ENGINEERING BRIEF

Critical Path Simulation

Case Studies in Finite Element Analysis

Identifying and Executing Critical-Path Simulations Prior to Architecture Definition

Introduction

Finite-element analyses in the form of structural and thermal simulations are a critical component of the modern product development process. Often, these simulations are used to validate a product architecture and predict how the proposed solution will satisfy defined requirements. However, in some cases identifying and conducting a simulation should actually be the first step in the product development process, after requirements definition. This is especially true in products whose success is heavily dependent on the success of a single subsystem.

This paper will consider three case studies in which critical-path simulations were identified and executed prior to architecture definition. This strategy accomplishes three objectives: (1) product architecture can be intelligently driven by critical requirements; (2) some level of feasibility can be proven even prior to conceptual design; and (3) return-on-investment can be increased both in terms of NRE/design effort expended and in terms of the resulting product cost (COGS). We will consider the thermally-driven design of a telecom equipment cabinet, the structurally-driven design of a large rack-mounted test system, and the structurally-driven design of a rifle scope. In all three cases product architecture was defined based on simulation results and concurrent cost analysis was used to quantify and realize significant ROI from the simulation activity.

About Acorn

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) 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 in a number of different vertical markets and technologies, including telecom/server, industrial equipment/ robotics/defense, medical, and consumer products. With offices in Silicon Valley, Boston, Texas, and Dongguan, China, we support our clients' manufacturing activities both in the US and abroad.

Case Studies in the Identification And Execution of Finite-Element Analyses Early in the Design Process to Assure Feasibility and Increase ROI

Presented at the International Association for Engineering Modeling NAFEMS World Congress, 21-24 June 2015

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Exploring the product development process

The process a company uses to control and document new product designs varies widely between companies. There is a great deal of variation even in the theory taught in design classes and texts[1].

In an effort to deliver solutions that allow our clients to meet their demanding development schedules and budgets, we employ several design and analysis tools. As consultants, we are tool-agnostic, leveraging experience with SolidWorks, CREO, SolidWorks Simulation, SolidWorks Motion, MacroFlow, CFDesign, Ansys, IcePak, Mechanica, FlowTherm, and many others. Using these tools allows us to accurately analyze concepts early enough in the design cycle that our findings can be leveraged to achieve a more manufacturable product design that optimally meets the design requirements. This paper focuses on three case studies where structural or thermal analyses were employed early in the design cycle, prior to concept development. We will review the benefits and caveats associated with employing analysis tools so early in the design cycle, the methodology employed, the specific problems presented by each case, and the results achieved in each case. Where applicable we will also review concurrent early-stage cost analysis that accompanied the analysis to maximize client ROI.

The Product Development Process

The process a company uses to control and document new product designs varies widely between companies. There is a great deal of variation even in the theory taught in design classes and texts[1]. In our over 20 years of experience in product design, we have found many companies default to a product design process like the one pictured in Figure 1.

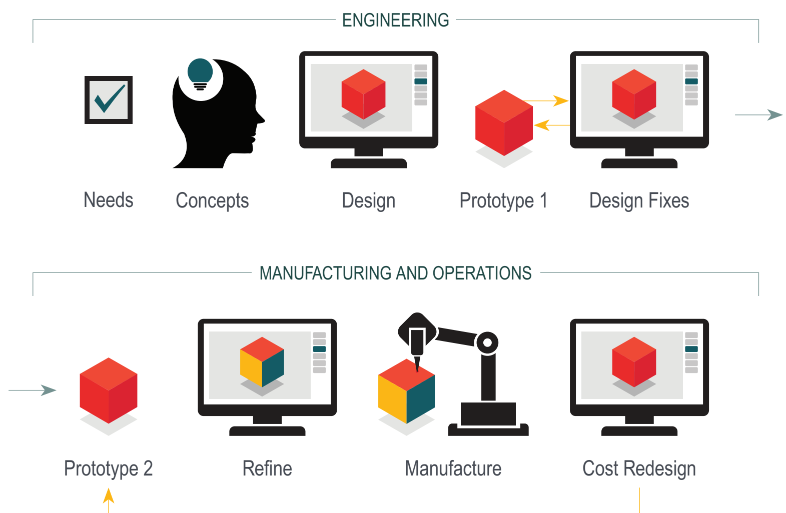


Figure 1 Typical product development process

Despite the variances seen between different theories and processes, there are several common characteristics seen in these typical development processes. The most obvious is a clear division between design and manufacturing roles. In this paradigm design engineers develop the product to some point of viability, usually involving at least one prototype and optimizing the design to meet functional metrics. Then, the design is "thrown over the wall" to manufacturing engineers, who are tasked with actually producing the design in the real world. Since at this point the design is optimized for technical metrics and not necessarily for cost or manufacturability, manufacturing engineers often find themselves backed into a corner, required to use a costly, exotic, or tightly toleranced process to manufacture the design.

Typically, many subsequent prototypes are required to validate functionality, including a costly after-the-fact cost reduction effort or expensive late-stage re-involvement of the design group. This approach is often characterized by a "prototype and pray" mentality, where functionality is verified by prototypes instead of analysis.

Acorn's product development process is structured differently, born out of heuristic experience and the realization that unifying the design and manufacturing processes yields a more optimal result. Figure 2 shows what a unified process that leverages simultaneous design and manufacturing experience looks like.

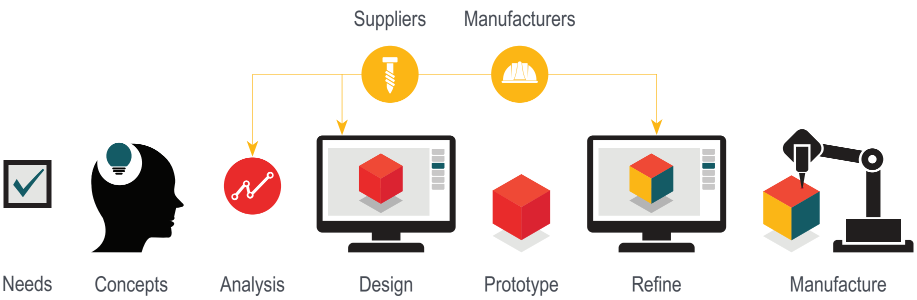


Figure 2 Acorn's product development process

Instead of a dividing wall between theoretical design and the "how to make it in the real-world" know-how, this process integrates cost and manufacturability early in the design process. Thus, all designs that get to a prototype stage are assured to have criteria like part cost, assembly effort, and any unusual manufacturing requirements included and understood as tradeoffs before attempting to produce the design. With the advent of widespread, relatively low-cost analysis techniques like simulation packages built into CAD, many companies are embracing methodologies like this. However, the results achieved are often only as good as the engineering team's experience and ability to interpret analysis results. When early-stage analysis is used to evaluate multiple brainstormed concepts in parallel, typically acceptable accuracy targets are in the +/- 20% range. This is accurate enough to provide a good comparison between concepts, but it's not accurate enough to give confidence to absolute performance metrics that might be required during a detail design phase.

Early-stage critical path analysis

The product development process as a whole trades off risk for development cost and effort. The lowest-risk approach to product design that assures a product will meet specified performance metrics is to make multiple iterative prototypes until all metrics are achieved. However, this is also the most costly approach in terms of development time and cost. As noted in Figure 2, some of this cost can be reduced with only a marginal risk increase by leveraging early-stage, low-cost analysis tools. Then, prototypes can be used primarily to verify predicted performance instead of iterating to achieve an optimal result. However, this approach is still predicated on comparing previously-defined concepts and isn't really good at addressing the case where the analysis shoulddrive concept definition.

Acorn product development process utilizes analysis tools early in the development process, sometimes even prior to brainstorming and concept ideation. This "critical-path analysis" is only undertaken in a specific sub-set of development projects, when functional or cost requirements are stringent enough to require concepts to be based on something more robust than brainstorming sketches and an engineer's intuition. Figure 3 shows what this process looks like, with an added critical-path analysis between requirements definition and brainstorming.

Integrating cost and manufacture-ability early in the design process

As time to revenue becomes more critical, early simulation and analysis of manufacturability and manufacturing cost can improve time to market and profitability.

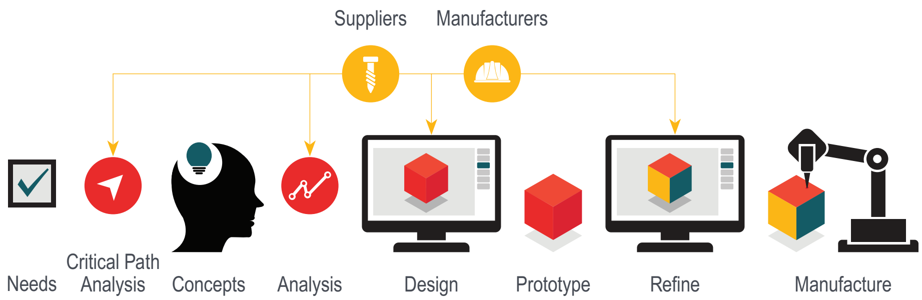


Figure 3 Product development process showing addition of critical-path analysis

This process continues further down the spectrum of tradeoffs between technical risk and development effort. Accordingly, it is only worthwhile in development cases that already have a lot of inherent risk; for example, if the system is expected to operate close to the limits of available technology or if drastic cost reduction (relative to a "typical" baseline) is desired. This approach is different from a feasibility study in that the system is not just being evaluated for technical feasibility, but cost, ROI, and programmatic feasibility as well. Because these tradeoffs are evaluated before (and even drive) concept brainstorming, accuracy targets closer to +/- 50% are acceptable. Generally this approach allows for fewer design concepts to be subsequently considered since the analysis has dictated the best approach. The goal is to use analysis to set an overall design direction very early in the program to avoid later costly missteps and rabbit trails.

Since setting a technical direction for the project so early in the development cycle carries with it some marginally increased technical risk, it is only useful in a specific type of development program—typically a program characterized by stretch goals. Ultimately it is up to the engineers involved to decide during requirements definition if the project warrants a critical-path analysis. Table 1 contains some questions that can help identify projects where it is useful.

Question	Example
Is there a single subsystem that drives most of the functional requirements?	Thermal, structural system (see Case 2 and 3)
Are the target performance specs out on the ragged edge of what is possible with the proposed technology?	Dissipating excessive heat for the available volume (see Case 2)
Are there significant cost savings that could be realized by an unconventional material choice or system architecture?	Low-cost material choices or manufacturing methods (see Case 1 and 3)

Table 1 Questions to ask to see if critical-path analysis is warranted

The case studies explored in this paper all fall into this category, where some amount of very-early-stage analysis was beneficial to set the technical direction for the development program and limit the scope of subsequent concepts.

Case 1: Design of a Rifle Scope

The first case we will consider is the design of a two-lens optical rifle scope. The configuration of the scope allows for one static lens and one focus element. There are stringent requirements around thermal and structural use cases. Thermal variation with temperature needs to be closely controlled to prevent the scope from going out of focus with shifts in ambient temperature. In addition to the normal shock and vibe requirements seen in most products (e.g. drop survivability and shipping), the scope needs to survive shock loading from repeated rifle fire. In several phases of the program, structural analysis drove concept development and product architecture as multiple construction materials were considered. Machined aluminium, thixomolded magnesium, and injection molded plastics were all considered for structural components in the scope, and each of these material candidates require different geometric concessions in the completed design. Figure 4 shows a cross-section layout of one of the scope configurations.

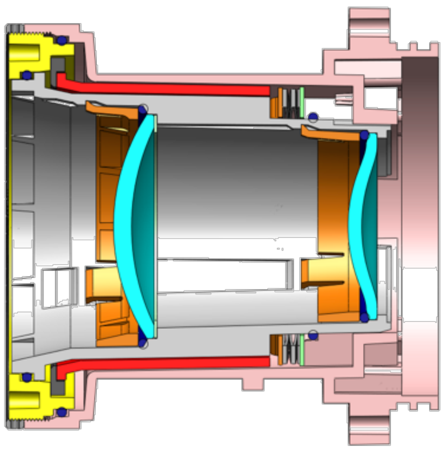


Figure 4 Cross-section of scope geometry

Multiple early-stage analyses helped define the product architecture, including shock loading, simulated drop loading, thermal expansion analysis, and cost analysis. Figures 5 and 6 look at representative results for various assembly elements under rifle fire shock loads and drop loads.

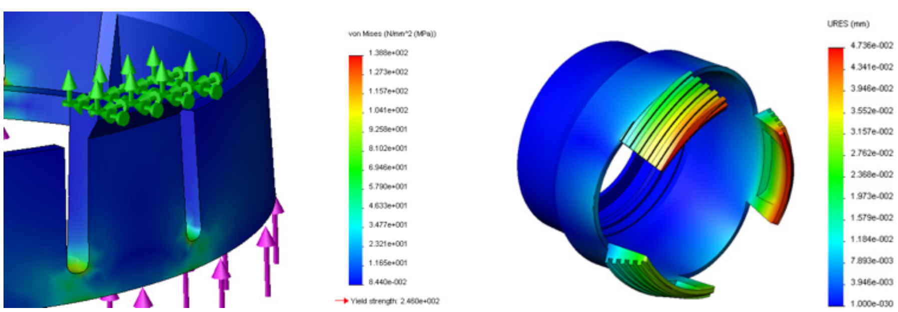


Figure 5 Lens retention clip and focus element under rifle fire shock load

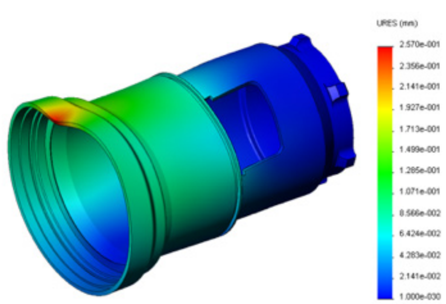


Figure 6 Simulated drop on thixomolded magnesium housing

None of the finite element analysis cases were sufficient on their own to rule out any of the material choices. All materials looked initially viable structurally. Only a few critical components in the assembly control the critical lens-to-lens distance, so the next step to evaluating potential material choices was to evaluate the effect of thermal expansion on these elements. Table 2 shows a representative calculation for thermal effects on this critical part stackup. Much like a tolerance analysis, the cumulative effect of each element of the stackup is summed to arrive at a final value for lens-to-lens variation over a specified temperature range.

Nominal (in) = Material = CTE =			A-Lens Height -0.1290 Germanium GeIR/0403 0.0000059	B-Lens Holder 0.0200 6061-T6 0.000023	C-aThermal Length -1.1950 Tivar		D-Lock Ring Length -0.8820 Stat-Kon OEL36A, axial 0.0000082	E-Outer Housing 2.7300 Stat-Kon OEL36A, axial 0.0000082
.start T.	end	△T(ºC)	Calculated △L	Calculated △L	CTE	Calculated △L	Calculated △L	Calculated △L
22	25	3	-0.000002	0.000001	0.00015678	-0.000562	-0.000022	0.000067
25	30	5	-0.000004	0.000002	0.00016007	-0.000956	-0.000036	0.000112
30	35	5	-0.000004	0.000002	0.00016376	-0.000978	-0.000036	0.000112
35	40	5	-0.000004	0.000002	0.00016787	-0.001003	-0.000036	0.000112
40	45	5	-0.000004	0.000002	0.00017246	-0.001030	-0.000036	0.000112
45	50	5	-0.000004	0.000002	0.00017757	-0.001061	-0.000036	0.000112
50	55	5	-0.000004	0.000002	0.00018325	-0.001095	-0.000036	0.000112
55	60	5	-0.000004	0.000002	0.00019206	-0.001148	-0.000036	0.000112
60	65	5	-0.000004	0.000002	0.00019778	-0.001182	-0.000036	0.000112
	Total	**43**	**-0.000033**	**0.000020**		**-0.009016**	**-0.000311**	**0.000963**
	Sum = -0.008377 in							
	-0.213 mm							
	Goal = 0.213 mm toward (-) FPA							

Table 2 Thermal expansion calculation

The final results of the thermal analysis indicated that temperature-stable thermoplastics (like PEI or Tivar) were viable candidates for these lens-to-lens elements in addition to the baseline aluminium construction. One result from the analysis was the suggestion that the lens-to-lens focus distance be initially calibrated at a mid-range temperature (like 30 degrees Celsius) instead of the baseline 22 C temp. This would allow the thermal expansion to better “split the distance” from the initial calibrated point.

The final critical-path analysis that was completed to set the initial direction of the design and decide on component material selection was a comparative cost analysis. Initial numbers for molding operations were calculated from heuristic models based on factors like the part volume, press size, number of cavities per mold, and labor rates for the specified manufacturing region.

These initial estimates were confirmed by preliminary quotes from potential vendors across all three potential material choices. Table 3 shows the cost rollup for changing several casing parts from machined aluminium to thixomolded magnesium. It can be seen that in the quantities quoted (~3000/year) the thixomolded magnesium parts resulted in an average savings of 50% over aluminium across several parts.

Piece Part Pricing

Part No.	Description	500	1,000	2.500	5,000	Finish-ing	Tooling	Trim Die	Machining Fixture(s)	Total Tooling	Tooling/ part	Total Cost	Current	Savings
23217-204	EL-1 housing	$17	$16	$15	$15	$10	$46,000	$11,000	$1,250	$58,250	$18	$43	$78	-$35 -45%
23217-207	Rear flange	$13	$11	$10	$10	$8	$17,000	$6,000	$1,125	$24,125	$7	$25	$84	-$59 -70%
23217-205	Focus knob	$14	$12	$11	$11	$8	$17,000	$6,000	$1,125	$24,125	$7	$26	$40	-$14 -34%
23217-208	Focus cell	$14	$12	$11	$11	$5	$19,333	$7,000	$1,083	$27,417	$8	$24	$78	-$53 -69%
23216-202	EL-1 housing	$15	$13	$12	$12	$5	$19,333	$7,000	$1,083	$27,417	$8	$25	$47	-$22 -46%
23216-207	Rear flange	$12	$10	$9	$9	$8	$17,000	$6,000	$1,125	$24,125	$7	$24	$55	-$31 -56%
23216-203	Focus knob	$14	$12	$11	$11	$8	$17,000	$6,000	$1,125	$24,125	$7	$26	$49	-$23 -46%
23216-206	Focus cell	$14	$12	$11	$11	$5	$19,333	$7,000	$1,083	$27,417	$8	$24	$55	-$31 -56%

Common tool for focus rings, rear flanges; common tool for EL1 housing on 23216 and focus cells
Tooling amortized over 3,300 parts (one year)
Total cost = 2,500 unit cost + finishing + tooling/part; finishing costs are estimates

Table 3 Cost summary for thixomolding components

Table 4 shows a summary of material choices for parts internal to the assembly. It was shown that some housing components could be changed from aluminium to injection molded plastics without any structural penalty. Because the critical lens-to-lens components required more exotic materials to limit thermal expansion effects, it is only financially worthwhile to injection mold these parts if the quantity is around 5000/year or higher (larger than our anticipated production quantities). For that reason the athermal component was left as a CNC aluminium part and only the casing elements were changed to injection molded materials.

No.	Component	Description	Material	Process	Est. Part Cost	Tooling Cost	Total Cost
1		Flange	40% CF PPS	Injection mold	$12 to $18 + $8 for post op	$35 k to $45 k + ~2 k for fixtures	$28
2		Focus cell	40% CF PPS	Injection mold	$8 to $12	$30 k to $40k	$14
3		Retainer	40% CF PPS	Injection mold	$5 to $8	$12 K to $15 K	$10
4		Athermal	Tivar 1000	CNC	$12	$0	$12
5		L1 retainer	PEI 30% GF	Injection mold	$2 to $4	$8 k to $10 k	$5
6		L2 retainer	PEI 30% GF	Injection mold	$2 to $4	$8 k to $10 k	$5

Table 4 Cost summary for injection molded components

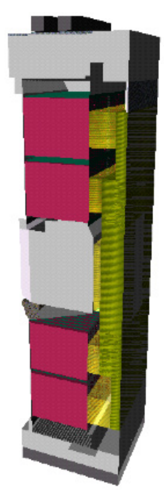
After completing all these analyses, we determined that while all material choices were structurally and thermally viable, the cost considerations were the main consideration in driving material choices for all parts in the assembly. Casing elements were selected to be thixomolded magnesium, internal housing and lens-retention elements are injection molded, and critical lens-to-lens elements are CNC aluminium. The result was a significant cost-of-goods-sold savings to the client, allowing the design to proceed with material choices defined for most subassemblies. Defining material choices before brainstorming detail concepts significantly reduced development time, since component geometry could be optimized for the selected material from the start of the design. Additionally, the structural analyses gave designers good starting points for component refinement since potential issues like stress concentrations were captured early.

Case 2: Design of a Telecom Equipment Cabinet

The second case we will consider is the design of a 42-U cabinet telecom switch. During the initial requirements definition it was immediately obvious that the thermal system would be the driving functional system (mechanically) due to the high power dissipation required for the volume. The thermal system would have to dissipate ~8.5 kW of power and not be affected by multiple redundant fan failures. Additionally, due to the presence of thermally-sensitive RF equipment, thermal gradients across certain components had to be minimized (<10 degrees Celsius).

Determining that the thermal system required critical-path analysis early in the design cycle allowed the thermal simulation of the system to be the first step of the design, prior to complicating tradeoff analyses with other less-important requirements (structural layout, etc.). In all subsequent design concepts, the thermal system drove the layout of fans, switches, power supplies, and cards, so only thermally viable concepts were considered. Additionally, risk was reduced very early in the project by proving that the required dissipation was at least theoretically feasible in the rack.

Early in the design, the thermal analysis dictated the product architecture by determining that two separate thermal zones would be required with separate banks of fans cooling each zone. It was found that 6 axial fans were required per zone. Flow impedances were calculated along each of three flow paths through the system. Figure 7 shows the overall system layout and one of the flow paths through the system.



The various flow impedances are broken down in terms of regions.

1	Wire mesh (58% open), 1/2" UAF 25 PPI air filter
2	Papst DV6200TD axial fans, louvers
3	Honeycomb at inlet and exhaust of card cage (0.275" thick, 1/16" Hex), 0.3" gap between each card blockage
4	Honeycomb at exhaust of card cage (0.275" thick, 1/16" Hex), 0.3" gap between each card blockage
5	Equivalent flow resistances to represent the cabling
6	Honeycomb (0.25" thick, 1/8" Hex)

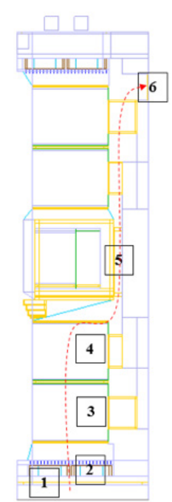


Figure 7 System layout and representative flow path

The primary thermal system components were defined and modelled, including heat sources, fans, and loss coefficients along the defined flow paths. The system was simulated both for nominal operation and in the case of a fan failure in each zone. FloMerics was used as the computational fluid dynamics tool for the simulation. It was found that the axial fans used in each zone developed about 375 Pa of pressure (75% of max value for the fan) with a flow rate of about 150 CFM each (36% of the no-load flow rate). The total flowrate through the system was 1600 CFM with an overall temperature rise between 8.4 and 9.1 degrees Celsius. Figure 8 shows results from the thermal analysis in terms of temperature and flow speed through the system.

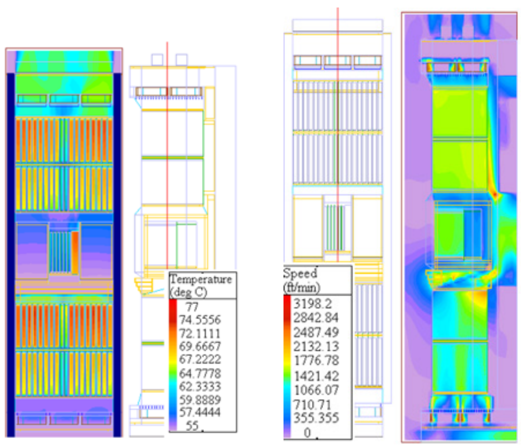


Figure 8 Temperature and airflow speed through the system

A subsequent analysis showed that in the case of two simultaneous fan failures (one in each zone), the thermal rise through the system only increases by 0.5 degrees Celsius. In addition to an overall thermal rise through the system of less than 10 degrees Celsius, the temperature rise over critical RF components was only 3-5 degrees Celsius.

Conducting a thermal analysis as the first step in the design of the 42U rack allowed the most important design elements to drive the rest of the design. The product architecture was defined with the most critical sub-system (thermal) as the driver, so all subsequent design concepts and layouts would work thermally. Additionally, a baseline for future analysis and optimization was defined so any proposed design changes could be evaluated against a known quantity. Development risk was significantly reduced since it was proven that not only would the system work under nominal conditions, but also under fan failure conditions as well. Conducting this analysis before any other concept brainstorming ultimately saved the customer significant development time and budget since thermally infeasible designs were immediately eliminated from consideration.

Case 3: Design of a Rack-Mounted Test System

The third case study we will consider involved the design of a sheetmetal frame used as the backbone of a two-meter tall rack of test equipment. Tolerances within the rack are important since the equipment in the rack is accessed by a 6-degree-of-freedom PUMA robot. The other driving requirements included cost of the rack construction and structural strength to bear the weight of the test equipment (more than 800 lbs) and resist lateral impulse loads from the robot. These three critical-path analyses (tolerance, cost, and structural analyses) were performed to drive definition of the initial concepts for rack construction. This case study is the most involved of the three since all three critical-path analyses were conducted concurrently.

The three concurrent analyses drove us to consider three different rack construction concepts that were fundamentally all tradeoffs between stiffness and part count (part count subsequently affecting weight and assembly effort). Three potential construction geometries considered are pictured in Figure 9.

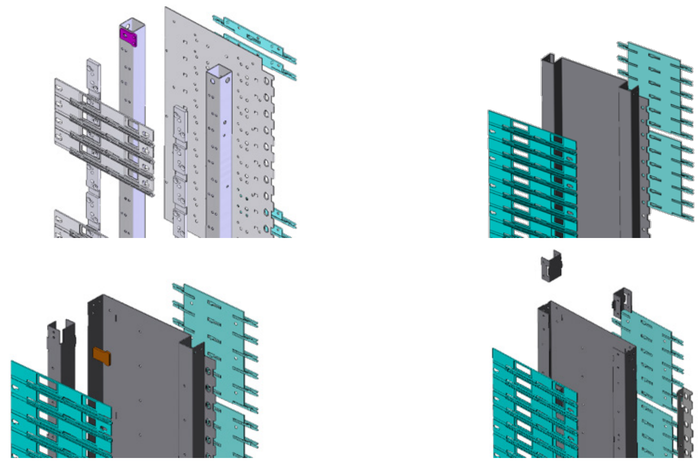


Figure 9 Rack construction options

These three concepts were arrived at as a result of critical-path analyses that evaluated the feasibility of moving away from an existing multi-part rack structure to one of these three more integrated solutions. A detailed cost comparison was undertaken, capturing both the overall assembly (part count, hardware, etc.) and piece-part manufacturing costs. Table 5 shows a representative calculation for piece-part sheetmetal manufacturing cost estimation. This cost estimation tool for sheetmetal parts was designed by Acorn based on heuristic models. Factors such as flat pattern area, material, thickness, number of bends/hits, hardware installation, labor, and post-processing are all factored in.

NC Sheet Metal Cost Estimator

				Calculated Costs							
Part	Locale	Material	Guage	Material	Fabrication	Hdwe	2nd Ops	Misc	Profit	NRE	Part Cost
Cross bar (nc punch)	Malaysia	CRS	0.048"	$0.56	$0.94	$0.00	$0.59	$0.00	$0.42	$62.50	$2.49
Concept A											
Brace, front-back (nc)	Malaysia	CRS	0.048"	$0.42	$0.67	$0.00	$0.45	$0.00	$0.31	$18.50	$1.84
Tube, normal	Malaysia	CRS	0.048"	$12.53	$66.08	$9.87	$13.20	$0.00	$20.34	$166.50	$122.03
Tube, extended	Malaysia	CRS	0.048"	$18.80	$6.83	$9.87	$19.80	$0.00	$11.06	$166.50	$66.36
Concept B											
Brace (and mirror)	Malaysia	CRS	0.048"	$2.52	$2.55	$0.00	$2.65	$0.00	$1.54	$74.00	$9.26
Tube insert	Malaysia	CRS	0.048"	$3.31	$1.57	$4.94	$3.49	$0.00	$2.66	$55.50	$15.97
Tube, normal	Malaysia	CRS	0.048"	$11.70	$63.23	$4.94	$12.32	$0.00	$18.44	$111.00	$110.62
Tube, extended	Malaysia	CRS	0.048"	$17.59	$4.28	$4.94	$18.53	$0.00	$9.07	$111.00	$54.41
Concept C											
Front skin	Malaysia	CRS	0.035"	$7.47	$1.34	$0.00	$10.79	$0.00	$3.92	$0.00	$23.52
Extension	Malaysia	CRS	0.048"	$8.28	$1.69	$0.00	$8.72	$0.00	$3.74	$37.00	$22.43
Tube	Malaysia	CRS	0.048"	$11.69	$4.06	$9.87	$12.32	$0.00	$7.59	$74.00	$45.53
Bracket/spacer	Malaysia	CRS	0.048"	$0.03	$0.27	$0.00	$0.04	$0.00	$0.07	$18.50	$0.41
Plate, front-back	Malaysia	CRS	0.048"	$0.44	$0.42	$0.00	$0.47	$0.00	$0.27	$37.00	$1.60
Form plate	Malaysia	CRS	0.048"	$0.15	$1.68	$0.00	$0.16	$0.00	$0.40	$37.00	$2.40

Table 5 Sheetmetal cost estimator

The estimates for various sheetmetal parts were rolled into a top-level cost model for the entire rack subassembly, including cost estimates for hardware and assembly time/labor. Weight estimates were derived from the CAD system used. Table 6 details the differences between costs and weights for each of the concepts.

Per System

	Part Count		Cost					Mass			
Concept	Parts	Hdwe	Part	Hdwe	Assembly	Total	Delta	Part (kg)	Hdwe (kg)	Total (kg)	Delta
Existing	10,040	62,830	$42,556	$3,400	$1,784	$47,740	—	697.75	42.08	739.84	—
A	2,020	17,280	$9,111	$1,156	$471	$10,738	-$33,445	715.77	10.61	726.38	-13.46
B	1,900	18,240	$10,128	$1,266	$508	$11,902	-$32,428	849.85	11.22	861.07	121.24
C	4,430	18,640	$7,407	$1,312	$523	$9,243	-$35,149	758.91	11.47	770.38	30.54

Table 6 Concept cost and weight analysis

In addition to the cost analysis, tolerance analyses were completed for all three concepts to evaluate the relative position of equipment in the rack in X, Y, and Roll. As stated above, these relative positions are critical for automated robot access to the equipment in the racks. We use a direct linearization method for tolerance analysis that is a weighted sum of several statistical distributions for manufacturing and assembly tolerances.

The result is a statistical confidence interval that is much more accurate than a typical worst-case tolerance stackup. A representative tolerance loop using this method is captured in Table 7. This particular loop shows a confidence of 2.1 sigma (relatively low) that the equipment may crash when installed into the rack due to inconsistencies in the roll dimension. The tolerance analysis allowed this to be recognized as a risk to one of the concepts that could be addressed in a subsequent design phase.

Tolerance Stack-Up Analysis

Loop Name: Heavy Duty Rotation X, Concept A

Element Name	Nominal	±Ti	PDF	Effective Process Variation	Normal SD	Z	Cp	Sigma^2	Delta
S–slot Slot height		0.6800	n	0.226667	0.2267	3.00	1.00	0.051378	36.5%
A–card guide Top of rail to hole, plastic feature		0.1290							
A1–card guide at slot tip	Scaled	0.4938	n	0.164590	0.1646	3.00	1.00	0.027090	19.2%
B–vertical plate Hole to hole, shtml flat pattern		0.1470							
B1–vertical plate at slot tip	Scaled	0.5627	n	0.187556	0.1876	3.00	1.00	0.035177	25.0%
C–card guide Hole to top of rail, plastic feature		0.1290							
C1– card guide at slot tip	Scaled	0.4938	n	0.164590	0.1646	3.00	1.00	0.027090	19.2%
Measured GAP 1.28 mm–0.381 mm Measured at tip of slot to slot	.0889								
Nominal gap	.0889	**Z predicted**	**Alpha (single sided)**	**DPPM**	**Percent Defects**		**Total Standard Deviation**	0.375146	100%
Upper spec limit	1.778	2.37	0.008900	8900	0.89%				
Lower spec limit	0	2.37	0.008900	8900	0.89%				
			Total DPPM	17801	1.78%				
			Effective Z	2.10					

Table 7 Direct linearization tolerance analysis

A summary of tolerance results for X, Y, and roll for all concepts is captured in Table 8. It can be seen that any departure from the existing design, which had lots of alignment pins and extra hardware, resulted in lower statistical confidence that the equipment could be safely accessed in the rack by the robot.

	Effective Z			
	Baseline	Concept A	Concept B	Concept C
X Binding	6.17	4.18	4.08	5.73
Y Binding	3.63	3.63	3.63	3.63
X Rotation	2.10	2.10	2.10	2.10

Table 8 Concept tolerance summary

Finally, two structural analyses were performed to compare the relative performance of departures from the existing design. A modal analysis was undertaken to evaluate overall stiffness of the various rack concepts, along with a static analysis to see how the different rack concepts responded under robot load. Figure 10 shows the constraints and loading conditions for the robot load analysis. The rack was constrained at the base and a distributed load (representing the distributed weight of the installed equipment) was applied along the height of the rack. In addition, a larger load representing support equipment was applied to the top of the rack.

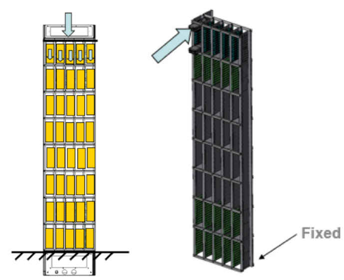
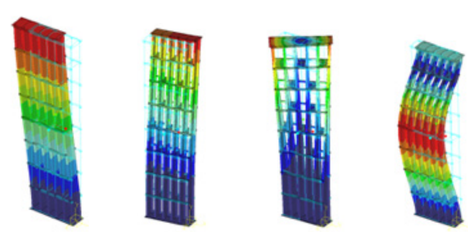
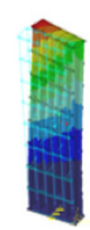


Figure 10 Structural analysis loading and constraints

Figure 11 shows the modal and static displacement analysis results for the different rack concepts. It can be seen that the third rack construction concept is the stiffest option (highest resonant frequency for each mode shape) and had the lowest static deflection under the lateral robot load.





Design	Mode 1	Mode 2	Mode 3	Mode 4
Baseline	10.14 Hz	14.94 Hz		
Concept A	9.95 Hz	11.74Hz		
Concept B	10.49 Hz	12.85 Hz		
Concept C	12.67 Hz	14.26 Hz		

Design	Deflection
Baseline	0.19 mm
Concept A	0.31 mm
Concept B	0.31 mm
Concept C	0.16 mm

Figure 11 Modal and static loading results

The final result of these analyses and the tradeoffs between tolerance, cost, and structural integrity led us to select the third rack construction concept going forward. It had the lowest overall cost, acceptable tolerances, and stiffest structural response at a cost of slightly increased weight and fairly large part count. Defining the overall structure and construction method of the rack allowed all subsequent concept brainstorming to be based off of a vetted base concept that was known to be an optimal balance of cost, tolerance, and structure.

Summary and Conclusions

In all three case studies considered, critical path analyses realized significant benefits to the cost and schedule of the development program. Initial design direction was driven primarily by analysis, allowing all subsequently derived design concepts to enjoy a shared level of proven feasibility. Additionally, concurrent cost analyses often facilitated the selection of an optimal design direction that achieved significant savings for the product on a cost-of-goods-sold basis. Table 9 contains a summary of the results of the three case studies.

Case	Technical Result	Program Result
Rifle Scope	Optimal materials selected for each subassembly, structural and thermal expansion requirements met	Saved ~50% cost on casing parts and ~20% on internal parts, reduced development time and cost
42U Telecom Cabinet	Successfully dissipated 8.5 kW with redundant fan failures	Reduced development time and cost, assured component layout viability
Rack Structure	Selected optimal construction geometry for primary structural element	Reduced system cost by ~$35K, decreased part count, assured tolerance and structural viability

Table 9 Case study summary

In these three examples there were significant benefits gained from the increased technical risk of letting analysis drive early concept development. While not optimal in every development program, in programs with high risk or stretch goals this approach can mitigate risk, decrease development time and cost, and increase product ROI.

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Brad joined the Acorn team in 2011 and founded the Acorn Design Center in Dallas, Texas. A mechanical engineer, Brad has worked on a wide range of projects, including those with complex mechanism, thermal, and cost reduction challenges. Brad has authored and presented several engineering papers at conferences and is very active in the Dallas engineering community. He holds a BS/MS in mechanical engineering from Georgia Institute of Technology.

About Acorn

Founded in 1993, Acorn Product Development is based in Silicon Valley with design centers in Texas, Boston, and China. We provide comprehensive product engineering services—from turnkey product development, subassembly development, and engineering analysis to materials cost analysis and manufacturing cost reduction—for leading companies around the globe.

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