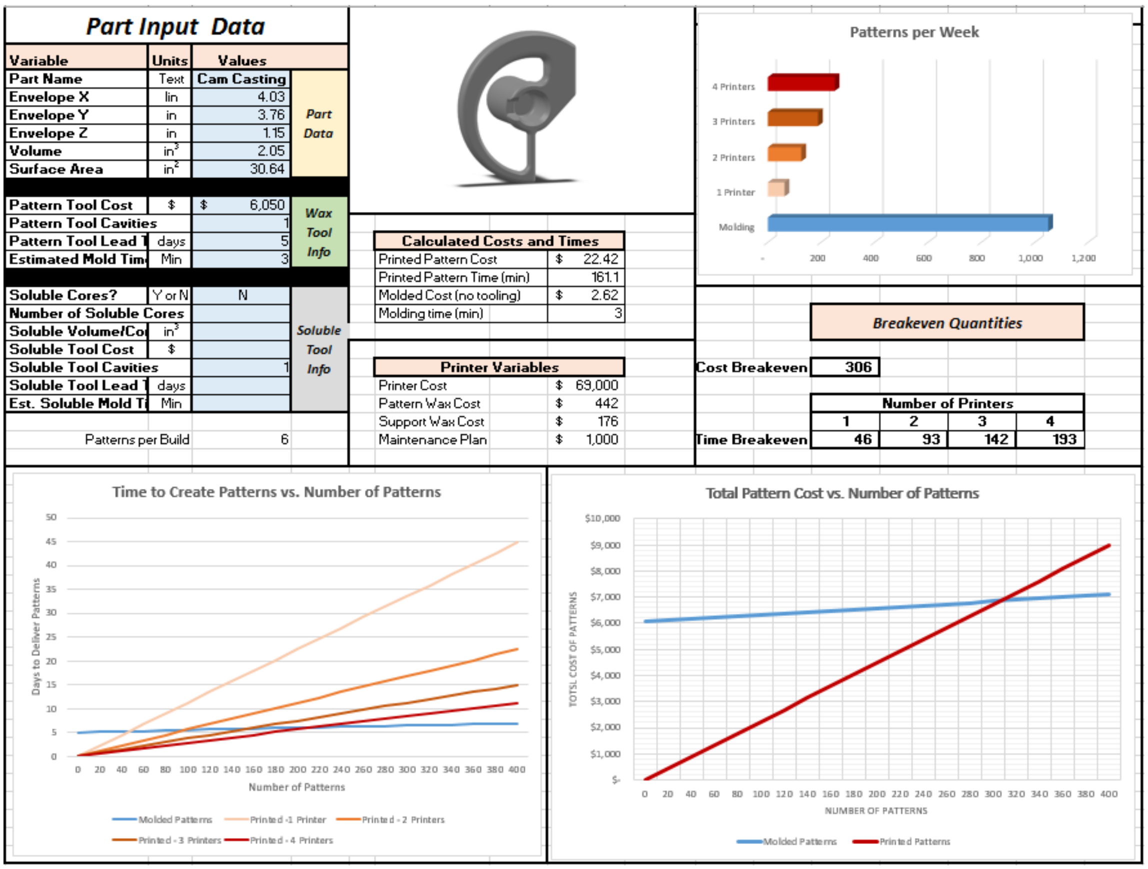
Each of the 15 pattern samples obtained from foundries was modeled to create cost and time break-even curves. Several examples are now discussed. In Example 1, the pattern volume and build envelope is relatively small.



Example 1. Small Part Volume

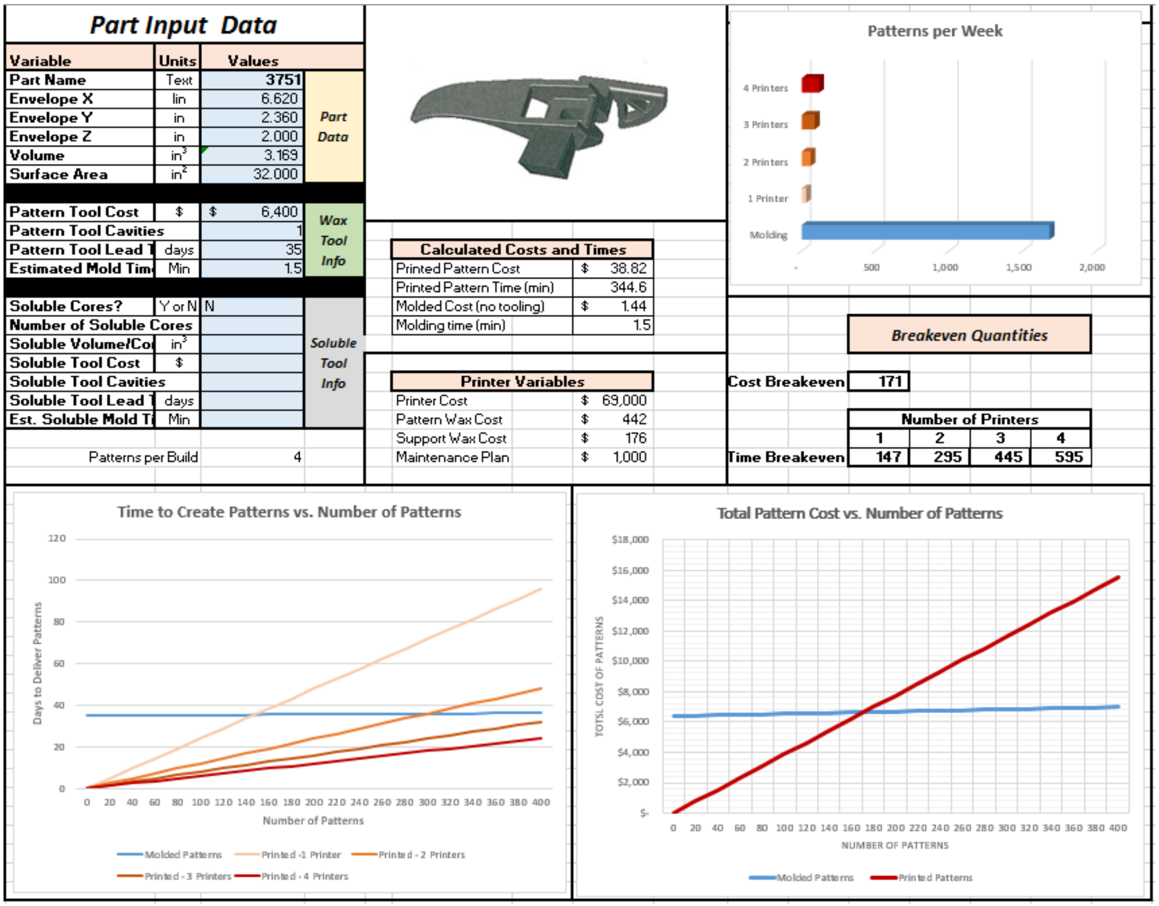
This allows the patterns to be built quickly and doesn't use much build material. For these reasons, both the cost and time break-even points are very high. The cost break-even point is over 800 patterns, meaning that it is more cost effective to print the patterns than make a tool up to quantities over 800 patterns. The time break-even for one printer is over 400 patterns, meaning that it is quicker to print patterns than make a tool for quantities up to 400 patterns.

In Example 2, the pattern volume is about five times larger. Due to the increased volume of the pattern, the cost break-even is lower than the first example but still provides a benefit for medium volume production to about 300 patterns. The time-break even is not as favorable unless multiple printers are used. In this example, the tooling lead time was very short (5 days).



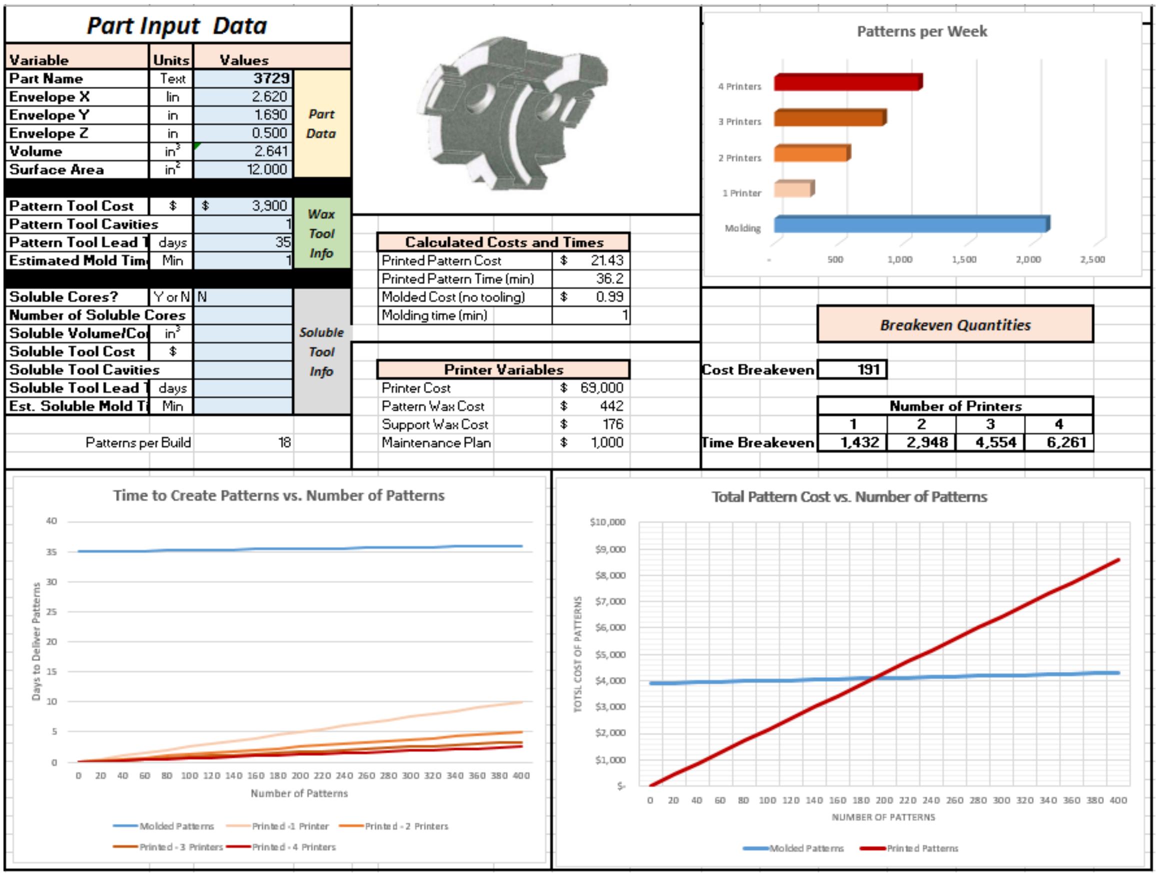
Example 2. Short Lead Time

In Example 3, the pattern is slightly larger volume than the Example 2 with typical tooling cost and lead times. The cost break-even is very similar (a bit lower due to larger volumes but still medium production range). The time break-even is significantly higher than last example showing the effect of tooling lead times. The time break-even is also in the medium production quantity of 147 for a single printer and with two printers 295 patterns can be produced in the same time it takes to create parts from a tool.



Example 3. Typical Part

Example 4 illustrates the impact of packing density. The pattern volume is similar and between the two previous examples but due to the aspect ratio of the pattern the packing density per build is significantly higher. The other three examples have packing density between 4 and 6 patterns per build. Example 4 has 18 patterns per build packing density.



Part Input Data			
Variable	Units	Values	
Part Name	Text	3729	Part Data
Envelope X	lin	2.620	
Envelope Y	in	1.690	
Envelope Z	in	0.500	
Volume	in^3	2.641	
Surface Area	in^2	12.000	
Pattern Tool Cost	$	$ 3,900	Wax Tool Info
Pattern Tool Cavities		1	
Pattern Tool Lead T	days	35	
Estimated Mold Tim	Min	1	
Soluble Cores?	Y or N	N	Soluble Tool Info
Number of Soluble Cores			
Soluble Volume/Co	in^3		
Soluble Tool Cost	$		
Soluble Tool Cavities			
Soluble Tool Lead T	days		
Est. Soluble Mold Ti	Min		
Patterns per Build		18	

Calculated Costs and Times		
Printed Pattern Cost	$	21.43
Printed Pattern Time (min)		36.2
Molded Cost (no tooling)	$	0.99
Molding time (min)		1

Printer Variables		
Printer Cost	$	69,000
Pattern Wax Cost	$	442
Support Wax Cost	$	176
Maintenance Plan	$	1,000

Breakeven Quantities				
Cost Breakeven	191			
	Number of Printers			
	1	2	3	4
Time Breakeven	1,432	2,948	4,554	6,261

Example 4. High Pattern/Build

The cost break-even is 191 patterns even with a tool nearly half the cost of Example 3. The effects on the time to complete patterns is significant: the completion time with only a single printer to create 400 patterns is 3 times faster than the time it takes to build a tool.

Summarized Model Results

The output of all the individual pattern data are summarized in Table 1.

Tooling Data Points															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Envelope X	6.62	2.392	4.03	4.402	4.375	7.5	6	2.62	6	1.51	5.03	4	4	3.59	4.9
Envelope Y	2.36	0.895	3.76	2.896	2.529	6.2	2.26	1.69	3	1.51	2.16	5.75	5.75	4.06	4.9
Envelope Z	2	1	1.15	5.282	1.07	3.35	1.1	0.5	4.2	1.8	2.92	5.21	5.21	1.19	0.84
Volume	3.169014	0.328	2.05	7.697	0.439	24.64789	9.859155	2.640845	10.8	0.55	7.746479	17.95775	17.95775	6.690141	4.225352
Surface Area	32	7.142	30.64	71.342	13.791	113	56	12	105	15.2	64	106	106	30	95
[redacted]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pattern Tool Cost	6400	6500	6050	5000	7500	7100	5500	3900	17000	6700	10000	5600	7800	3000	2650
Pattern Tool Cavities	1	2	1	1	1	1	1	1	2	4	1	1	1	1	1
Pattern Tool Lead Time	35	35	5	28	45	35	35	35	49	28	42	21	42	28	28
Estimated Mold Time	1.5	1	3	3	1	3	1.5	1	5	0.462	2.5	5	2.857143	2	1.333333
[redacted]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soluble Cores?	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Number of Soluble Cores	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soluble Volume/Core	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soluble Tool Cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soluble Tool Cavities	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Soluble Tool Lead Time	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Est. Soluble Mold Time	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pattern build time	4	36	6	4	6	1	5	18	3	35	6	4	4	6	2
Pattern per build	345	25	161	742	155	2033	188	36	815	37	304	734	734	164	408
Cost Breakeven	171	2,413	306	57	818	26	68	191	152	1,262	145	35	48	54	55
Time Breakeven - 1 printer	147	2,115	46	55	422	25	270	1,432	87	1,115	201	42	83	248	99
Time Breakeven - 2 printer	295	4,415	93	110	849	50	543	2,948	175	2,259	404	84	166	503	199
Time Breakeven - 3 printer	445	6,926	142	165	1,282	75	822	4,554	265	3,433	612	126	250	764	299
Time Breakeven - 4 printer	595	9,679	193	221	1,721	100	1,105	6,261	355	4,639	823	170	335	1,032	400

Table 1. Summarized 15 Part Data

The tabulated data is charted to help find correlation and trends in the data. One of the most interesting charts is shown in Figure 5. From this chart, we can see that the cost break-even is a strong function of the pattern volume. A trendline using a power equation can be drawn thru the data with good correlation (R^2 about 88%).

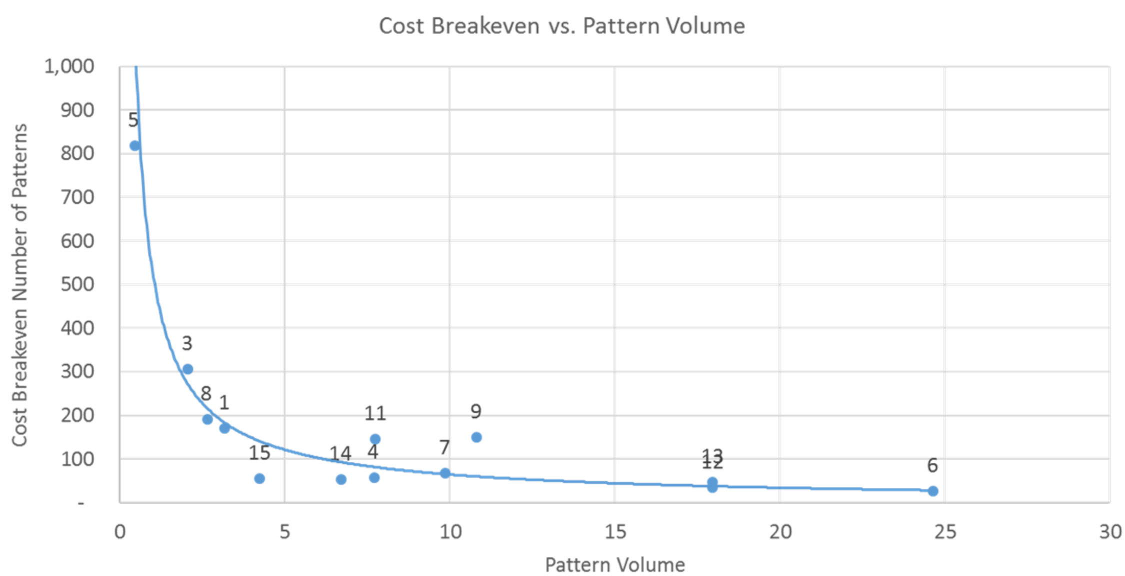


Figure 5. Cost Break-Even

As illustrated in the examples given earlier, part volume spans a large range of part dimensions. For medium production volumes of several hundred patterns the cost break-even point is in pattern volumes between 2 and 4 cubic inches. An informal survey done last year revealed that about 40% of orders were for 300 or fewer castings.

Looking at the data points that are outliers give another clue to another cost driver. The tool cost for the 2 data points above the curve (9 and 11) are both tools with costs above $10k. The 2 data points below the curve (14 and 15) have the lowest tool costs, below $3k. All other parts have tooling costs close together and average $6200 per tool. These two observations provides foundries with a simple method of understanding when a printed pattern would be beneficial: the pattern quantity at which printed patterns are a better value can be calculated with the following formula:

Cost_Breakeven = Tooling cost/(Pattern_Volume*Material_Cost)

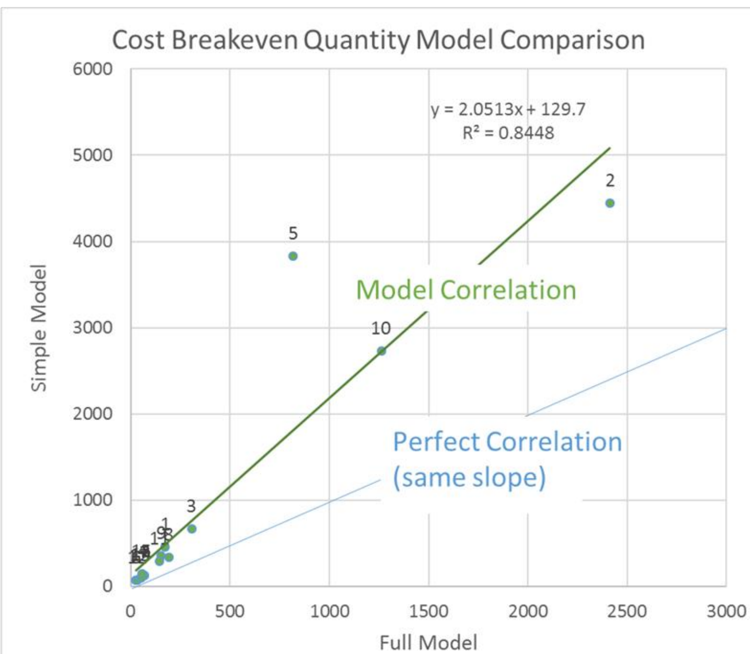


Figure 6. Simple vs Full CBE Model

The comparison of the two models is shown in Figure 6. The correlation is good with R^2=84%. The two outliers are the lowest volume parts. The simple model predicts a higher cost breakeven point than the full model by about 2x but is a good back of the envelope calculation.

For the time break-even point the correlation with pattern volume is poor with $R^2 < 60\%$. Surface area provides a stronger correlation with R^2 about 75% (Figure 7).

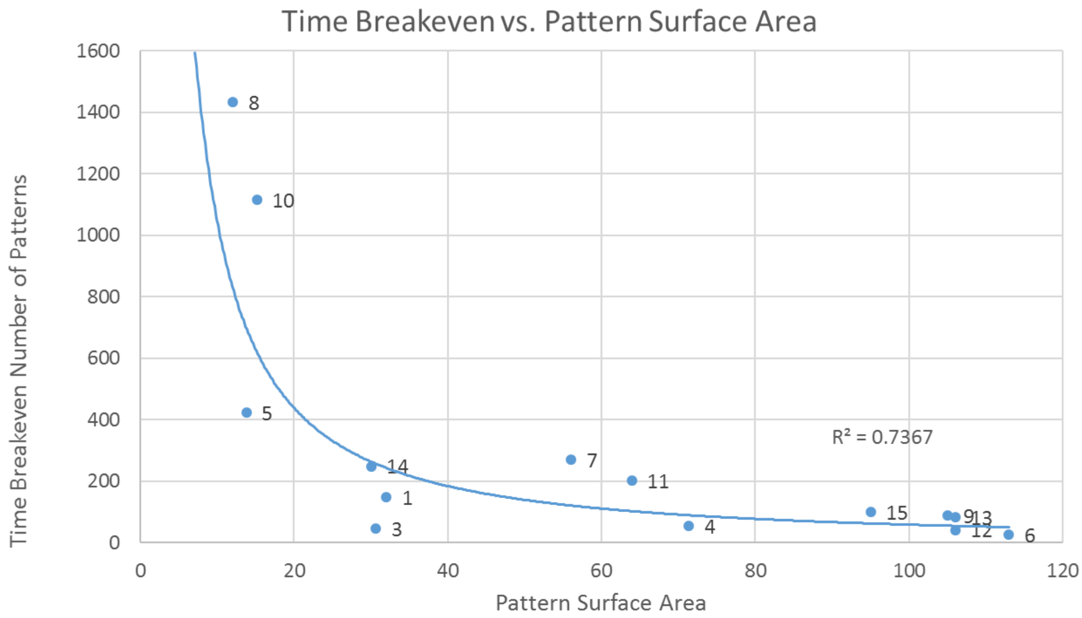


Figure 7. TBE vs Surface Area

An interesting graph is shown in Figure 8. In this figure, tooling lead time is used as the independent variable. One can see that with the exception of three points the data is fairly well behaved. All three points are part geometries able to print a high number of patterns per build (18, 35 and 36) while all other patterns are below 6.

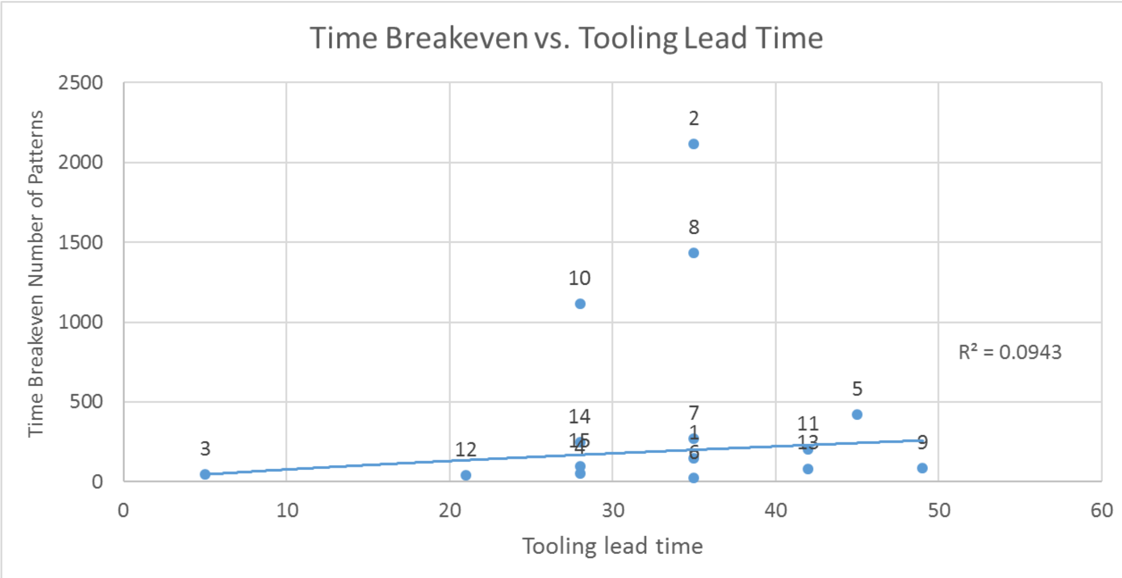


Figure 8. TBE vs Tooling Lead Time

Figure 9 is the TBE as a function of pattern print time. There are many factors that roll into the total pattern print time. The print time has a strong dependence of the individual geometry of the part and which can't be easily defined by a simple part metric available to foundries such as volume or surface area.

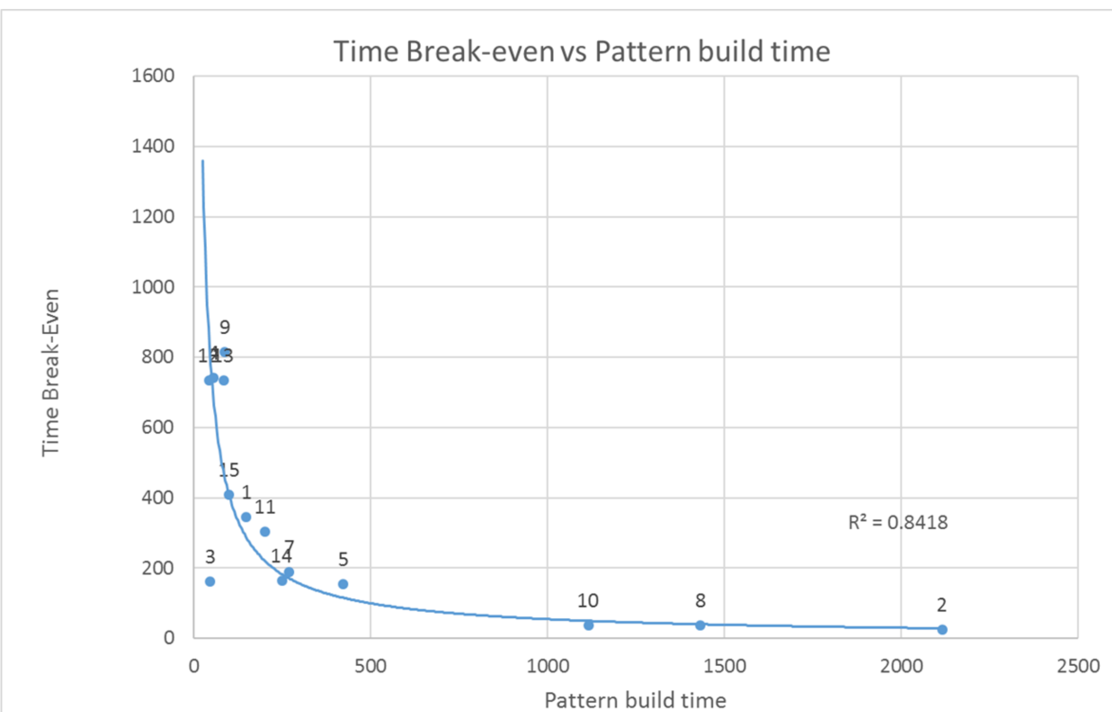


Figure 9. TBE vs Pattern Build Time

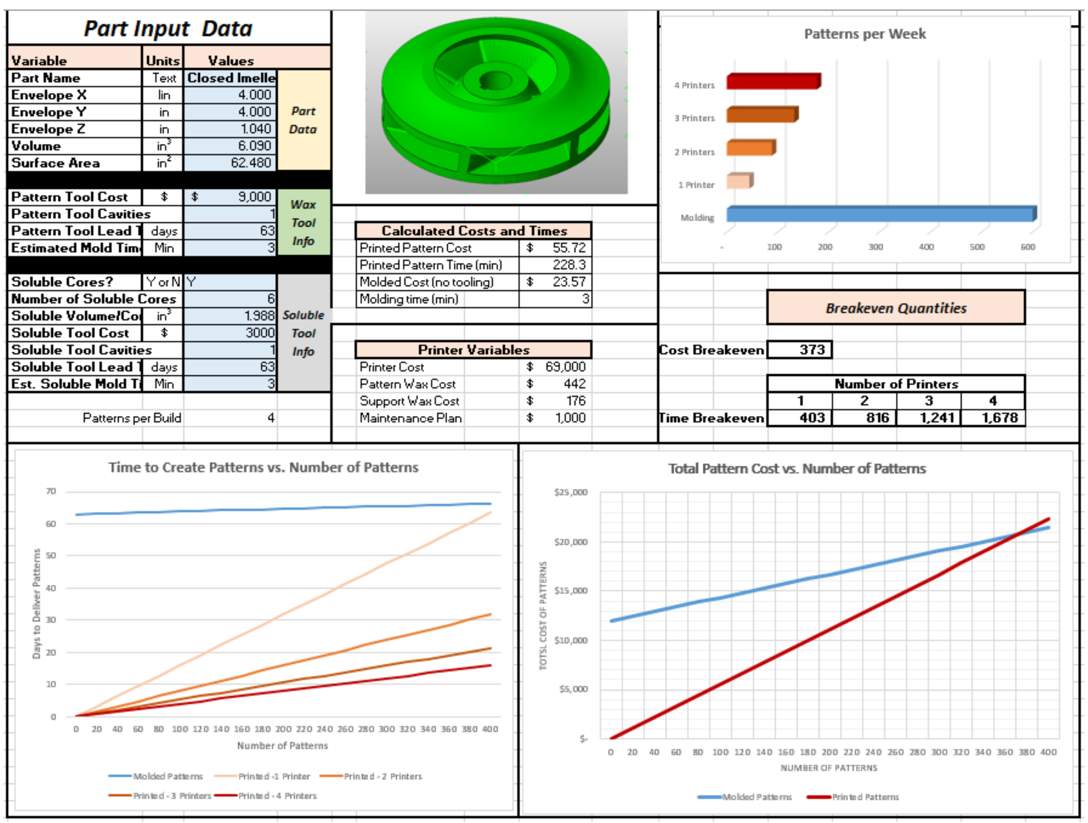
The ability to nest parts within the envelope of the build plate (not considered in this model) can significantly increase the number of patterns build in one build. Parts can also be stacked in layers (not considered in this model) which while making the individual run time longer allows the foundry the flexibility to tune the job length to end at a time an operator can be made available so that a machine doesn't sit idle.

The time break-even conclusions are summarized below:

- Time break-even is a strong function of tooling lead time and pattern print time
- Print time is a strong function of pattern geometry and layout within build
- Multiple printers used in parallel increases the time break-even

Additional Examples

Most of the examples obtained from foundries were for low/medium complexity tooling. Complex tools and patterns requiring soluble cores would increase the cost break-even quantities for printed patterns. An example with a soluble core is given in Example 5.



Part Input Data

Variable	Units	Values	
Part Name	Text	Closed Imelle	
Envelope X	lin	4.000	Part Data
Envelope Y	in	4.000	
Envelope Z	in	1.040	
Volume	in^3	6.090	
Surface Area	in^2	62.480	
Pattern Tool Cost	$	$ 9,000	Wax Tool Info
Pattern Tool Cavities		1	
Pattern Tool Lead T	days	63	
Estimated Mold Tim	Min	3	
Soluble Cores?	Y or N	Y	Soluble Tool Info
Number of Soluble Cores		6	
Soluble Volume/Co	in^3	1.988	
Soluble Tool Cost	$	3000	
Soluble Tool Cavities		1	
Soluble Tool Lead T	days	63	
Est. Soluble Mold T	Min	3	
Patterns per Build		4	

Calculated Costs and Times		
Printed Pattern Cost	$	55.72
Printed Pattern Time (min)		228.3
Molded Cost (no tooling)	$	23.57
Molding time (min)		3

Printer Variables		
Printer Cost	$	69,000
Pattern Wax Cost	$	442
Support Wax Cost	$	176
Maintenance Plan	$	1,000

Breakeven Quantities

	Number of Printers			
Cost Breakeven	373			
	1	2	3	4
Time Breakeven	403	816	1,241	1,678

Example 5. Soluble Core

The part is a closed impeller and has 6 vane segments Two tools and seven molding operations are required: six soluble segments and one investment casting wax injection. The cost break-even for this example is 373 patterns. Comparing this to Example 2 that had a similar cost break-even of 306 patterns, this pattern is twice the volume of Example 2. In other words, the cost break-even for patterns requiring soluble cores is twice that of patterns produced without. Whether that is true for all cases would need further study however recalling that the high outliers on Figure 5 (CBE vs part volume) also had high tooling costs, it is clear that the total tooling costs drives cost break-even.

One feature not considered in the model and foundry benchmark parts are patterns that can only be created with additive manufacturing. The 3DSprint infill feature for ProJet 2500 IC with cellular structure allows the user to build a sparse structure of wax within the pattern using pattern wax.

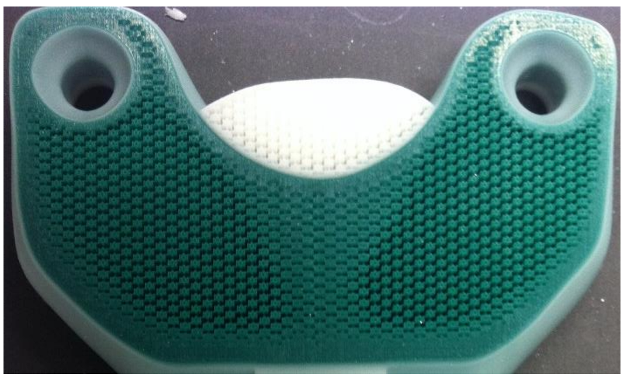
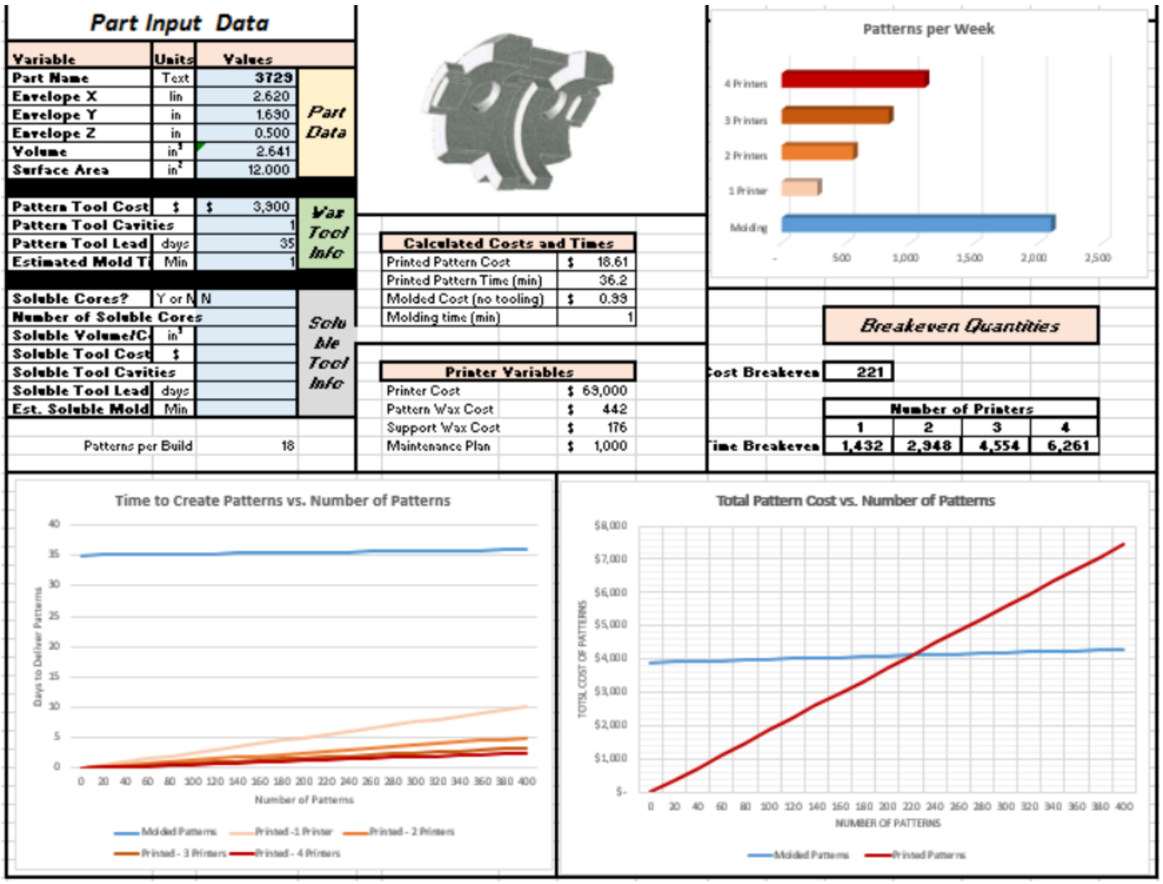


Figure 10. Cellular Structure Infill

The amount of pattern wax reduction depends on geometry and can range from 10% to 40%. The part in Example 4 is used to illustrate this feature. For this part, a 20% materials reduction was modeled. This resulted in a 13% printed pattern cost reduction and 16% increase in the cost-break even, moving the CBE from 191 to 221 patterns. The estimated results are shown in Example 6.



Example 6. Sparse Infill with AM

Conclusion

Additive manufacturing technology has advanced to a point where it should be considered for use beyond prototyping and low volume production into medium volume production. The typical arguments of casting difficulty, higher costs and slow production have been addressed in this paper.

The use of printed wax patterns provides a drop in solution for foundries. The wax pattern can be cast using the same processes you might use for molded wax pattern. They can produced with the same steps and equipment. No additional steps for venting, cooling shells, cleaning and patching vents are necessary.

With additive manufacturing as soon as a digital file is available pattern creation can begin. No tooling lead time and the flexibility of using multiple printers in parallel to speed production allows the foundry opportunity to offer shorter lead times to customers.

Digitally created patterns allow for design iterations and optimization within a build. In addition, space for tooling storage is no longer needed.

Printed wax patterns can be competitive with molded max patterns for patterns around three cubic inches in volume for quantities of 300 patterns for basic tools. When the consideration of more complex tooling such as the use of multiple cavities or soluble cores is considered, the cost break-even of printed patterns are even better as the cost of printing patterns is not a function of the part complexity.

Finally, additive manufacturing printers can create expand part capability for foundries. Generative design and topology optimization are being rapidly adopted and are creating designs that are not manufacturable by conventional means. Most people assume they will be printed in metal, however it is cheaper and faster to print patterns and investment cast them.

Figure 11. Printed Unmoldable Design

Acknowledgements

The authors thank the foundry participants for providing the benchmark data for the cost and time studies. We also thank 3D Systems management and employees who supported and helped validate the data in this study.