RAPPORT – Loket 4

Överblick

There is a customer in need of a 3d printed prototype of a toy train. The customer's desire is to compare the 3d printed PLA version of the design with one that has been machined traditionally out of stainless steel. They supply us with a CAD drawing in STP file format and ask for a quote on a fully printed and assembled train.

Throughout this document we will walk through the steps one might take to complete this task from accepting the job to completion as well as comparing the initial quote to the actual time it took to complete the process.

Figure 1
Fully printed and assembled train in xPLA

Planering

To plan for this process, we must know the use case of the final product. Different use cases require different approaches to the planning. We assume the final assembly is to be a prototype printed using PLA, so we can move on investigate the CAD drawing and compare it with FDM design rules. We check the model to see fitment of parts keeping a close eye for how the model is to be assembled. We need to find out if the CAD model is ready to print or if there is interference, threads or other considerations. Some questions will also arise in which we will need to clarify with the customer.

How familiar is the customer with the FDM process?

If unfamiliar with the 3d printing process the customer might not know what to expect in terms of surface finish and what tolerances the machine is capable of achieving. The anisotropic properties of printing layer-by-layer means less strength in the Z direction than the X and Y. The FDM process produces a specific surface finish which is not as smooth as would be achieved in a machine shop. We should keep seam positions and layer line resolution in consideration.

Should the final part be solid or is a reduced infill percentage acceptable?

The strength of an FDM printed part is mostly distinguished by the printed part's skin thickness. The infill is primarily to support the shell while printing. Reducing the infill can have a dramatic effect on print time and mass savings and increasing the shell thickness has shown to increase the strength[1].

[1] "INFILL pattern and SHELLS – How to get the maximum STRENGTH out of your 3D prints?." *YouTube,* uploaded by CNC Kitchen, 25 Feb 2018, https://youtu.be/AmEaNAwFSfI.

How close to the original design should the model be printed?

There are some design rules that make a much smoother printing process. We could reduce or eliminate the need for support material if we taper overhangs. We could reduce the need for some of the final assembly by combining parts.

What are the expected tolerances between parts?

In my experience I have found that if parts need to fit and move freely amongst each other there should be at least a 0.2 mm tolerance gap designed into the model.

Will this be a one-off product or is there a future potential to print multiples?

If there is the potential to print more of the same in the future, it could be interesting to do even more testing and investigation into each part and streamline the approach to make printing the next parts or batches easer.

Anpassningar

Corrections to the supplied CAD model

Changes to the CAD model and printed tests are required to ensure form, fit and function. In figure 2 we can see all of the coincident and interfering volumes in the original CAD drawing. As we examine closely, we see that there are two major interfering volumes, one with the hub to axel and another one at the fitment of the boiler to the cabin. Using the push/pull command we remove 1.4 mm of material from the inner face of the wheel *(fig 3)*. The cabin interference is only a problem when the boiler is turned 90 degrees *(fig 4)*. This is a required change because the bayonet fitting between the cabin and boiler will not function otherwise.

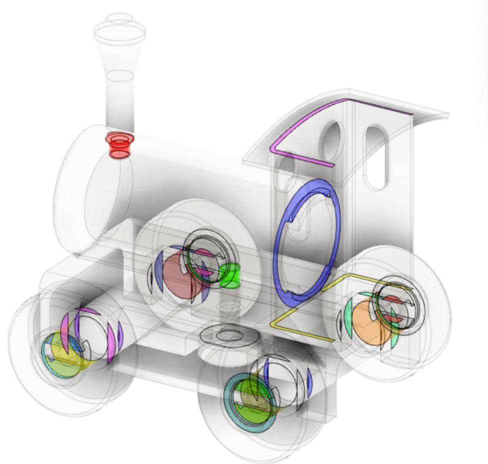


Figure 2
Coincident faces and interfering volumes in original CAD model shown by the colored sections. Screen capture from Fusion 360.

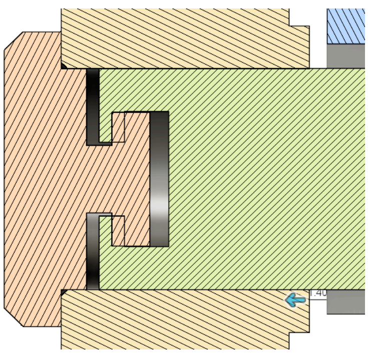


Figure 3
Note the interference of the hub can be eliminated by adjusting inner face of wheel. Screen capture from Fusion 360

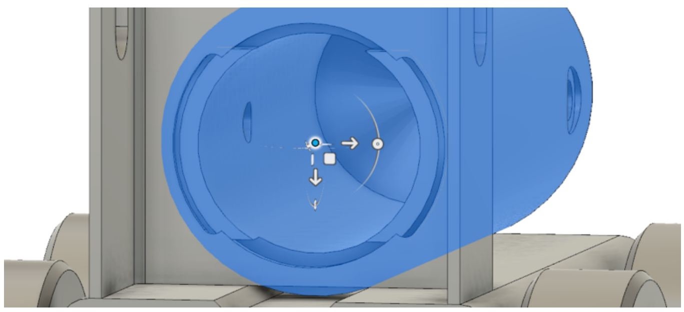


Figure 4
Boiler to cabin bayonet fitment interference when boiler is turned 90 degrees. Screen capture from Fusion 360

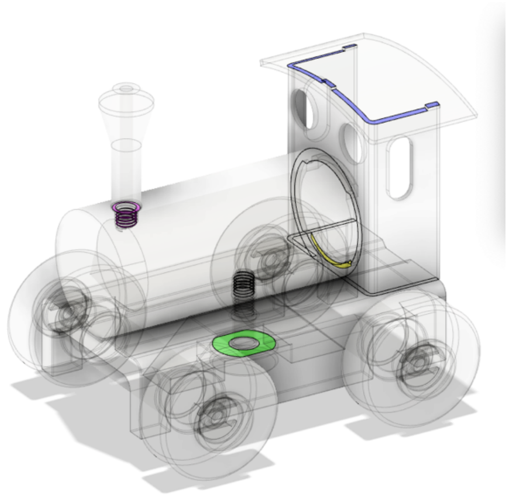


Figure 5
Coincident and interfering volumes after adjustment to the CAD file. Coincident volumes shown are acceptable and will not interfere with assembly.

Tolerances

A tolerance of 0.2 mm is added to all coincident faces that needed to function together. Some examples of this are wheel to axel, hub to axel, axel to chassis and boiler to cabin. The Push/Pull function does quick work of this.

Threads

The threads were not modeled in the received CAD file. In order to have strong and working threads we must model them for printing. We will model the threads to be an m8 standard using the threads function in Fusion 360. Based on past experience we know that FDM printers often require a little extra tolerance added into the threads than is originally modeled using the threads function. We use the push pull function to add an extra 0.1 mm offset to every face of the modeled thread.

Slight adaptation

The roof and cabin do not have a mechanical joint. To make the assembly easier, and the roof removable after assembly, some small tabs are added to the top of the cabin and their respective locations on the roof are cut out to accept them. We can see this represented in purple on figure 5. This is accomplished within minutes with a sketch and the emboss command in Fusion 360. Tolerances are added. We are granted approval from the customer for this change.

Tests

Not all printers and filaments print as accurate and predictable as we would like them to. Tests must be carried out to ensure the tolerances and other changes are adequate and the parts will fit together in our situation.

Figure 6
All of the test pieces after printing.

A series of tests for every joint type are created in Fusion by reducing the part volume to only the section we need for testing, saving them as STL files and opening them in the slicer. We slice the parts with the settings we want to use for our final print quality *(fig 7)* and sent the prints off to the printer. These small test pieces *(fig 6)* take over two hours to print *(table 1)* but they can save us hours or more if we have assumed incorrectly with our tolerances and adjustments to the CAD models. Test printing will also give us a good chance to test the optimum part orientation and support structure.

The fitment of the hub to the axel was perfect but we find the rest will need slight adjustments. Here we are reminded why we take the extra time to run these tests. The wheel to axel, as well as the threads, have slightly too much tolerance for our liking. A quick edit to the push/pull feature already in the Fusion 360 timeline makes quick work of this and we send off the second and final batch of tests to the slicer *(fig 7)*.

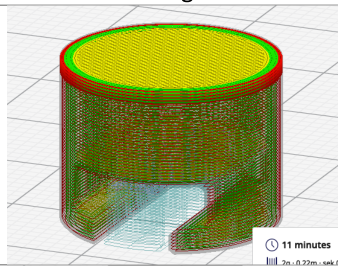
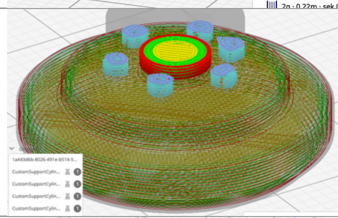
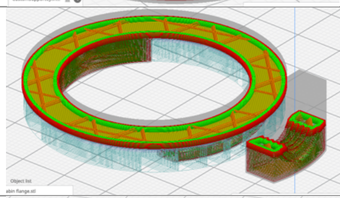
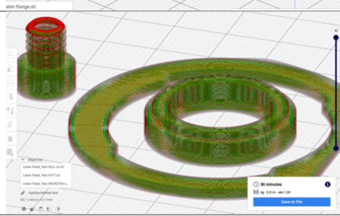
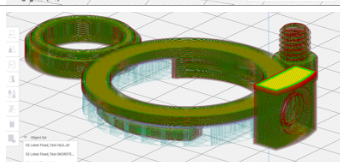
Test Prints				
Test Type	Prep time	Material use	Print duration	Image
Axel end	00:03	2 g	0:11	
Hub	00:04	2 g	11	
Boiler flange and threads	00:07	6 g	37	
Cabin, Wheel ID and Chimney threads	00:07	4 g	30	
Final test	00:06	8 g	52	
Totals	**00:27**	**22 g**	**02:35**	

Table 1
Representation of the time and material usage for the tests carried out in preparation for the final printing.

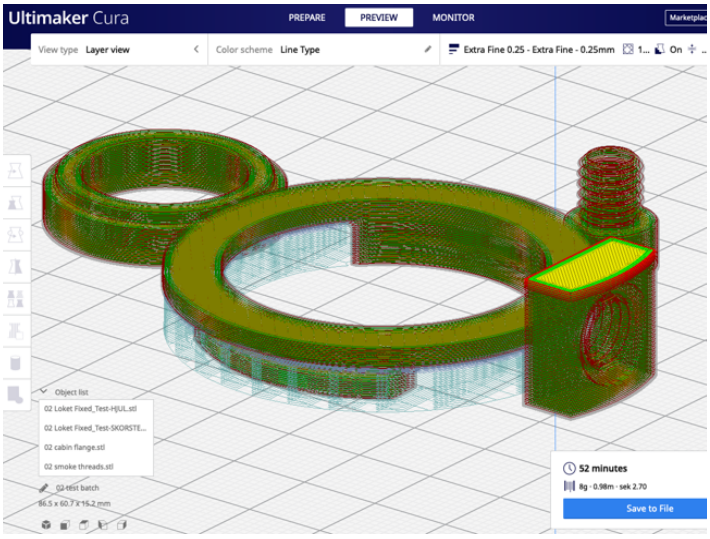


Figure 7
Test batch example. Wheel inner diameter, boiler flange, boiler and stack threads.

Kalkyl Uppskattad kostnad

Typ av kostnad	**Totalpris**
Kostnad operatör + maskiner	kr 2 477
Kostnad material	kr 167
Ändringar anpassningar	kr 742
Tests	kr 500
Unknown-unknowns	kr 389
Totalt	**kr 4 274**

Table 2
Best estimation of costs before printing.

Table 2 represents our best estimation of what printing this train could cost. Note the Unknown-unknowns. Previous experience tells us that there are most always going to be hidden costs or something we have not thought about. In this case we take a wild guess at how much that could be by simply assuming 10% extra to be added to the final costs.

Tillverkning

The manufacturing step involves printing, post-processing and assembly of the product.

Printing – Duration: 27 h 22 min

Printing is the actual time from powering up the printer, extruding filament to produce the part and to the point when the part is ready to be removed from the printer.

Post-processing and Assembly – Duration: 40 min

Post-processing is the work that is required to prepare a part for assembly. In our case this includes removing the parts from the build plate and removing the brim and other support material by breaking or cutting it away. Sometimes post-processing can also include sanding, polishing, sand blasting, painting, cutting threads or other finishing techniques.

Assembly is the last step which involves taking all of the printed and post-processed parts and joining them together creating the final product. In our case all of the parts fit together with simple joints which have been designed into the part. Sometimes the assembly process could involve adding various hardware like screws, or adhesives to join parts together.

Printing Parameters

We have discussed in the Planning section that this train is to be a prototype to compare a basic FDM manufactured product to a traditionally machined train of the same size. Here we should list some of the printing parameters we will use.

Printer	Ultimaker 2+
Bed surface	Glass
Nozzle	0.4 mm
Material	Add:north xPLA black
Slicer	Ultimaker Cura 4.8.0
Hot end temperature	193 °C
Bed temperature	66 °C
Ultimaker print profile	Extra Fine (plus changes listed below)
Layer height	0.25 mm
Wall thickness	1.05 mm
Infill density	20%
Infill Pattern	Cubic
Speed	50 mm/s
Support	Only with batch 2 and 3
Build plate adhesion	Brim only on batch 2 and 3

Table 3
Printing parameters used for this project

Kalkyl Verklig kostnad

Typ av kostnad	Totalpris
Product operatör + maskiner	kr 2 712
Product material	kr 167
Ändringar anpassningar	kr 742
Tests Operator + machine	kr 277
Tests Material	kr 8
Övrigt	kr
Övrigt	kr
Totalt	**kr 3 906**

Table 4
Actual calculations based on our real-world result.

Reflektion / Övrigt

When we compare and reflect upon our estimated and real-world cost comparison, we can see some discrepancies. Below we will investigate these differences and dive into other considerations. We will also compare traditional versus additive manufacturing of this train.

Cost discrepancies

Even with years of experience it is difficult to correctly estimate what costs will exist when carrying out a project. In our case we were successful in eliminating the chance that we would estimate lower than the actual cost. We did this by calculating ten percent of the final estimation and adding that to the final outcome. We listed this as "unknown-unknowns" in table 2. We keep in mind that all calculations are on our cost and not the amount we would charge the customer. In the end our real-world cost was actually around 300 kr less than our estimate (*table 4)*.

Unknowns

Figure 8
Saving a print batch.

Being the green 3d printing specialists that we are, there were some uncertainties we needed to figure out. We could only assume how long would it actually take us to prepare, post process and assemble the train. Some areas, like the connection between the support and the ninety-degree overhang above the boiler flange, print with strange results on the Ultimaker, requiring extra clearance. We learned that removing support material can be more or less difficult depending on how we configure the print orientation and slicer settings.

The printing process failing on some parts was one of the biggest unknows in this case. Printing in batches on a glass bed gives the opportunity for a single part print failure to ruin an entire batch.

There were three instances of failures during my two batches. The first was a bed leveling issue which I quickly noticed and remedied during the first layer and restarted the print, this took very little extra time.

The second failure was on the first batch. The Låsskruv broke free from the bed within the first ten or twenty percent of the printing process. There was already a significant amount of plastic extruded relative to the amount of plastic which would be lost if we would continue printing so I decided to continue on and count the screw as a loss and save the rest of the batch. I added a few layers of tape to the build plate under where the screw would continue to print. Surprisingly it finished printing quite well *(fig 8)*, but it would not be good enough to send to a customer, so I printed the screw again in the second batch.

The third failure I didn't realize until I was about to assemble the train. I have learned a lesson here which is to check the layout very closely after using the auto arrange function in Cura *(fig 9)*. I would not be able to remove the stack from the roof without damaging the surface of both, so I created a third batch. This was very quick to create and relatively quick to print.

Figure 9
When your slicer thinks the smokestack is better served as a bazooka.

The amount of time for preparations is another major unknown in our case. It is difficult to anticipate how long it will take to arrange all of the parts in the slicer, make sure supports are where they should be and not where they shouldn't and have an intuition of how well the parts will hold onto the build plate. I spent many more minutes in the slicer than I had originally estimated.

Post processing

There was some difficulty removing some of the supports. It took roughly 40 minutes to remove the supports and assemble the train. I realize that If I spend more time interrogating and micromanaging my print batches, I could have saved twenty-five to thirty minutes during this process. The issue was in some extra supports printing where I was unaware it was going to happen, or I incorrectly thought that I had already placed support blockers in those locations. My goal was too print two batches, one without supports and one with supports and brim. The type and areas of the supports varied during the second batch making it more difficult to get it right the first time.

Traditional versus Additive

It is unfair to judge which method is best between traditional machining versus additive manufacturing of this train because the final product is in two very different materials. Instead, we can consider the differences.

With both manufacturing approaches the machine + operator time equally dominates as the most expensive portion of the process with the cost per material being a very small percentage of the overall cost. Traditional machining costs were around three times more than the costs we have figured on for additive manufacture. This has much to do with the large amount of handling required for each piece when machining. With additive, the pieces grow out of raw material within one machine. With traditional machining each piece goes through multiple processes sometimes on multiple machines to produce the same shapes.

Suitability of Printing this train

We should always start with the question of "Should we print this?" The idea for this train was to be a direct-as-possible comparison between the traditionally manufactured train and the additively manufactured train. In this case we are successful. There is, however, much room for adapting this design to better suit FDM additive manufacturing.

The anisotropic properties of printing in the X/Y versus the Z direction makes some parts very weak where they should perhaps have some added strength. If we take the hub for an example *(fig 10)* we see that there is a very small surface area where one layer is to adhere to the next. This is supposed to be what holds the wheel to the axel. If we require more strength, we could adjust the model to have some other fitting style which increases the surface area of those layers while still maintaining a similar slide-together function holding the wheel to the axel like in figure

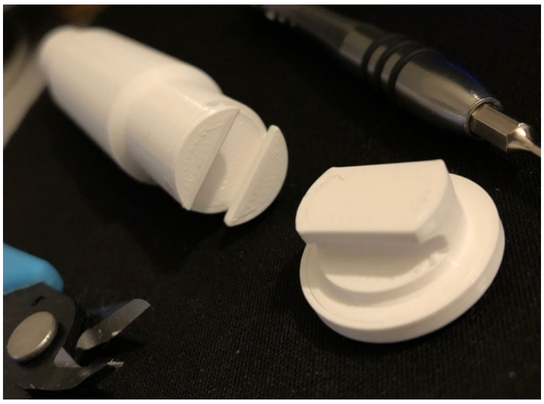


Figure 10
Alternate method of designing the sliding joint between the hub and axel.

Concluding thoughts

In conclusion I would like to reiterate the need to scrutinize the use case. It is important for us as 3d printing specialists to judge whether or not a design is suitable for additive manufacturing or if changes to the design should be recommended. It is often not obvious to the world outside of additive manufacturing to know what materials or printing styles can or should be used and what can and should be printed. We can often improve a design by completely changing our view and redesigning for 3d printing. Does the product need to be assembled or can the parts be consolidated? Could we redesign the product to be printed without support? Should there be traditional joints and rigid structures, or could there be compliance built in? Sometimes just knowing the use case and scrapping the design allows for the flexibility and brilliance that additive manufacturing brings to the table. I am excited for the next assignment where we get to redesign the train specifically for the FDM process, test print and compare our results to what we have learned here.

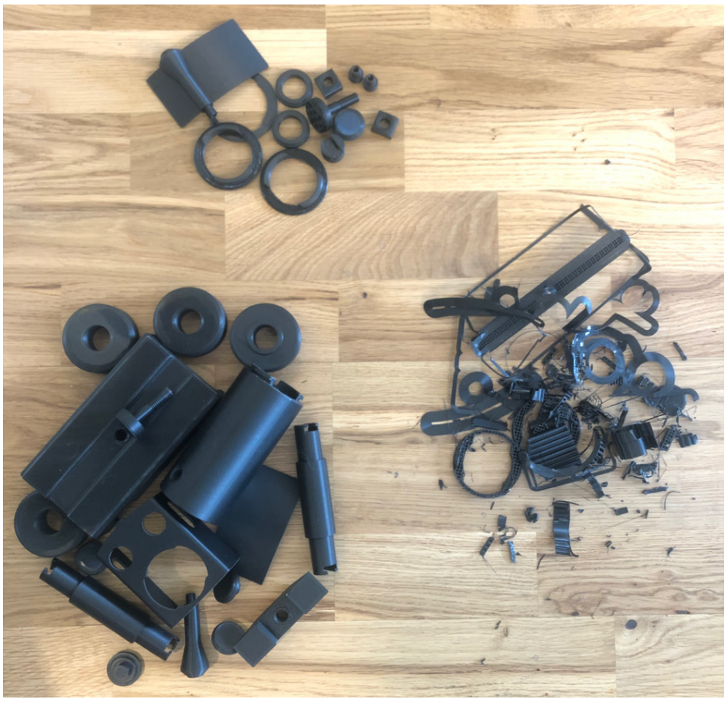


Figure 11
All of the PLA plastic that has given its life for the cause. Top: Test bits and failed prints. Left: Post processed pieces ready for assembly. Right: Sacrificial support and brim material.