Improved Database for 3D Printing (3DP) in Space

Final Design Review

Chad Fisher, Scott Lee, Nicolas Terrazas

Agenda

1. Motivation
2. User Needs and Specifications
3. Prototype Description
4. Testing Results
5. Next Steps
6. Conclusion

Sending spare or replacement parts to space is **costly** and **slow**

$69,000,000/yr

used to send and replace spare parts from the ISS

97.7%

of this could be saved with In-Space Manufacturing (ISM)

The Problem

But, there is <u>no good infrastructure</u> in place to leverage this technology

Barriers to ISM

parts not ready
for 3DP

information not
clearly stored

equipment not fully
developed

Barriers to ISM

parts not ready for 3DP

information not clearly stored

equipment not fully developed

Project Goals

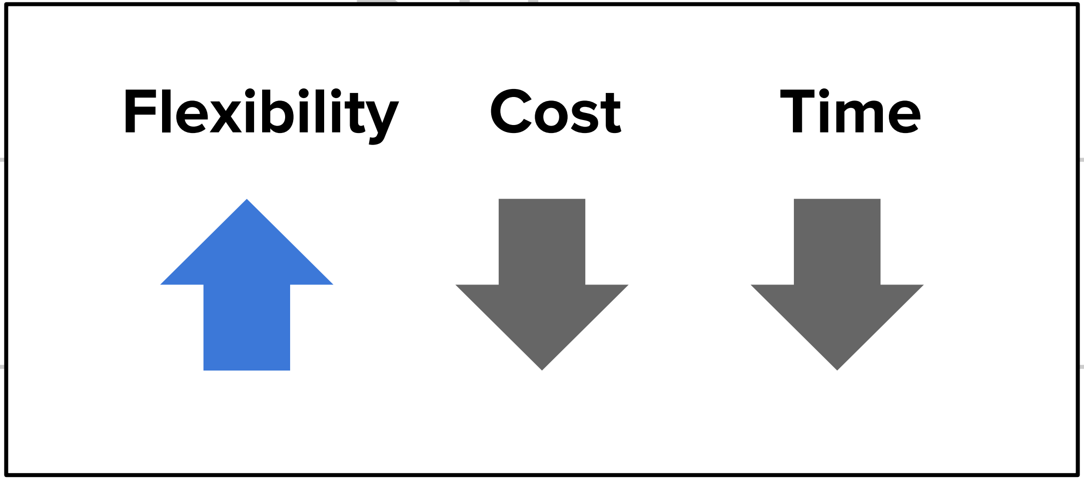
Redesign Process

Reduce material usage and print time

Database

Increase organization and usability

Project Goals



Reduce material usage and print time

User Needs and Specifications

Redesign Needs

Less material

Faster print time

Size

Better Comfort

Parts Specifications

Specification 1: Average infill percentage of the part

Specification 2: Average time to print the part

Specification 3: Size of longest dimension of part

Specification 4: Survey on comfort, functionality, and ease

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Parts Specifications

Specification 1: Average infill percentage of the part

< 50% Infill

Specification 2: Average time to print the part

Specification 3: Size of longest dimension of part

Specification 4: Survey on comfort, functionality, and ease

Parts Specifications

Specification 1: Average infill percentage of the part

< 50% Infill

Specification 2: Average time to print the part

< 50% of original

Specification 3: Size of longest dimension of part

Specification 4: Survey on comfort, functionality, and ease

Parts Specifications

Specification 1: Average infill percentage of the part *< 50% Infill*	Specification 2: Average time to print the part *< 50% of original*
Specification 3: Size of longest dimension of part *< 230 mm*	Specification 4: Survey on comfort, functionality, and ease

Parts Specifications

Specification 1: Average infill percentage of the part

< 50% Infill

Specification 2: Average time to print the part

< 50% of original

Specification 3: Size of longest dimension of part

< 230 mm

Specification 4: Survey on comfort, functionality, and ease

> 4 out of 5

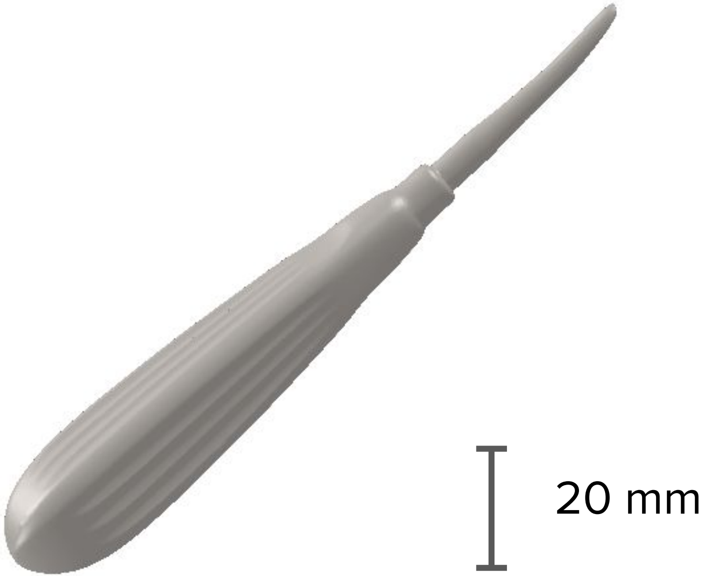
Optimization Process

Parts Redesign Process

1. **Initial Print**
   - Ensure it can be 3D printed
2. **Usability survey**
   - Subjects perform mock procedure
   - Rank statements about comfort, functionality, and ease of use
3. **Topology Optimization**
   - Optimize material layout while maintaining exterior geometry
4. **Final Redesign**
   - Combine results into final product

Dental Elevator

- Used to loosen teeth for extraction
- Has a large handle for possible material reduction
- Independent functionality
- 1 piece



Step 1: Initial Print

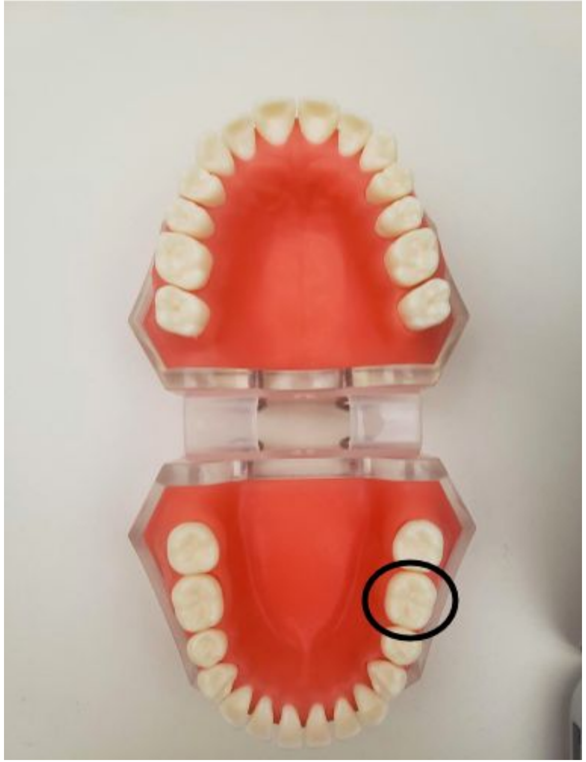
Redesign tool to be 3D printed

Decreased width along tool length

20 mm

Flat bottom for fixed support while printing

Step 2: Usability Testing



Subjects shown a dental model with removable teeth, and asked to use the dental elevator as a lever to try to remove the indicated tooth

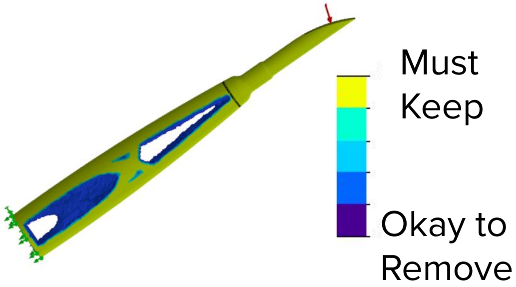
Step 2: Usability Testing

Criteria	Statements
Ergonomic Comfort	- Statement 1: The redesigned tool was comfortable - Statement 2: The redesigned tool was light
Functionality	- Statement 3: The redesigned tool could be securely held during the procedure
Ease	- Statement 4: The redesigned tool was easy to use

Step 3: Optimization

Optimizes material layout, while maximizing strength

Mesh with
applied loads

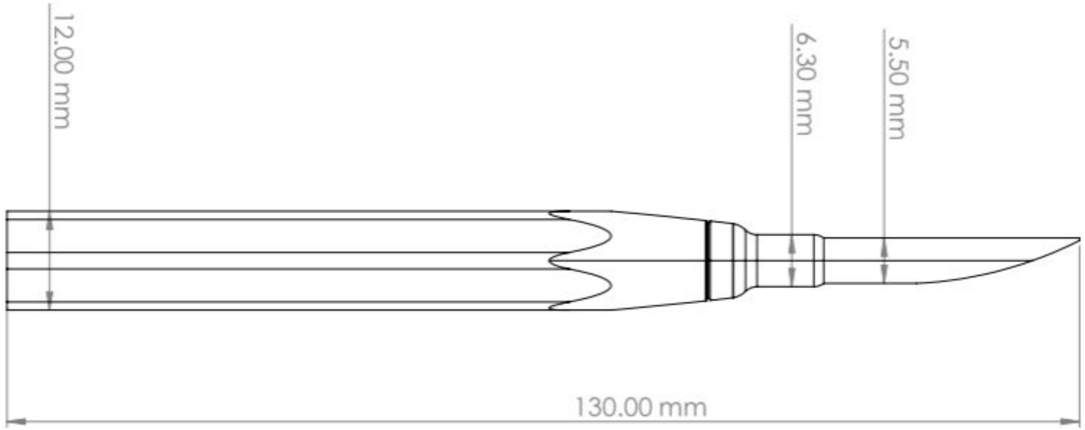


Topology
Optimization

Rough edges
smoothed out

Step 4: Final Redesign

Create a final prototype applying the knowledge gained from the usability survey and the topology optimization



Testing Results

Parts Specifications

Specification 1: Average infill percentage of the part *< 50% Infill*	Specification 2: Average time to print the part *< 50% of original*
Specification 3: Size of longest dimension of part *< 230 mm*	Specification 4: Survey on comfort, functionality, and ease *> 4 out of 5*

Parts Specifications

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< 230 mm

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Average Infill Percentage

Weight percentage of the final redesigned part compared to the original part with 100% infill

percentage = mass of redesigned partmass of part at 100%

Using SolidWorks, a 50% mass reduction was used with topology optimization to ensure the infill percentage was reduced

Parts Specifications

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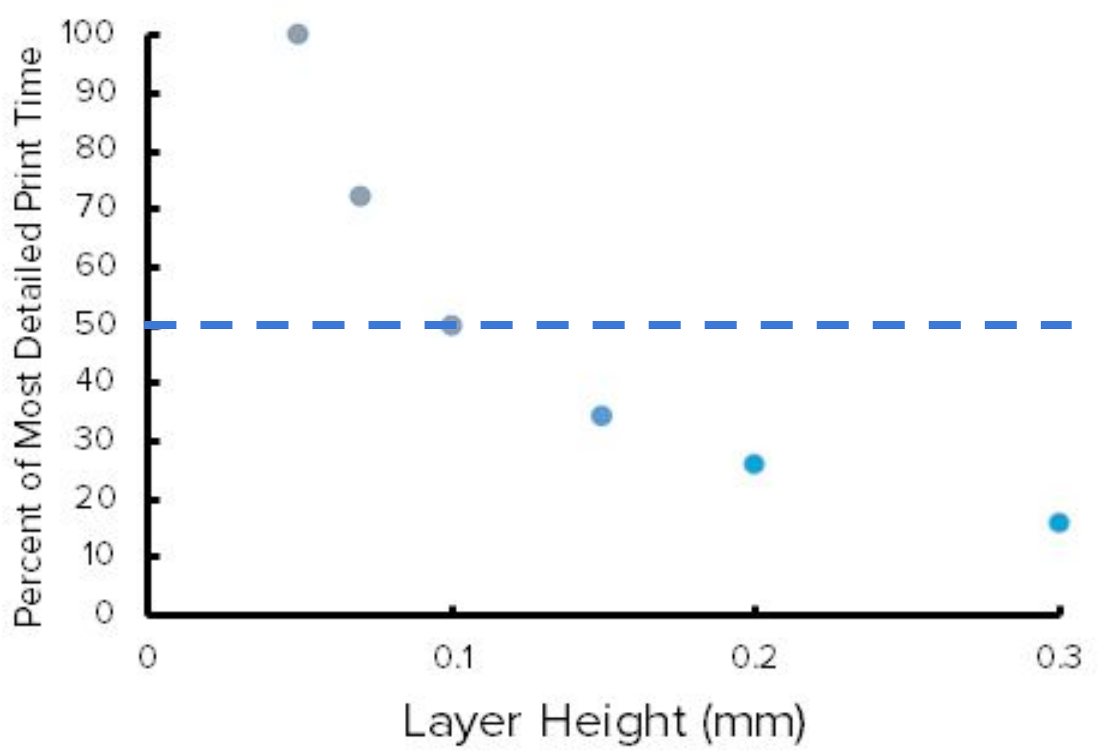
Print Time



Any layer height above 0.10 mm led to less than 50% print time

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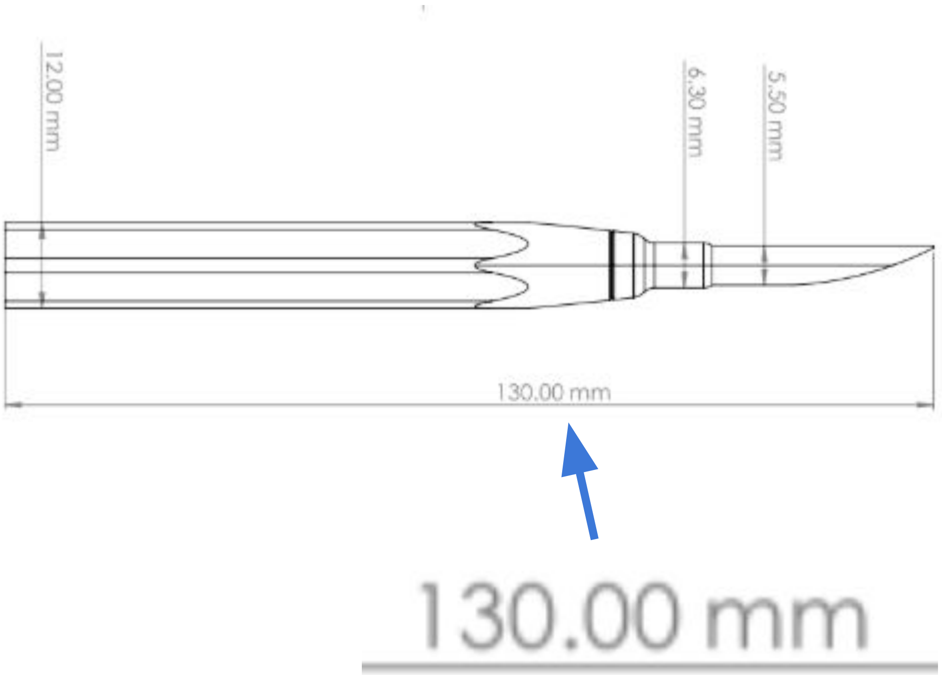
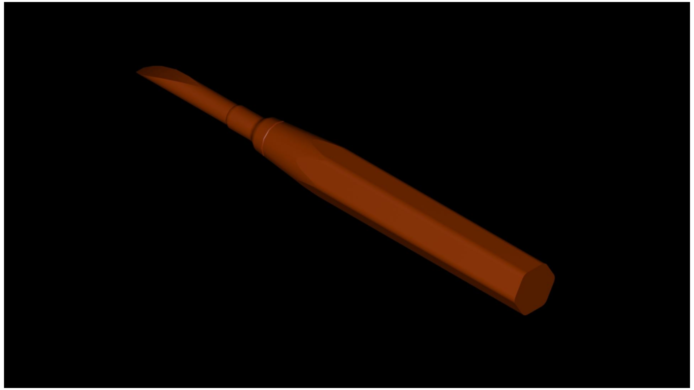
Footprint of Part





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> 4 out of 5

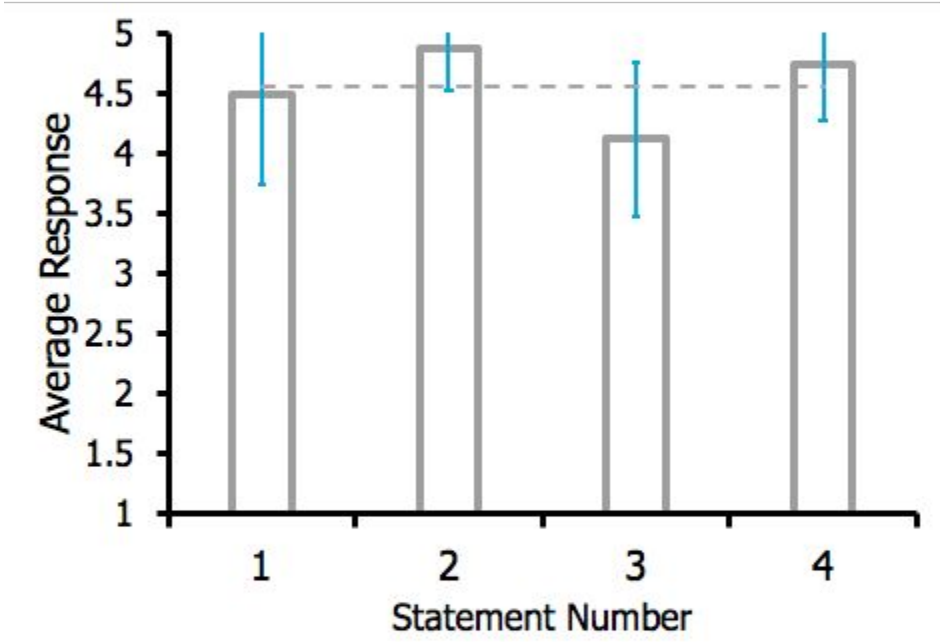
Subject Selection

- n=8
    - Tradeoff between recruiting ability and significance
- Semi-random selection
    - People we feel comfortable approaching
- Engineering students
    - Approximate possible users

Usability Statements

Criteria	Statements
Ergonomic Comfort	- Statement 1: The redesigned tool was comfortable - Statement 2: The redesigned tool was light
Functionality	- Statement 3: The redesigned tool could be securely held during the procedure
Ease	- Statement 4: The redesigned tool was easy to use

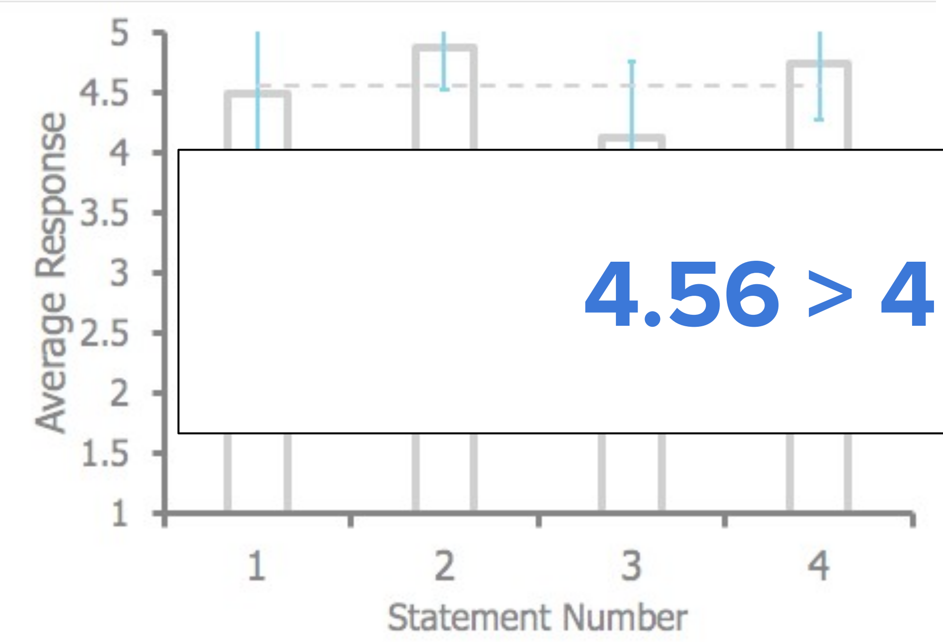
Results



Statements

1. Comfortable
2. Light
3. Securely held
4. Easy to use

Results



4.56 > 4

Statements

able

y held

use

Parts Specifications

Specification 1: Average infill percentage of the part

50% Infill

Specification 2: Average time to print the part

16 < 50% of original

Specification 3: Size of longest dimension of part

130 < 230 mm

Specification 4: Survey on comfort, functionality, and ease

4.56 > 4

Next Steps

Planned Work

Printing prototypes and Mechanical Testing

Topology optimization must be performed on each of the final redesigns

Printing prototypes with different materials

Look into other materials for 3D printing parts

Separate Processes

Create a separate redesign process specific to different user needs

Database

Project Goals

Redesign Process

Reduce material usage and print time

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Increase organization and usability

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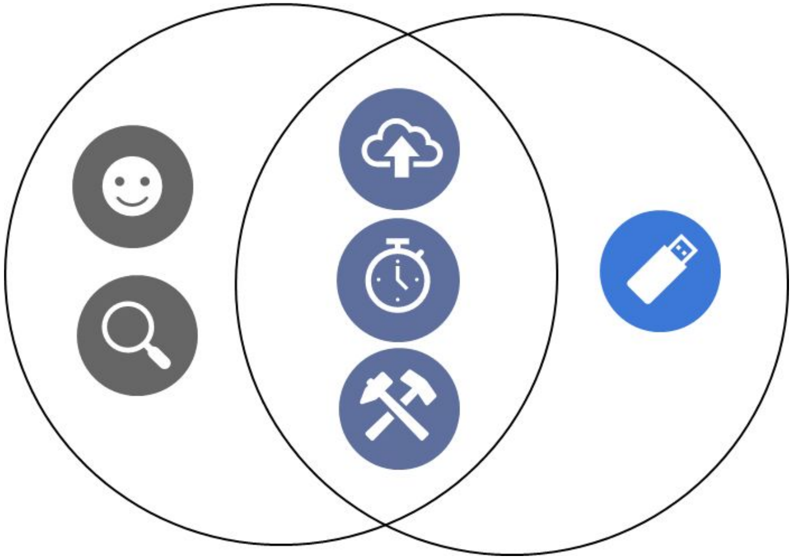
User Needs and Specifications

Software Needs

User Interface:

- Intuitive for high stress situations
- Searchable



Database:

- Small storage requirements

Both:

- Easy uploads
- Faster printing
- Includes characterization

Software Specifications

Specification 1: Storage space required for image, model, files

Specification 2: Average time for untrained user to find information

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Software Specifications

Specification 1: Storage space required for image, model, files

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Software Specifications

Specification 1: Storage space required for image, model, files

< 50 MB/part

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> 4 out of 5

Improved Database

Overview

PostgreSQL

Visual Studio

Open-source, commonly used back-end

Simple, intuitive, front-end user interface

ISM DATABASE

Overview

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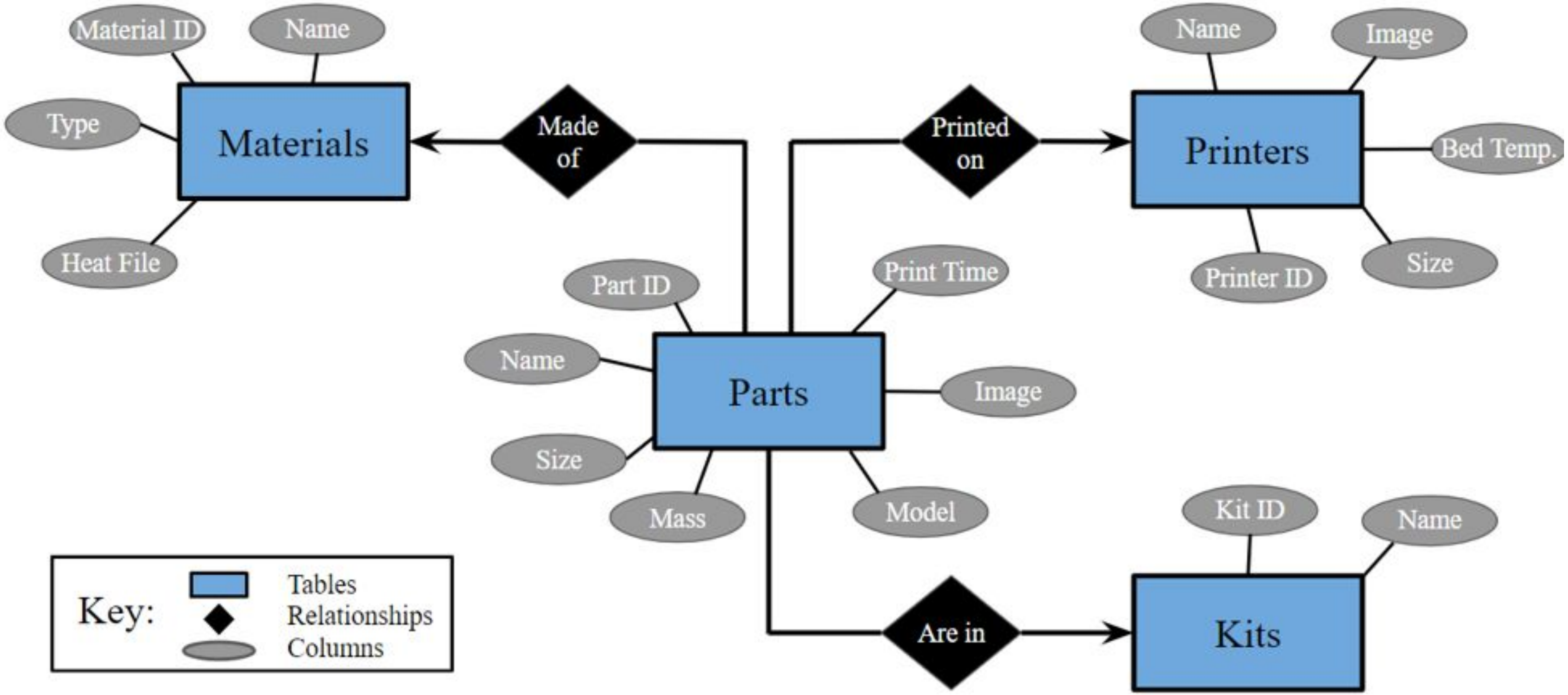
Back-end Structure



Customer Needs

Characterization included in Materials table and easily accessed

SQL structure prevents duplication and saves on file space

More organized than original Excel version; will allow quicker data retrieval

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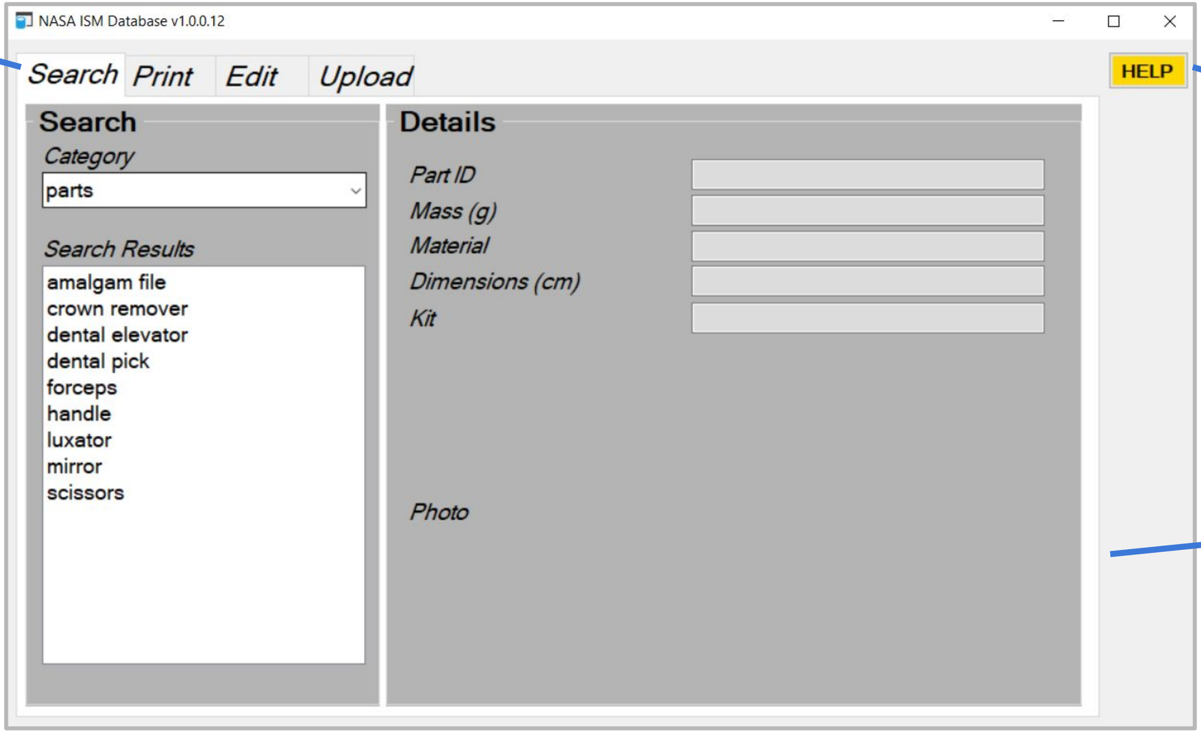
Front-End Interface

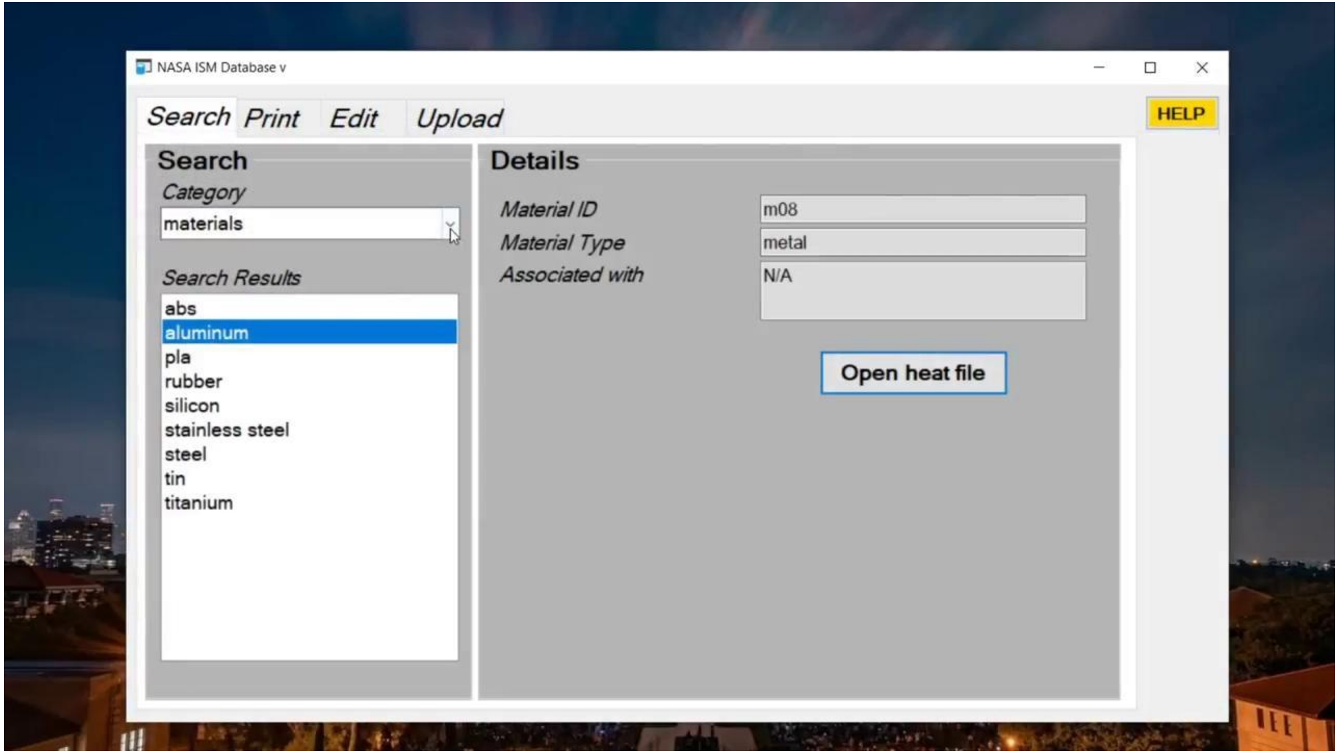
Multiple easy to use functions



Specific help for each function

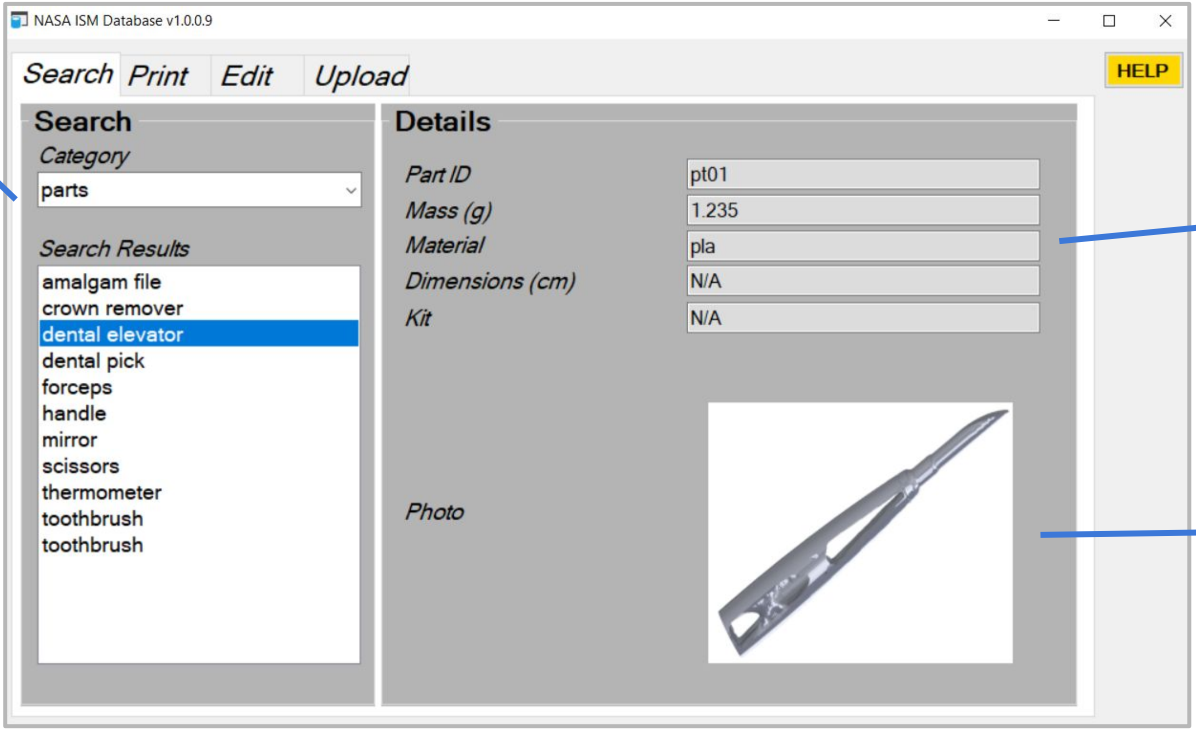
Frames help organize the views

Search Function



Search Function

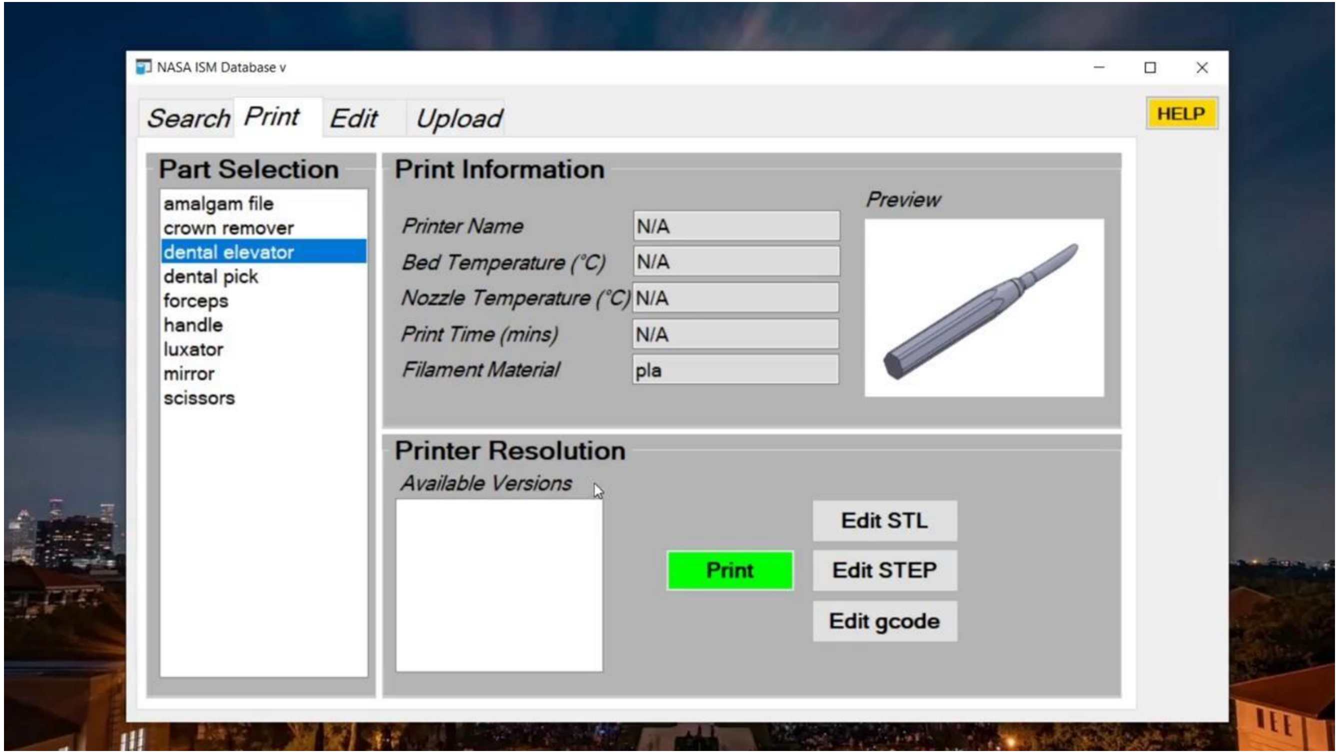
Search feature does not require knowledge ahead of time



Organized data display

Photo helps confirm selection

Print Function



Print Function

Easy alphabetical list

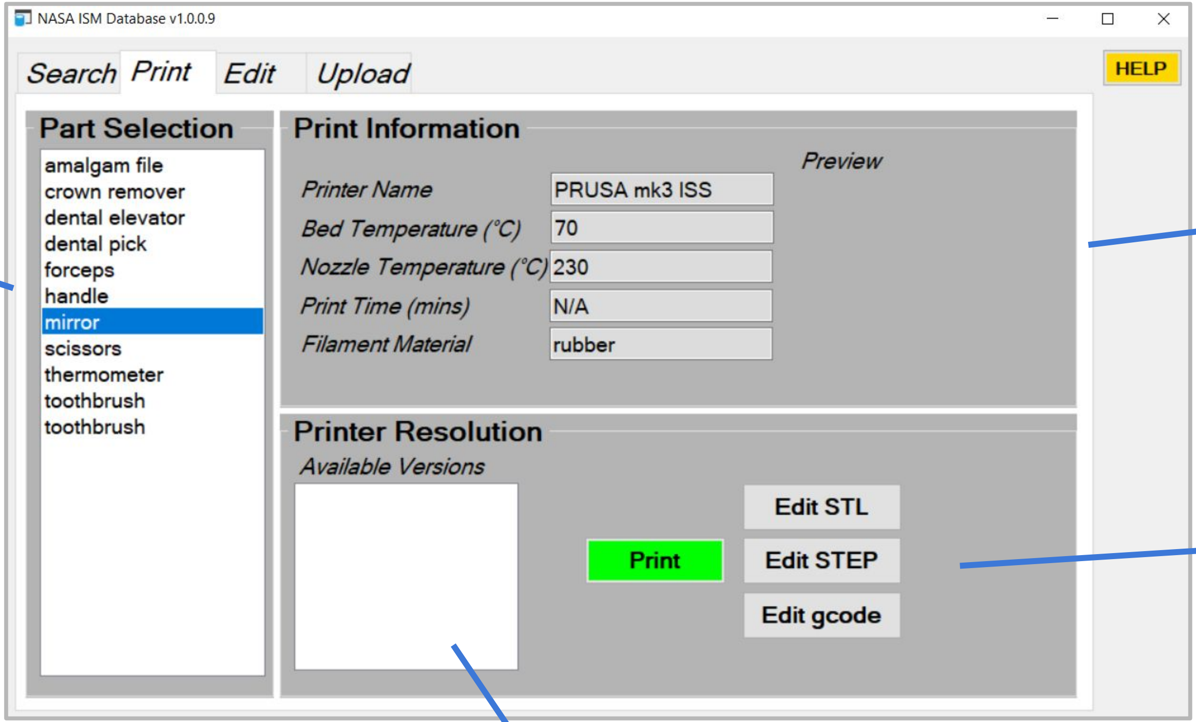
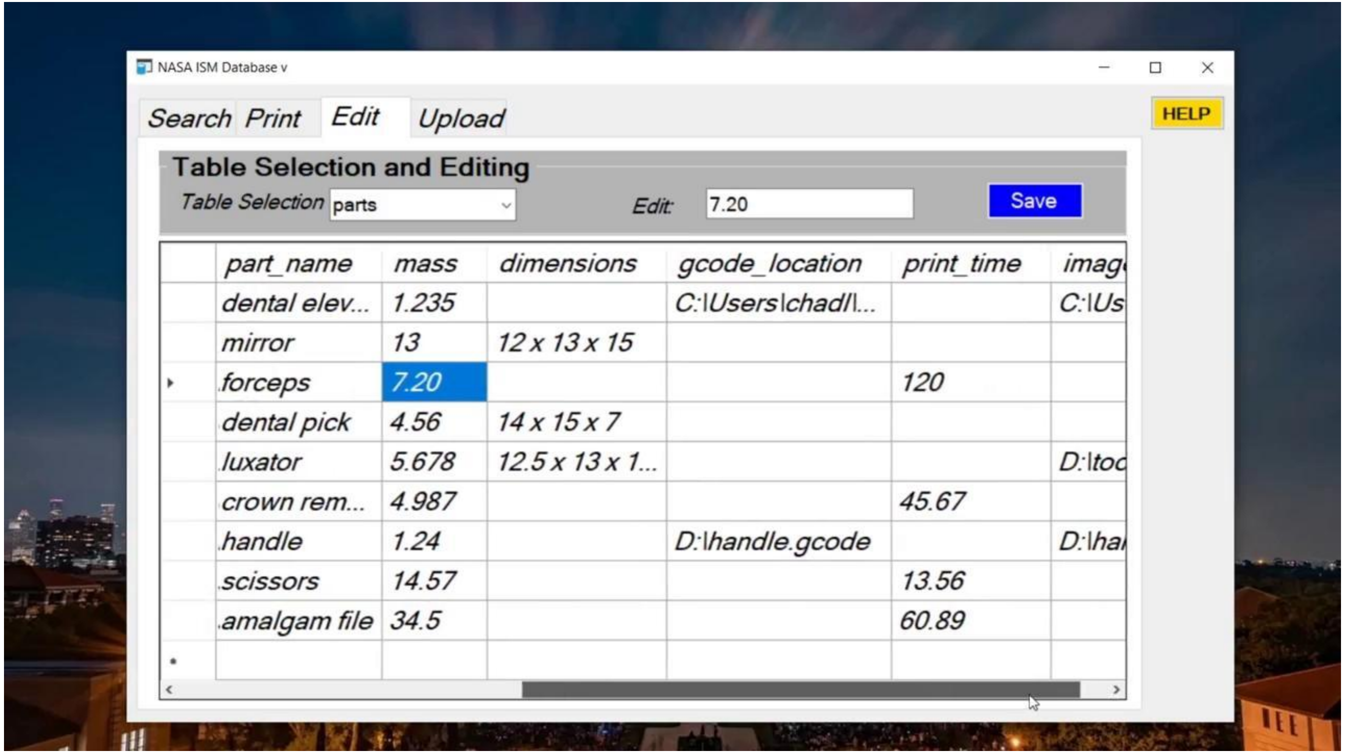


Photo preview of print

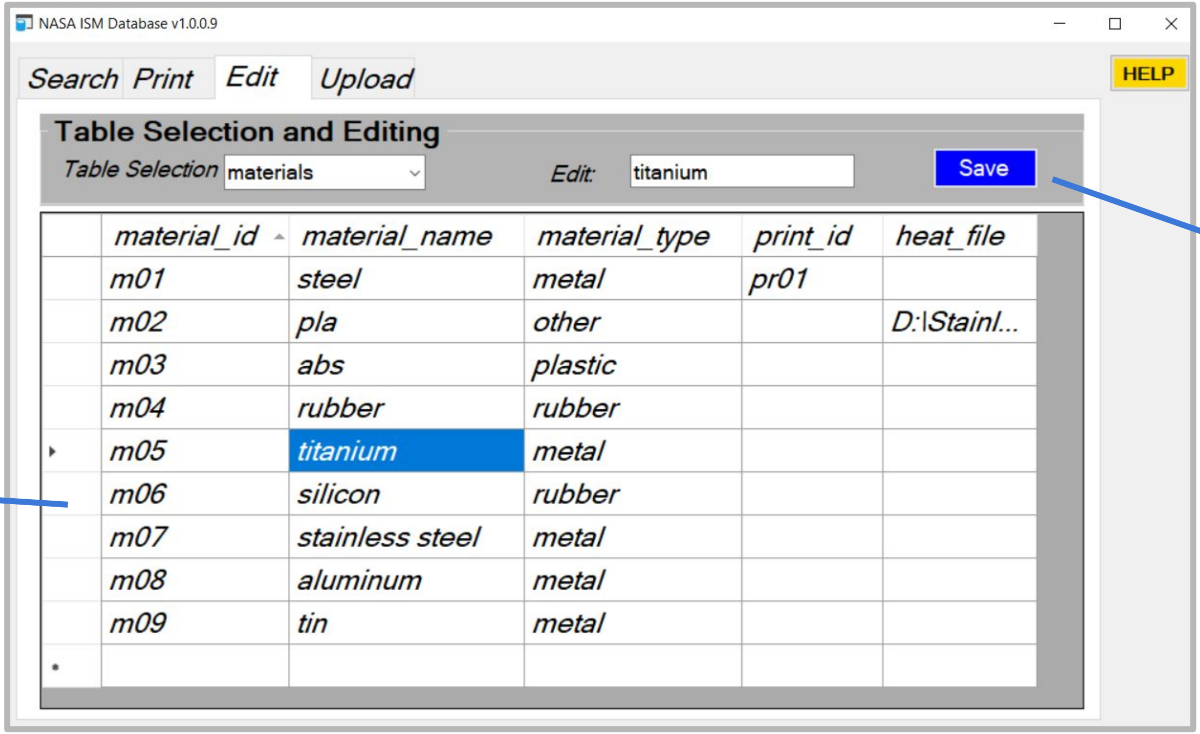
Access different 3D model files

Different versions

Edit Function



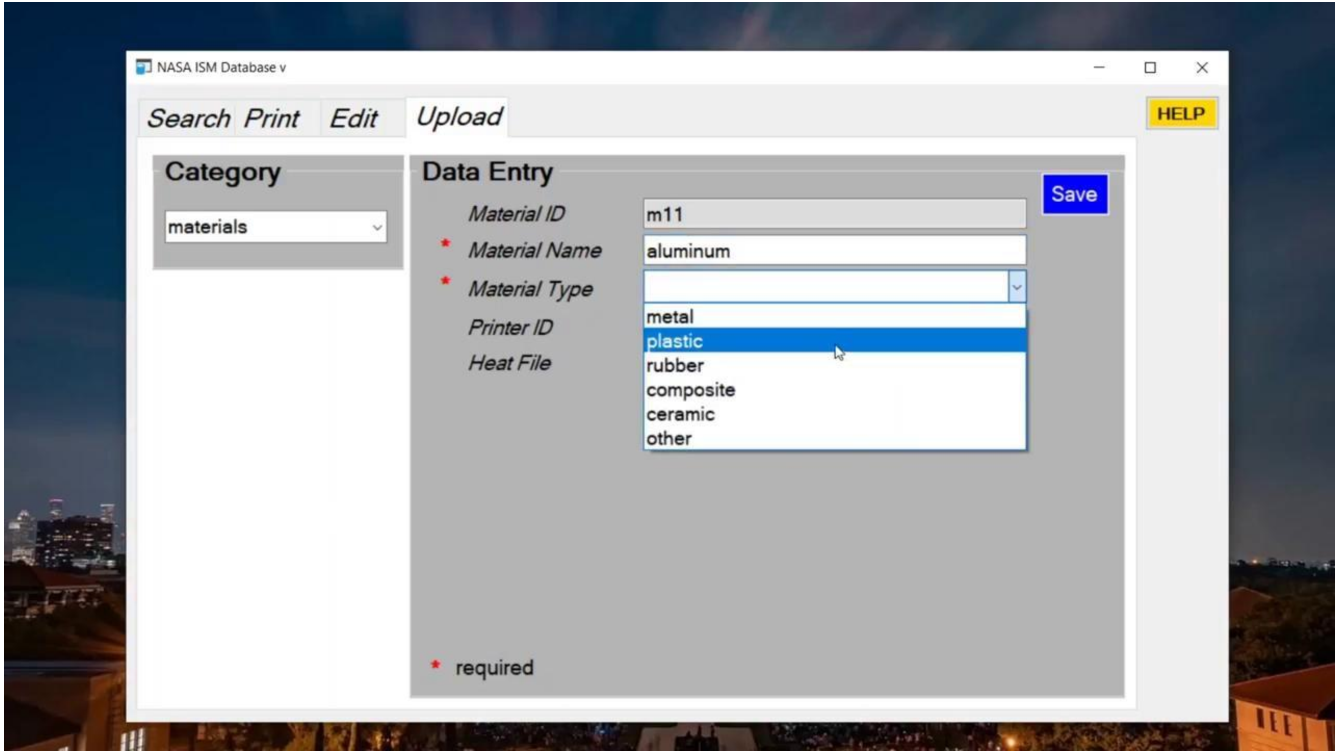
Edit Function



Clear editing feature

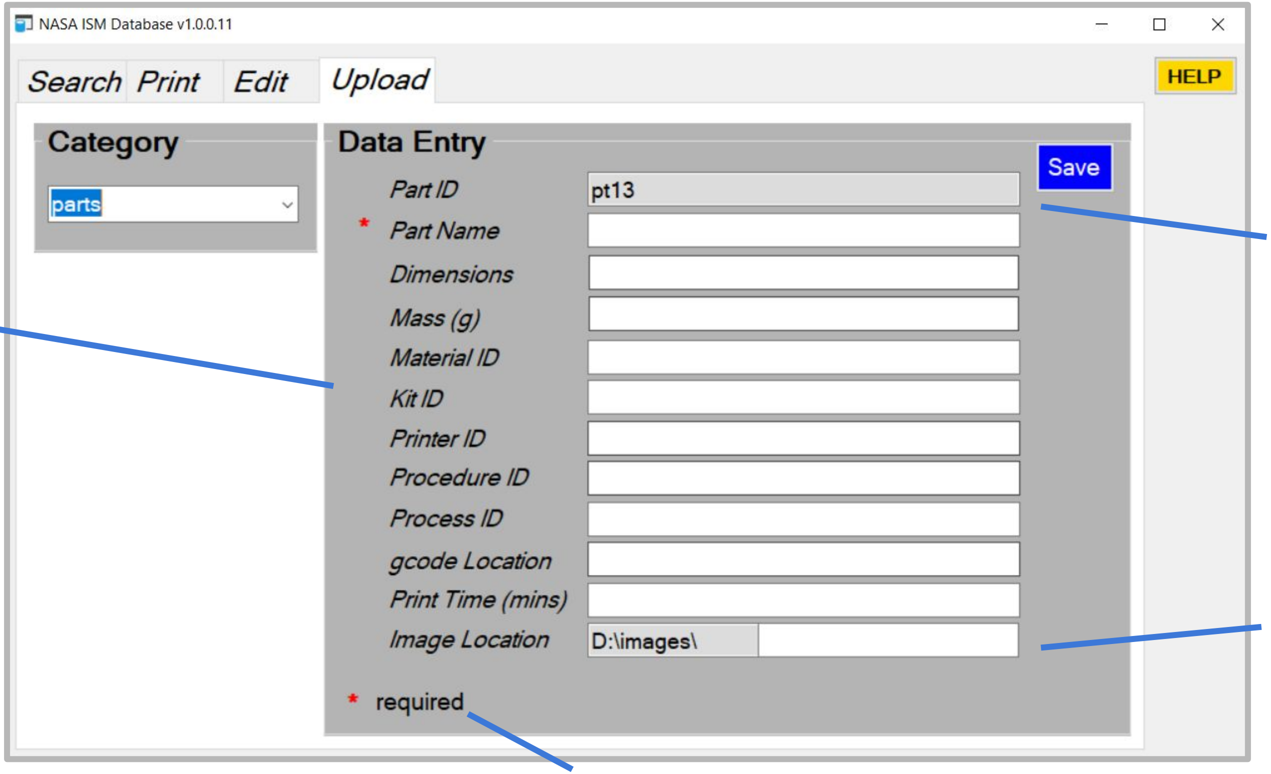
Easy to view table for editing

Upload Function



Upload Function

Specific categories based on type of upload



Unique identity assigned to entry

Autofilled file locations to simplify

Signals required data

Overview

PostgreSQL

Open-source, commonly used back-end

Visual Studio

Simple, intuitive, front-end user interface

ISM DATABASE

Documentation

The NASA ISM Database v.1.0.12

Welcome to the NASA ISM Database v.1.0.12! This open-source and intuitive software package enables 3D printing on deep space missions. It consists of a graphical user interface (GUI) and structured query language (SQL) database, both of which this documentation will aid you in using. Click on a link below to get started:

Customer Needs

- Simple upload tab with personalized help
- Quicker navigation through organized data
- Colors, frames, and instructions aid users
- Search-by-menu requires no foreknowledge

Testing Results

Software Specifications

Specification 1: Storage space required for image, model, files

< 50 MB/part

Specification 2: Average time for untrained user to find information

< 60 seconds

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< 120 seconds

Specification 4: Survey on appearance, organization, simplicity

4 out of 5

Software Specifications

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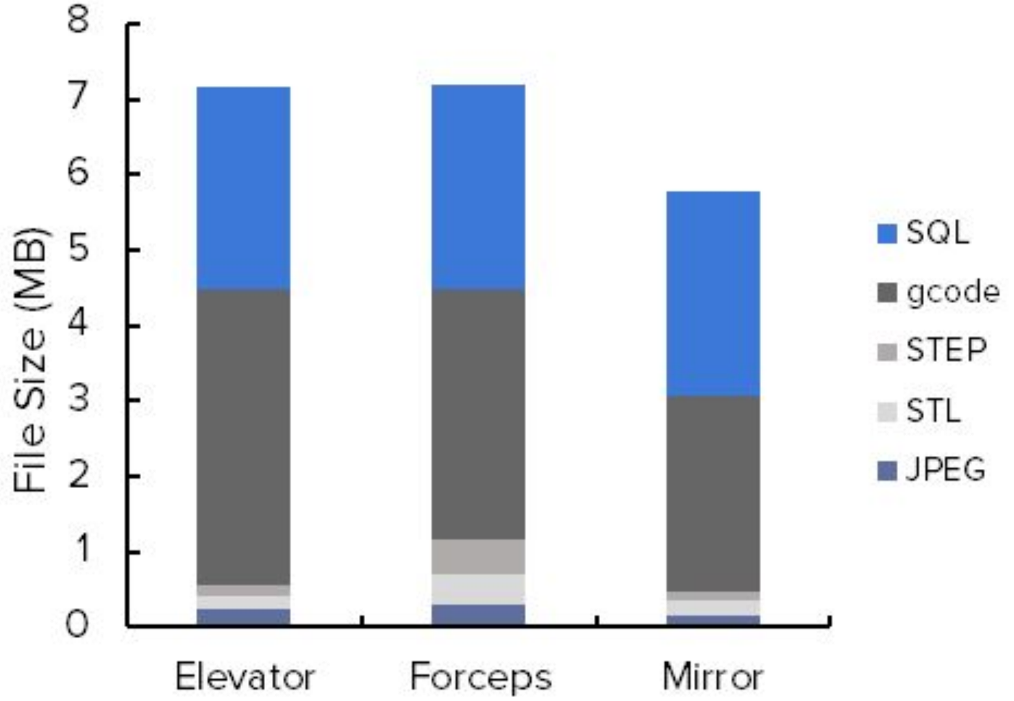
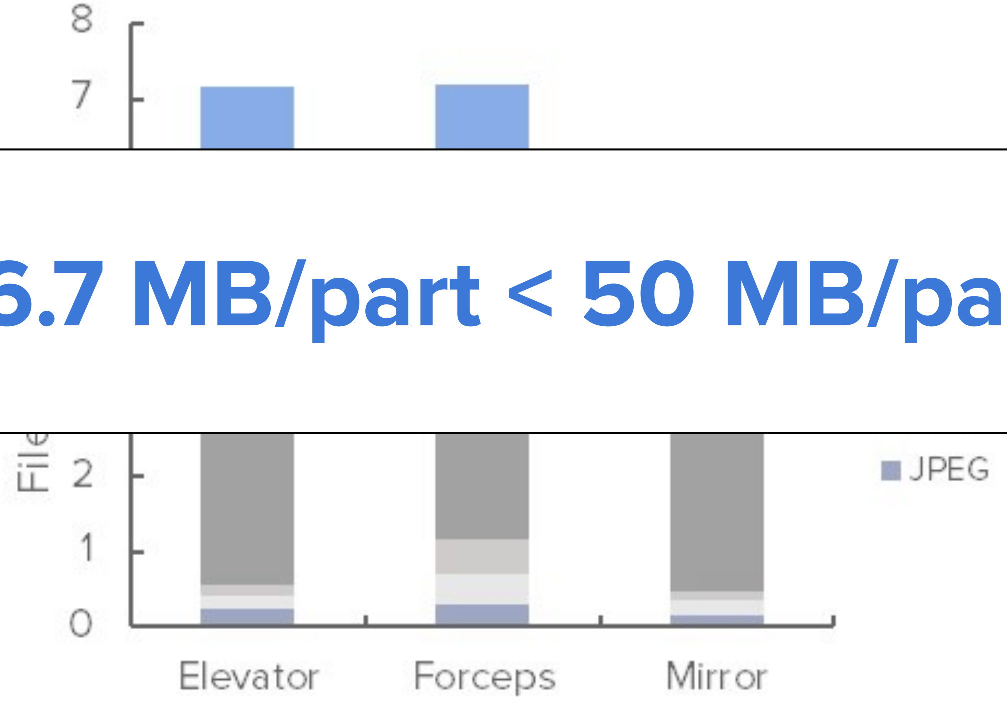
Storage Space Testing

Contribution	Method
Image	.jpg or .png size
3D Model	.STL, .gcode, and .STEP size
Text/Infrastructure	Full size of file through pgAdmin4 divided by 3 parts

Storage Space Testing



Storage Space Testing



6.7 MB/part < 50 MB/part

Software Specifications

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4 out of 5

User Testing

Subject Selection

n=40 semi-randomly chosen engineering student volunteers from the OEDK

Search & Upload Time Testing

Subjects are randomly assigned to tasks in groups of 5

Usability Survey

Subjects will be asked to rank their agreement with statements on organization, simplicity, design, and ease of use with the GUI

User Testing

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Subject Selection

- n=40
  - Trade-off between recruiting capabilities and statistical robustness
- Engineering students
  - Possibly representative of end users
- Untrained
  - No previous knowledge of program

User Testing

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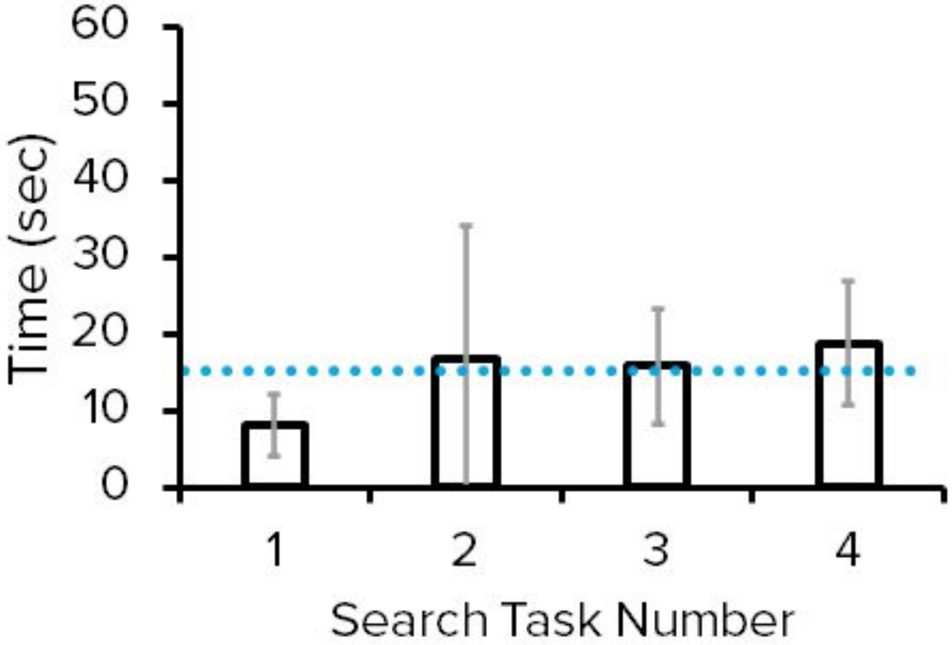
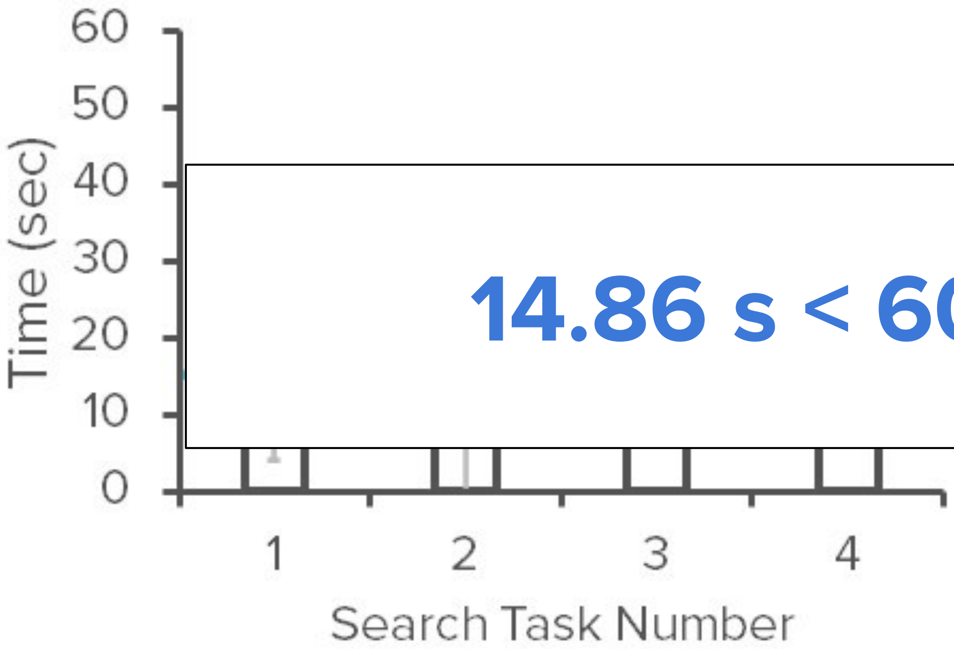
Search Results



Tasks

1. Mass of elevator
2. Mass of forceps
3. Material mirror is made of
4. Material ID of chromium

Search Results



14.86 s < 60 s

Tasks

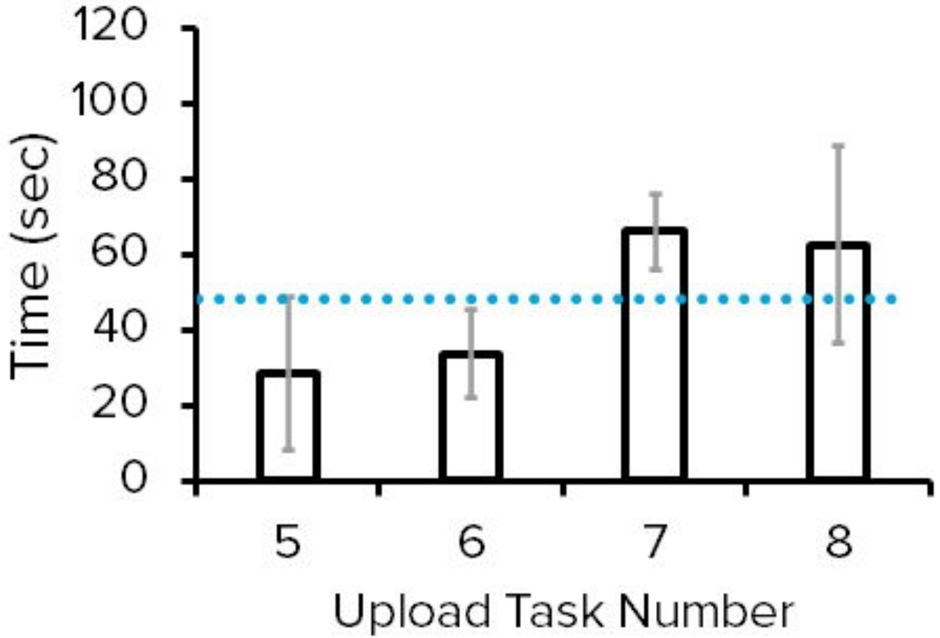
1. Mass of elevator

rceps

irror is

of

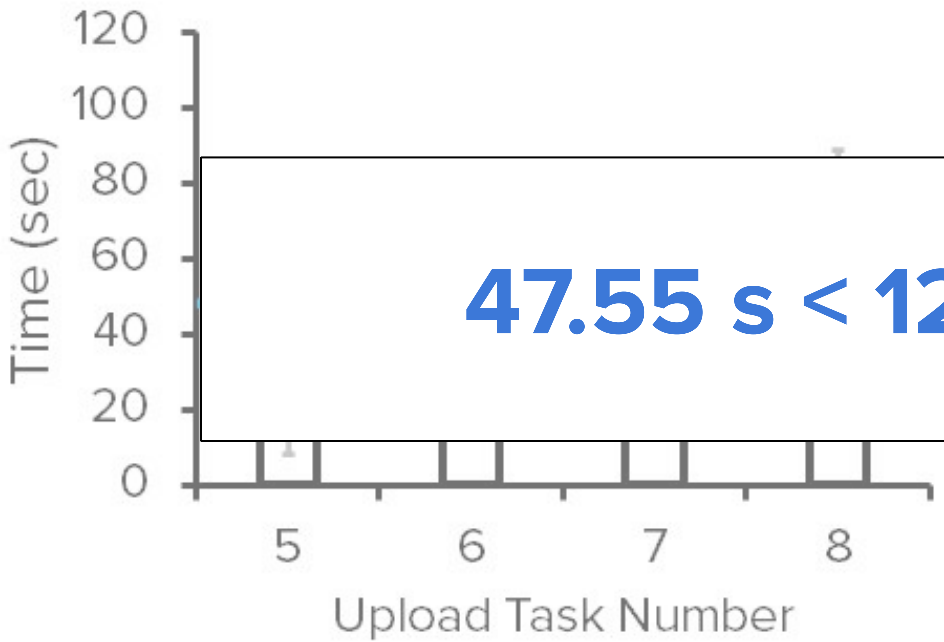
Upload Results



Tasks

5. New part named 'thermometer'
6. New part named 'luxator'
7. New material with type and heat file
8. New material with type and printer

Upload Results



47.55 s < 120 s

Tasks

5. New part named
r'
named
rial with
t file
8. New material with type and printer

User Testing

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n=40 semi-randomly chosen engineering student volunteers from the OEDK

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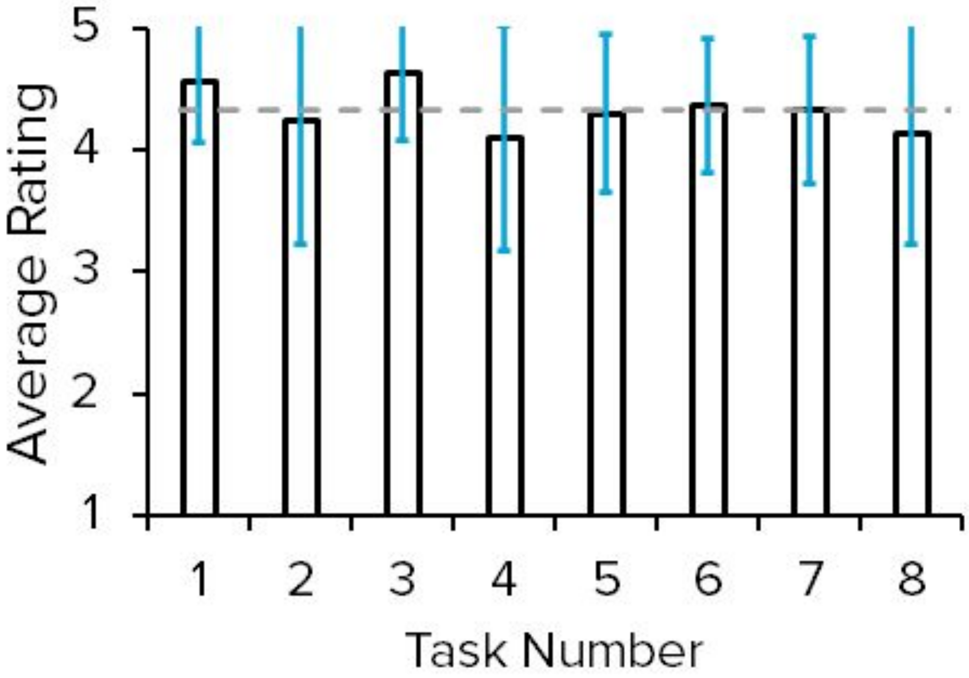
Usability Survey

Subjects will be asked to rank their agreement with statements on organization, simplicity, design, and ease of use with the GUI

Survey Questions

1. Appropriate color scheme
2. Appropriate font size
3. Clear and logical organization
4. Frames, labels, and instructions
5. No duplicated information
6. Easy to use

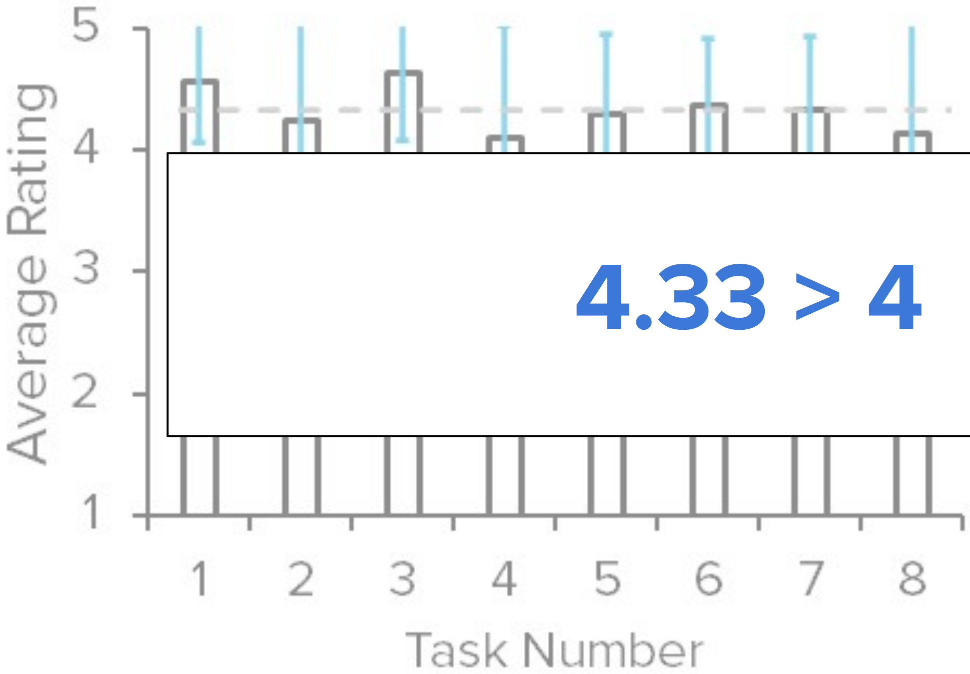
Survey Results by Task



Takeaways

- No significant difference between task with ANOVA
- Average score of 4.33 ± 0.75

Survey Results by Task



4.33 > 4

Takeaways

- No significant
ce
n task
OVA
e score of
.75

Software Specifications

Specification 1: Storage space required for image, model, files **6.7** < 50 MB/part	Specification 2: Average time for untrained user to find information **14.86** < 60 seconds
Specification 3: Average time for untrained user to create entry **47.55** < 120 seconds	Specification 4: Survey on appearance, organization, simplicity **4.33/5**

Next Steps

Planned Work

Connecting to a 3D printer

Testing the other functions of our GUI

Software Package

Planned Work

Connecting to a 3D printer

- What software used to print?
- USB? Network connection?

Testing the other functions of our GUI

Software Package

Planned Work

Connecting to a 3D printer

Testing the other functions of our GUI

- Student surveys?
- Remote testing?
- With NASA?

Software Package

Planned Work

Connecting to a 3D printer

Testing the other functions of our GUI

Software Package

- Check compatibility on different machines
- Where are programs downloaded from?

Planned Work

Connecting to a 3D printer

- What software used to print?
- USB? Network connection?

Testing the other functions of our GUI

- Student surveys?
- Remote testing?
- With NASA?

Software Package

- Check compatibility on different machines
- Are all necessary programs downloaded?

Possible Additions

Multiple versions of tool

Keyword searching

Video/GIF visualization of part

Drag-and-drop upload

Possible Additions

Multiple versions of tool

- Slider for in-fill?
- Preset print resolution?

Keyword searching

Video/GIF visualization of part

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Possible Additions

Multiple versions of tool

Keyword searching

- By first letters or by whole term?

Video/GIF visualization of part

Drag-and-drop upload

Possible Additions

Multiple versions of tool

Keyword searching

Video/GIF visualization of part

- In another program? (3D viewer, media player)
- Inside the GUI?

Drag-and-drop upload

Possible Additions

Multiple versions of tool

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Video/GIF visualization of part

Drag-and-drop upload

- Better intuition?

Possible Additions

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Keyword searching

- By first letters or by whole term?

Video/GIF visualization of part

- In another program? (3D viewer, media player)
- Inside the GUI?

Drag-and-drop upload

- Better intuition?

Commercialization

Before our software can be sold or implemented, we need to tackle:

Server/Online Hosting
Allow multiple users to access/edit at once

Security Permissions
Who can edit, delete, view, share?

Troubleshooting
How are errors reported?

Conclusion

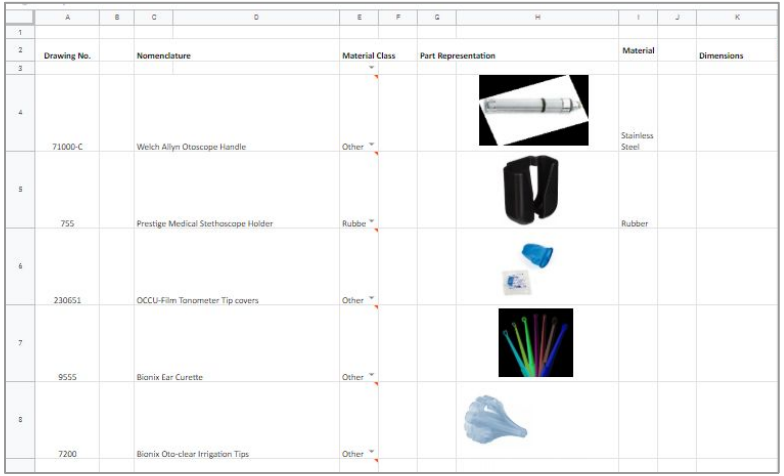
Our Process

1. **Initial Print**
   - Ensure it can be 3D printed
2. **Usability survey**
   - Subjects perform mock procedure
   - Rank statements about comfort, functionality, and ease of use
3. **Topology Optimization**
   - Optimize material layout while maintaining exterior geometry
4. **Final Redesign**
   - Combine results into final product

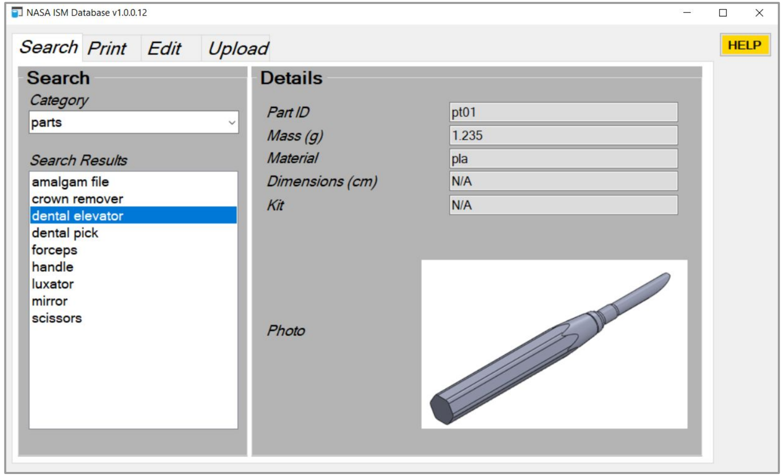
Our Process

- Reduces material
- Quickens printing
- Considers exterior and interior

Improved Database



- **Limited** functionality from Excel
- **Disorganized** & **overwhelming** data display
- **Unintuitive** design
- **No parts ready for 3DP**



- **Untrained** users able to perform **searches** and **uploads** in **< 1 min**
- **Specific** and **personalizable** help features
- All tools have been **optimized** for 3DP

RICE ENGINEERING
Bioengineering

RICE ENGINEERING
Mechanical Engineering

We would like to thank our mentors and advisors from:

Rice University Department of Bioengineering
Rice University Department of Mechanical Engineering
The Oshman Engineering Design Kitchen
Baylor College of Medicine
National Aeronautics and Space Administration

Oshman Engineering Design Kitchen

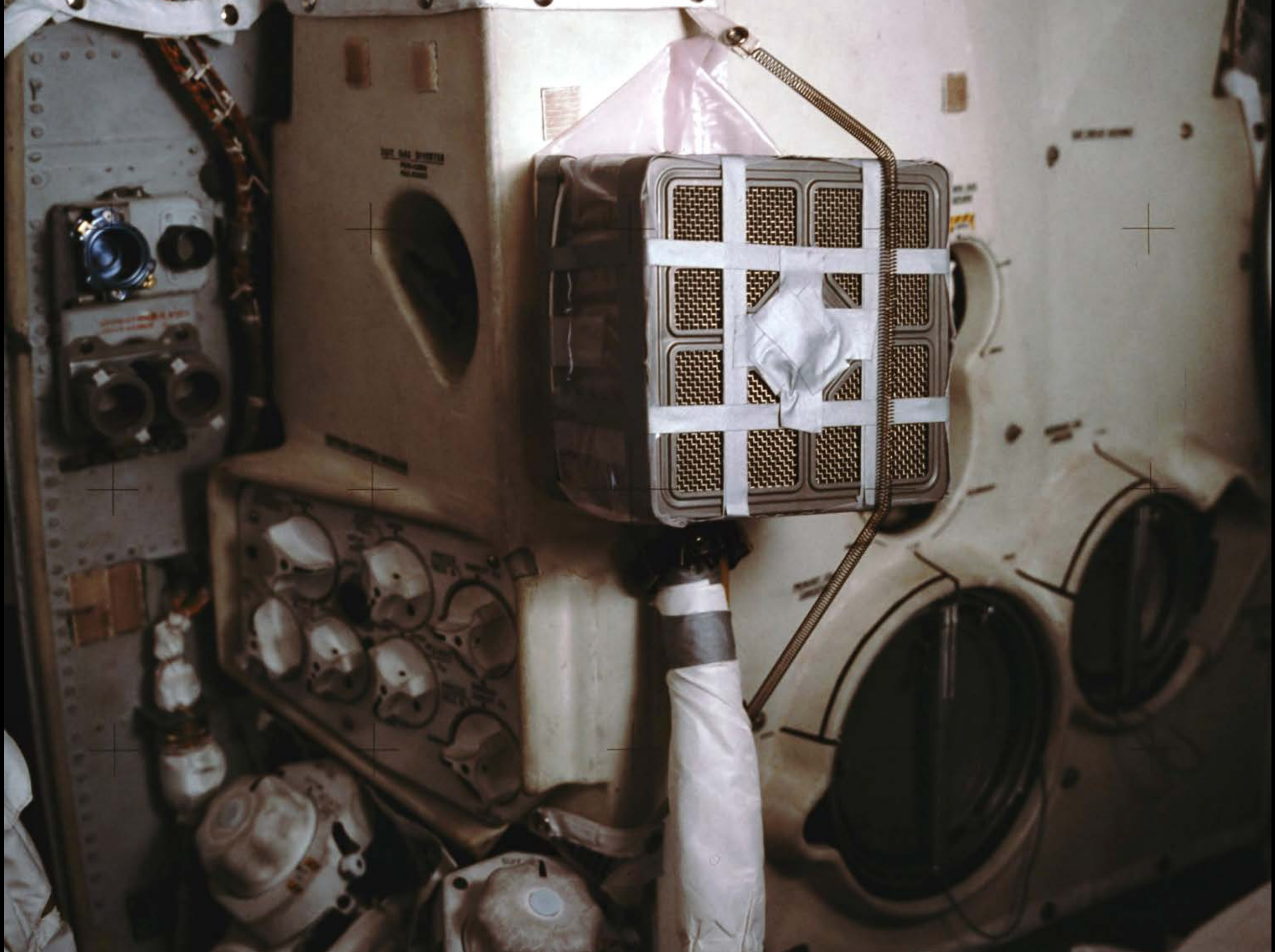
NASA

Baylor College of Medicine

NASA

RICE
ENGINEERING

SPACE STUFF

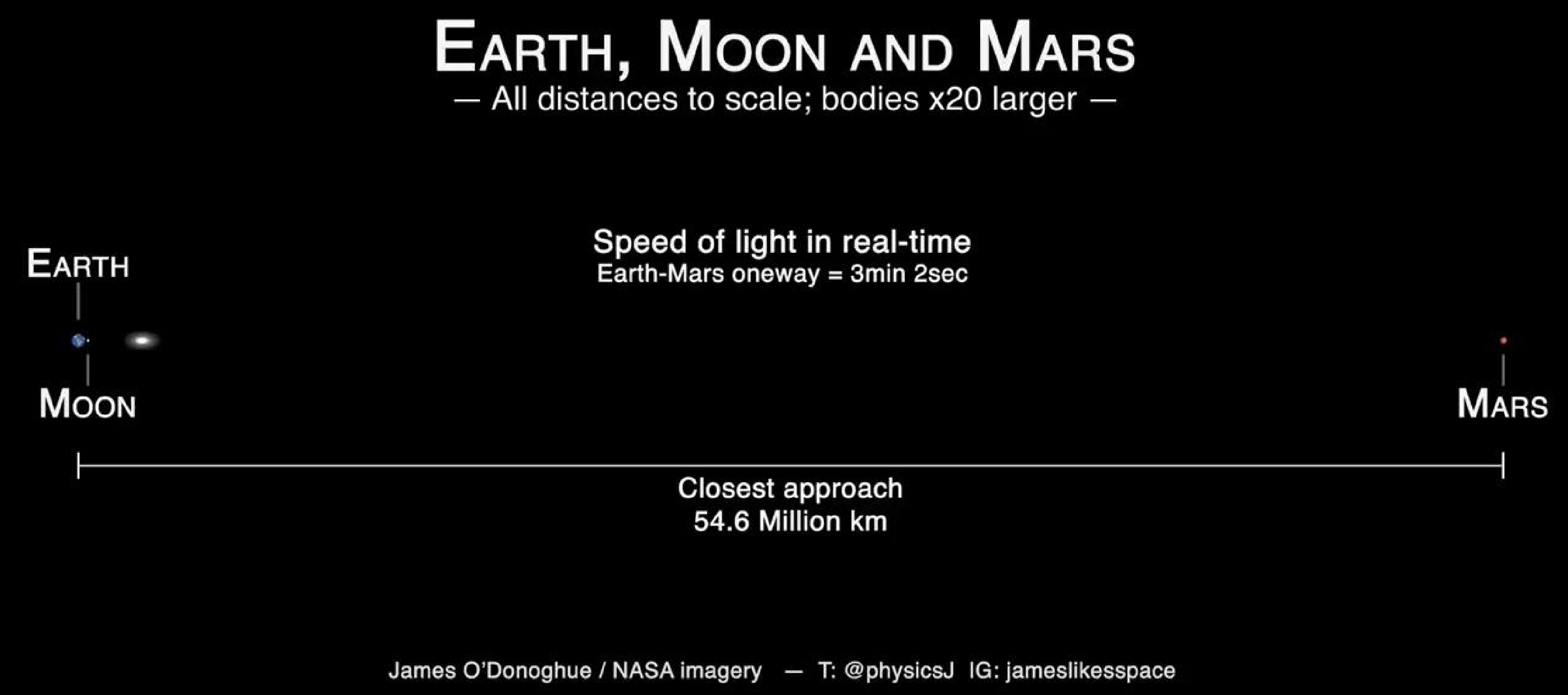


In-Space Manufacturing Final Design Review

Rice University

Team Live Long & Printer

Tori Joshi, Oliver Lopez, Colin Nyhus, & Paraksh Vankawala


Earth, Moon and Mars
— All distances to scale; bodies x20 larger —
Speed of light in real-time
Earth-Mars oneway = 3min 2sec
Earth
Moon
Mars
Closest approach
54.6 Million km
James O'Donoghue / NASA imagery — T: @physicsJ IG: jameslikesspace

Agenda

1. Motivation
2. User Needs
3. Final Specifications: Part Redesign
4. Final Specifications: Database Design
5. Future Work
6. Conclusion

Project Goals

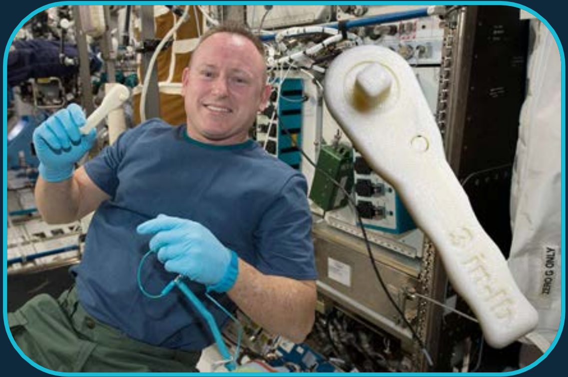
Project Goals

◇Optimizing STL files for in -space manufacturing

- Redesigning tools from current ISS catalogue
- Limited material filament must last entire mission
- Reducing use of unnecessary material

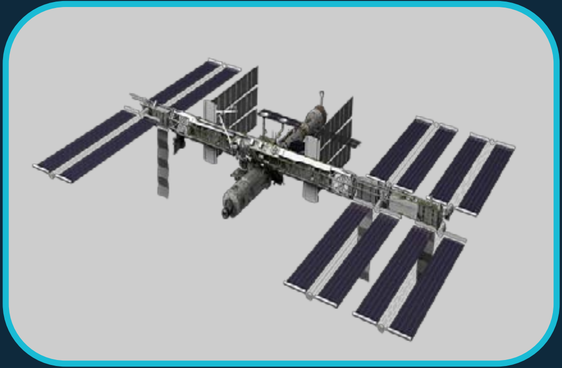
◇Creating database to store redesigned STL files

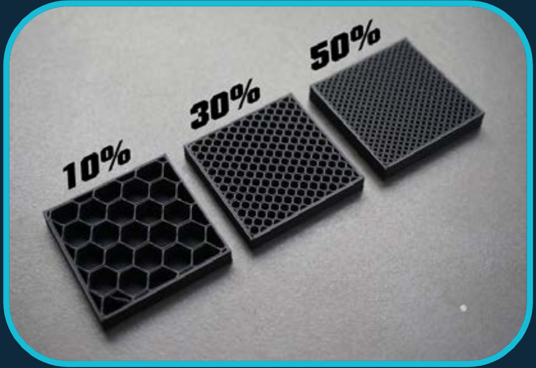
- Accessible Information
- Minimal training required
- Easy to Use



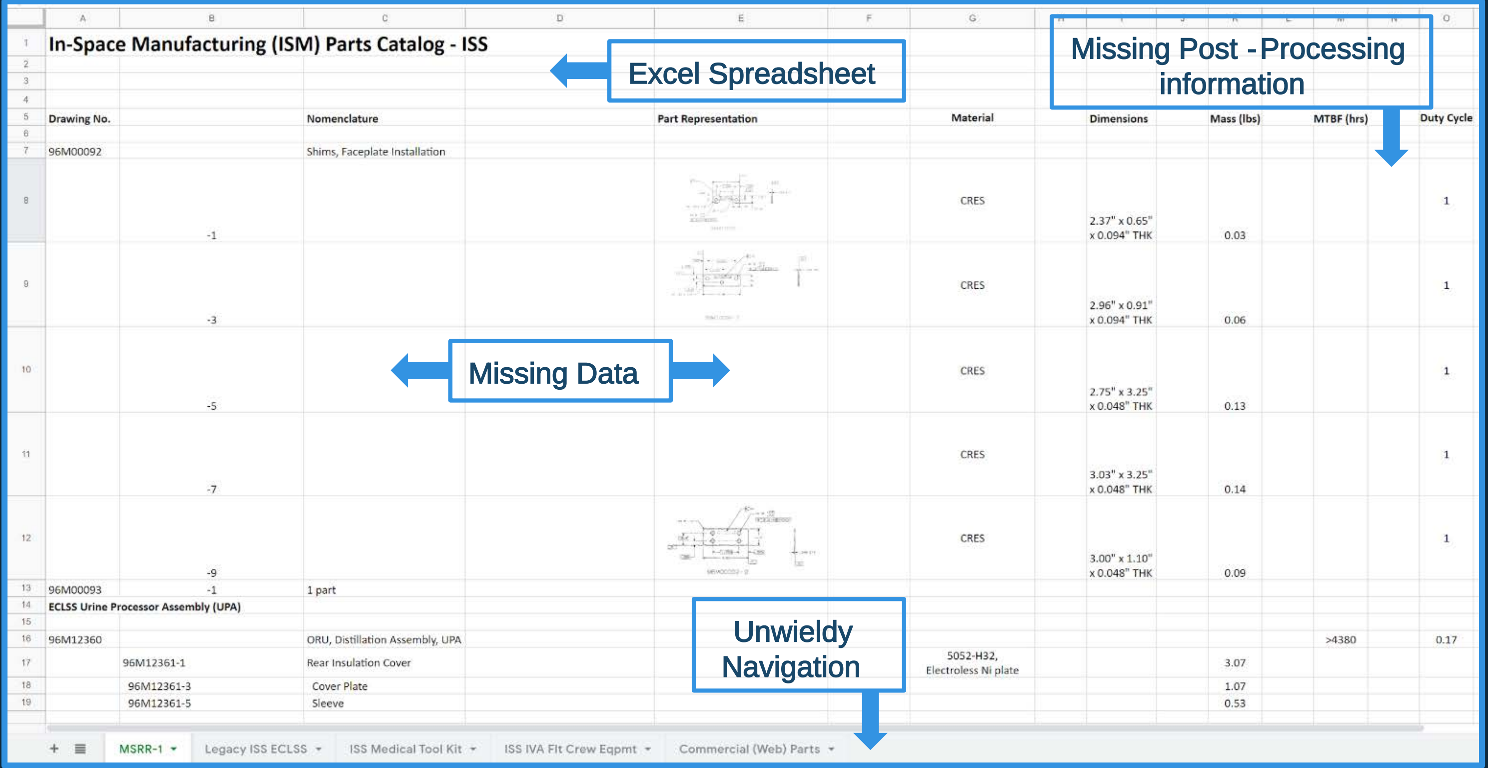
Current STL Designs

- Designed to withstand 3g launch forces
- Not optimized for microgravity
- Extraneous material use





Current Database



In-Space Manufacturing (ISM) Parts Catalog - ISS

Row	Drawing No.	B	Nomenclature	Part Representation	Material	Dimensions	Mass (lbs)	MTBF (hrs)	Duty Cycle
7	96M00092		Shims, Faceplate Installation						
8		-1			CRES	2.37" x 0.65" x 0.094" THK	0.03		1
9		-3			CRES	2.96" x 0.91" x 0.094" THK	0.06		1
10		-5			CRES	2.75" x 3.25" x 0.048" THK	0.13		1
11		-7			CRES	3.03" x 3.25" x 0.048" THK	0.14		1
12		-9			CRES	3.00" x 1.10" x 0.048" THK	0.09		1
13	96M00093	-1	1 part						
14	ECLSS Urine Processor Assembly (UPA)								
16	96M12360		ORU, Distillation Assembly, UPA					>4380	0.17
17		96M12361-1	Rear Insulation Cover		5052-H32, Electroless Ni plate		3.07		
18		96M12361-3	Cover Plate				1.07		
19		96M12361-5	Sleeve				0.53		

MSRR-1 | Legacy ISS ECLSS | ISS Medical Tool Kit | ISS IVA Flt Crew Eqpmt | Commercial (Web) Parts

LL&P Testing Plan

Cycle 3.0

Colin Nyhus, Oliver Lopez, Tori Joshi, and Paraksh Vankawala

Components

Customer Need	Objective	Scope	Equipment	Steps	Acceptance Criteria	Statistical Techniques
(13) Redesigned part can withstand expected use loads	Redesigned part showcases that it completes same function as original part without failing	The strength of the redesigned/optimized part	Vice grip, weights, rope, bucket	For the wrench provided by NASA: (1) Contain vice grip within safety shielding. (2) Secure bolt test-block in vice grip. (3) Fasten one end of a rope to the circular end of the wrench and the other end to a bucket. (4) Place bucket on a removable stand and (5) place crescent end of wrench over bolt. (6) Add desired weight to bucket and (7) slowly and carefully remove the stand so that the bucket is hanging freely from the wrench. (8) Continue process of adding and/or removing weight to achieve deformation and/or fracture of wrench. (9) Record weight in bucket at point of deformation and/or fracture including the weight of the bucket alone. (10) Using	Redesigned part fractures at or near the same moment value as the original part	Analyze using Weibull distribution
(14) Redesign for different material types	Provide manufacturing processes for at least 2 materials for at least one part	The needed steps for 2 indicated materials	None	For at least one component in the database, (1) ensure all post-processing instructions for (2) two or more material types are known and recorded.	For 2 or more material types, one or more of the components must describe all steps taken from the removal of the component from the print bed to the completion of the component.	N/A
(15) Redesign to optimize for weight of part	At least one redesigned part achieves a 25% weight reduction	Difference in mass between original part and redesigned/optimized part	Scale	(1) Weigh original part using a scale. (2) Weigh redesigned/optimized part using a scale. (3) Calculate ratio of the weight of the optimized part to the original part.	One or more of the redesigned/optimized parts weighs 25% less than its original counterpart	Uncertainty analysis of mass balance
(16) Redesign provides needed processes needed to complete part fabrication after printing.	Provide all applicable post-processing instructions for all designed tools	Post-processing instructions for part	None	For each version of each component in the database, (1) ensure all post-processing instructions for (2) all relevant material types are known and recorded.	Process describing steps taken from the removal of the part from the print bed to the part being fully ready for usage is known and recorded for all components.	N/A
(17) Consider filament cost for different materials	Cost of filament to print redesigned part equals 95% or less than that of original part	Cost of filament types in question	None	(1) Compare cost of the amount of PLA/ABS filament used to print optimized part to the cost of the amount of PLA/ABS filament used to print original part.	Cost of the amount of PLA/ABS filament used to print optimized part is equal to 95% or less of the cost of the amount of PLA/ABS filament use to print the original part.	Cost analysis for various filaments over time
(18) Design must comply with relevant NASA standards for structures/mechanics	Redesigned parts meet 100% of the relevant team standards	Compliance of optimized parts with standards and regulations	None	(1) Review compiled standards and regulations, and (2) ensure all elements of optimized/redesigned components are in line.	All standards and regulations obeyed	N/A

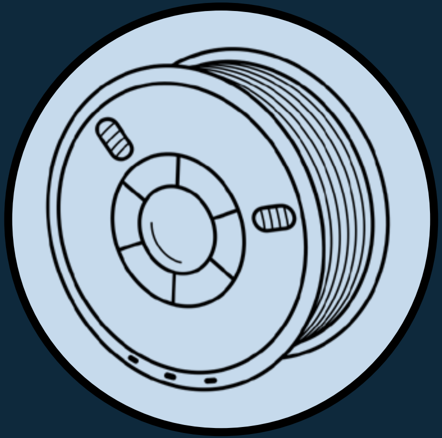
Database

Customer Need	Objective	Scope	Equipment	Steps	Acceptance Criteria	Statistical Techniques
(1) Database has user-friendly GUI	At least 85% of surveyed users are able to locate desired part in 15 seconds or less	Percentage of users able to locate indicated part in a limited amount of time	PC capable of running Access, test subjects	(1) Gather approximately 20 individuals for survey, (2) present them with prepared document containing part information, and (3) ask them to use the database starting from the homepage to navigate to that part. (4) Time how long it takes.	Greater than or equal to 85% of subjects are able to locate indicated part in 15 seconds or less	Standard statistical analysis
(2) Database package contains manufacturing process.	At least 85% of tested users can obtain a completed print using the database	Percentage of users able to navigate from database home to indicated part to initiate print process	PC capable of running Access, test subjects	(1) Gather approximately 20 individuals for survey, (2) present them with prepared document containing part information, and (3) ask them to use the database starting from the homepage to navigate to that part and open it in a slicer software.	Greater than or equal to 85% of subjects are able to initiate the print of a part and send gcode to a printer. Successful communication between the database and printer is all that is necessary, no parts need be printed.	Standard statistical analysis, binary success.
(3) Database is categorized by types of information	Database contains a single table for a single type of information. (No repeated information in multiple tables of the database)	Database maintains relational integrity	PC capable of running Access	(1) Examine database to ensure no tables are redundant and (2) no information applying to multiple components appears more than once throughout the database.	No tables are redundant and no information characteristic of one or more components is duplicated	N/A
(4) Database is categorized by component usage area.	Database contains a table listing at least 2 tool usage areas (tool kits)	Usage area for an indicated part	PC capable of running Access	(1) Check database back-end to ensure a toolkit table exists and (2) that it has at least two items.	A toolkit/usage area table exists and has 2 or more items	N/A
(5) Database contains search/find function for any category of information	There exists at least 1 designed query for each table in the database	All categories/tables of information searchable via 1 or more queries	PC capable of running Access	(1) Manually match each table to its one or more queries to ensure each table has at least one.	Each table has at least one query	N/A
(6) Database storage is minimized	Average package size is equal to or less than 150% of 3MB specification	Digital storage size of database	PC capable of running Access	(1) Monitor size of final database package folder.	The division of the total database size by the total number of components must be less than or equal to 4.5mb	N/A
(7) User must be able to print directly from the database.	Database provides hyperlink to software used to initiate print	Ease of initiating a print directly from database	PC capable of running Access and Slicer	For each part in the database, (1) navigate to part and (2) open it in a slicer software.	Each component can be opened in a slicer software via the database	N/A
(8) User has access to part shapefiles and appropriate modeling software should they need to redesign in space	Every tool in the database contains link to CAD software. When link is clicked, it displays desired part.	Ease of opening shapefile in CAD program from database	PC capable of running Access and CAD software	For each part in the database, (1) navigate to part and (2) open it in a CAD software.	Each component can be opened in a CAD software via the database	N/A
(9) Database allows for data entry and new package creation	At least 85% of users can access the ID table and insert a line of tool information using the design view of the database	Percentage of users able to add new component into database	PC capable of running Access, test subjects	(1) Gather approximately 20 individuals for survey, (2) present them with prepared document containing needed part information, and (3) ask them to use the database starting from the homepage to enter a new part and all of its information into the system.	Greater than or equal to 85% of subjects are able to fully enter the part information correctly into the database	Standard statistical analysis, binary success.
(10) Photograph or graphic representation of component	At least 85% of tested users can name part based on its photo alone	Percentage of users able to identify component by its visual representation	PC capable of running Access, test subjects	(1) Gather approximately 20 individuals for survey, (2) present them with prepared document of component photographs, and (3) ask them to identify and record what they think the parts are based on the photograph alone.	Greater than or equal to 85% of subjects are able to name part based on photograph alone	Standard statistical analysis
(11) The cost of software used for the database compared to existing commercial programs is reasonable	Cost of softwares used to operate database is equivalent to or cheaper than existing software packages	Cost of Microsoft Access	None	(1) Compare commercial package costs to individual license costs.	Software cost is on or below average of alternative solutions	Cost analysis for various softwares over time
(12) Database software must comply with relevant material in the NASA software engineering handbook.	Database meets 100% of relevant team standards	Compliance of database with standards and regulations	None	(1) Review compiled standards and regulations, and (2) ensure all elements of database are in line.	All standards and regulations obeyed	N/A

Part Redesign

Customer Needs: STL Files

Limit Part Size
for Printability



Reduce Filament
Use

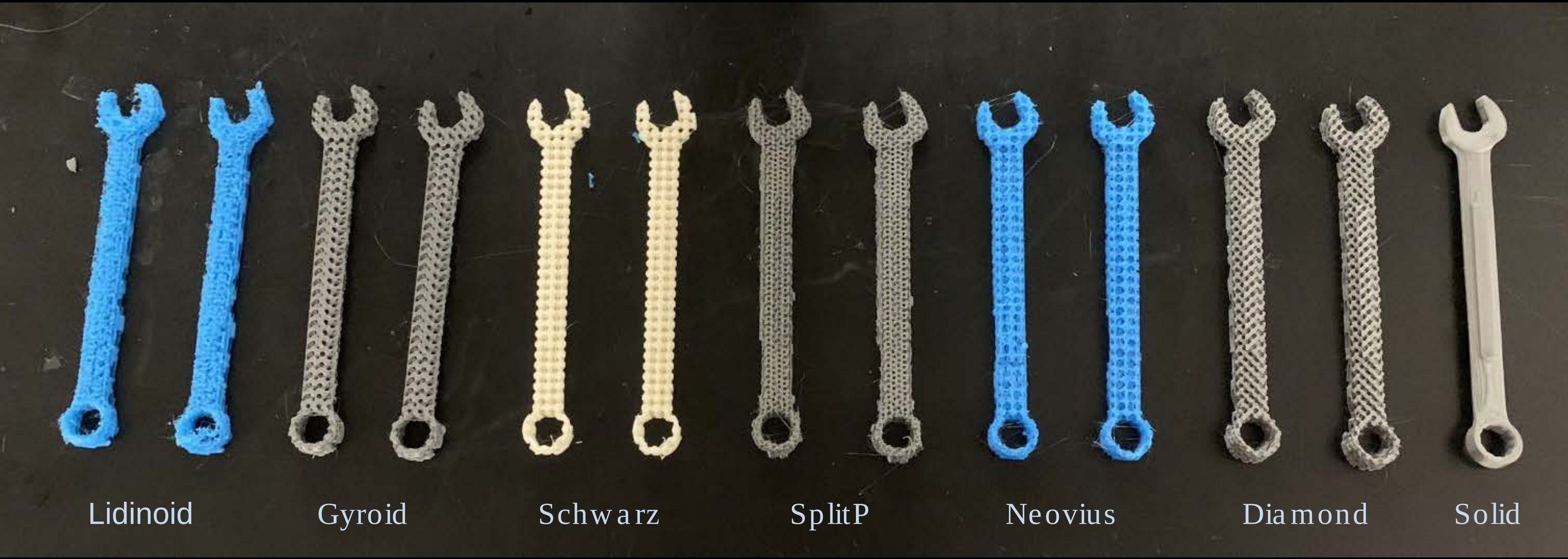
Minimize
Maintenance Time

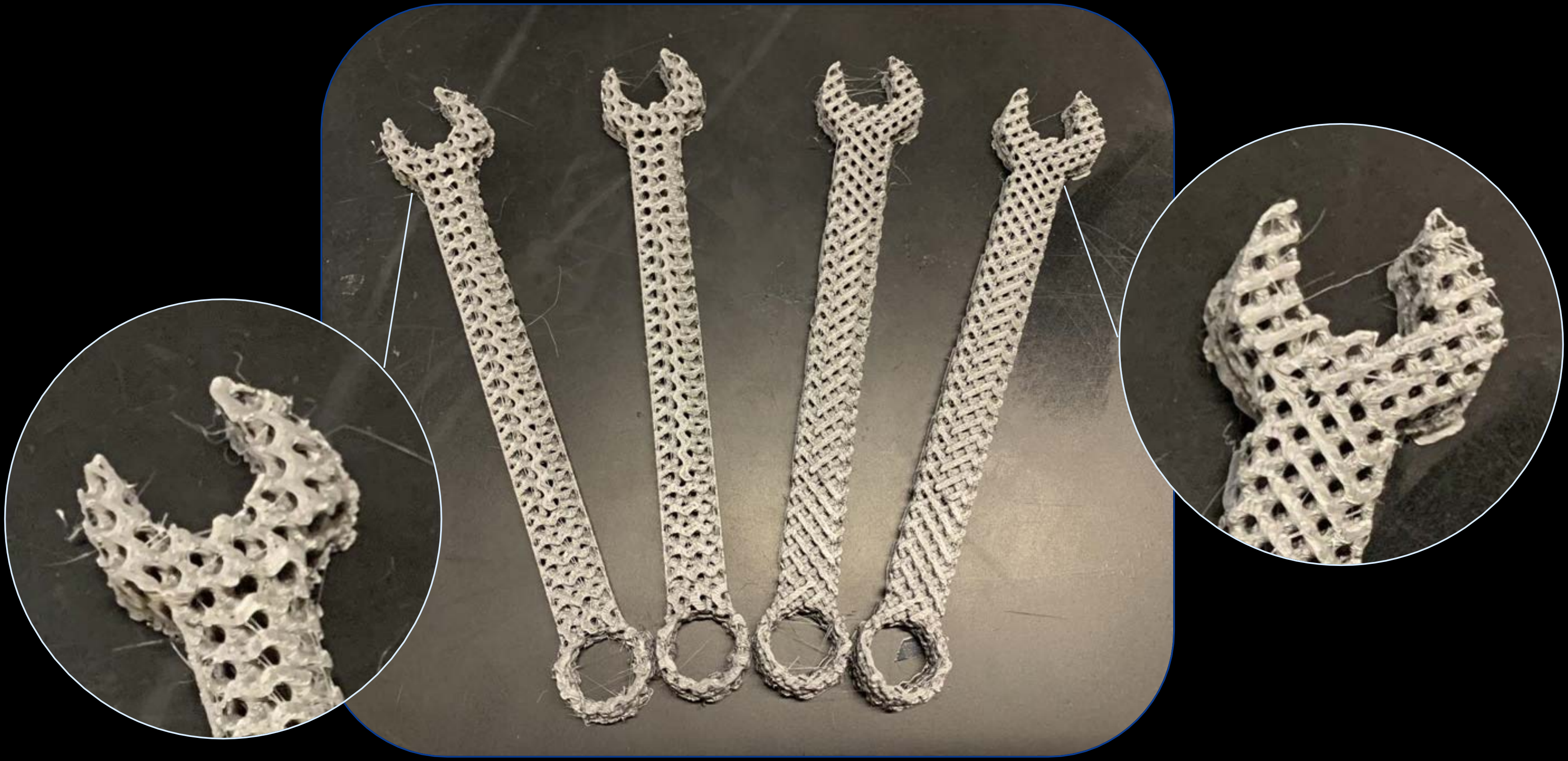
Material Reduction Plan

- ◇Minimizing material use to stretch resources on long space flights
- ◇Maintaining strength of original parts
- ◇Comparing parts to original mass
  - Parts 3D-printed in original filament with 100% infill
- ◇ Optimizing part infill & material mass
  - Prioritize material use, mass, then cost
  - If polymer filament cannot maintain strength,
    try metal with reduced infill,
    then carbon fiber, etc.

Modeling Internal Geometries

- ◇Modifying part infill to optimize material use
- ◇Utilizing nTopology (CAD software) to create complex internal geometries & periodic lattices of provided wrench STL files
  - Gyroid
  - Diamond
  - Lidinoid
  - Schwarz
  - SplitP
  - Neovius
- ◇ Running physical & simulated tests to determine relative strength of internal geometries


Lidinoid
Gyroid
Schwarz
SplitP
Neovius
Diamond
Solid



Examples of ISS Wrenches printed in PLA with gyroid & diamond infill patterns

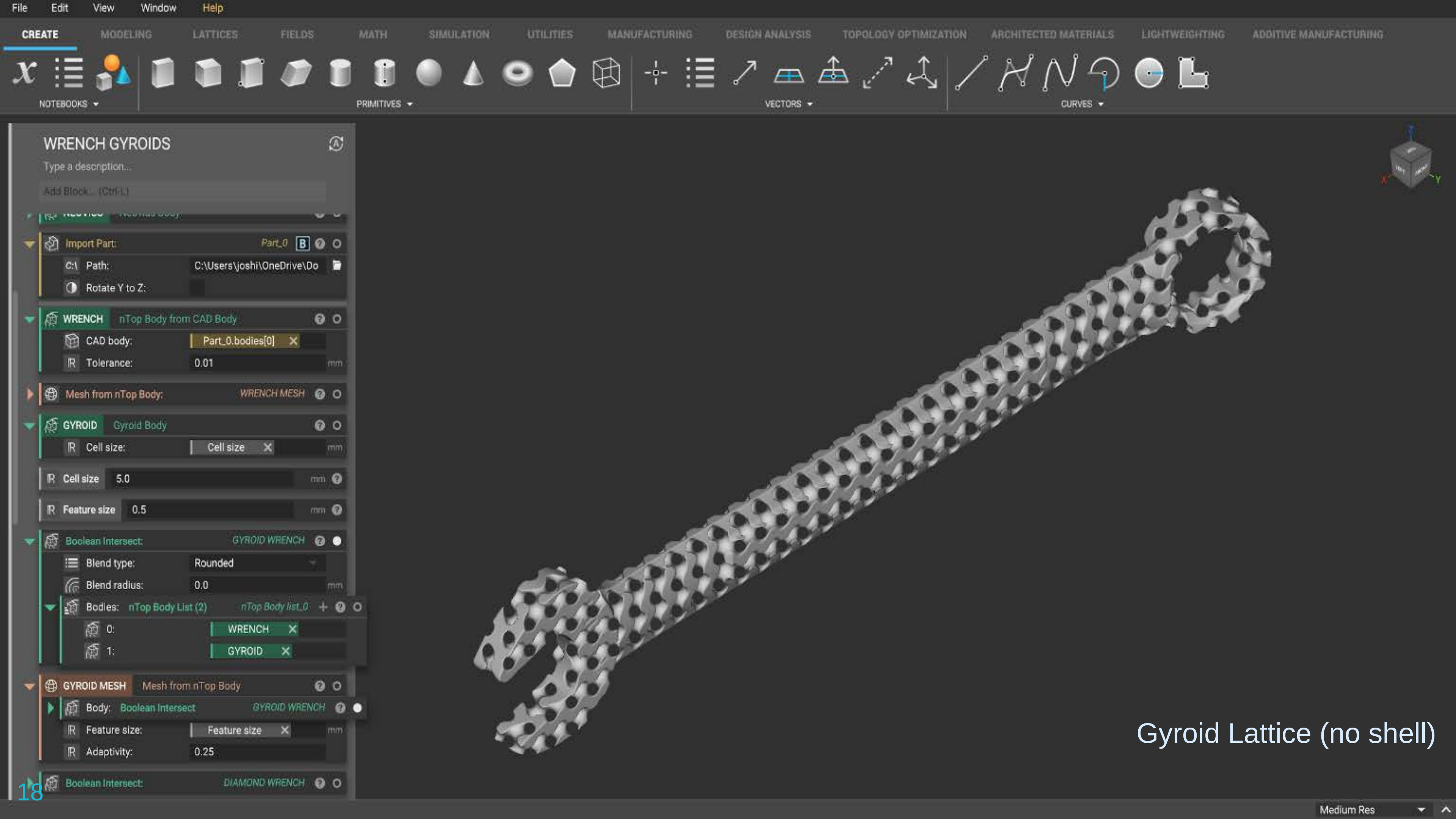
Comparing Internal Structures

Wrench Infill*	Strength (lbs)	Percent Difference: Strength (g)	Weight (g)	Percent Difference: Weight	Cost to Print ($)	Percent Difference: Cost
Unmodified Wrench	20	~	20.03	~		
Diamond	6	70.0%	10.63	46.9%		
Gyroid	5	75.0%	10.12	49.6%		
Schwarz	Inconclusive (too flexible)	~	10.4	48.1%		

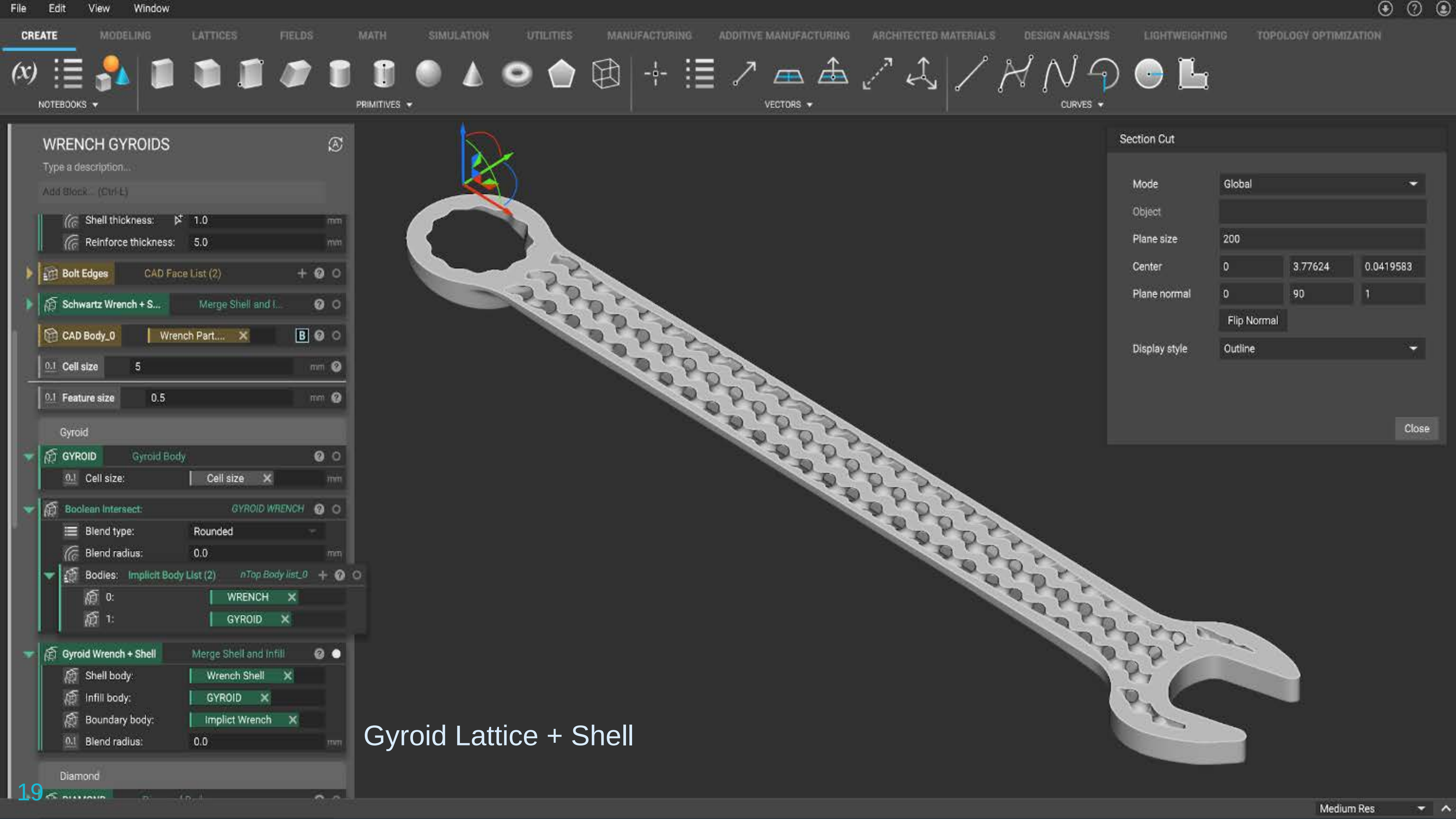
*Printed in PLA, with support

Objective 1

Showcase part, including internal lattice, can be modeled in software



Gyroid Lattice (no shell)



Gyroid Lattice + Shell

Objective 2

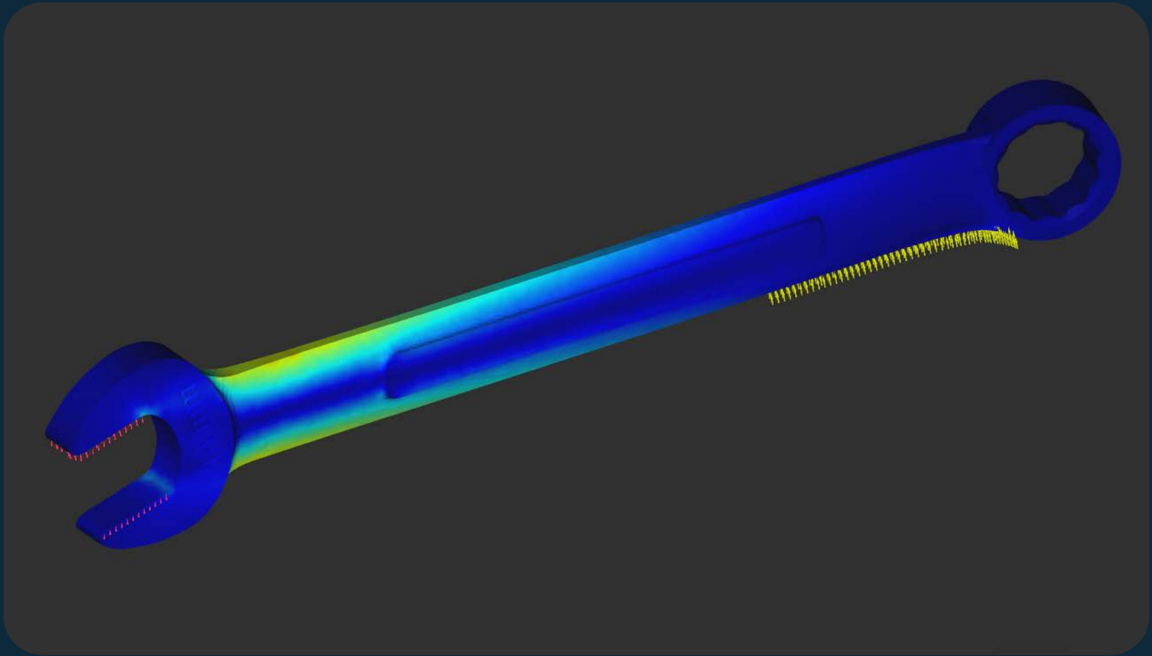
Complete a strength analysis on modeled part with reasonable results

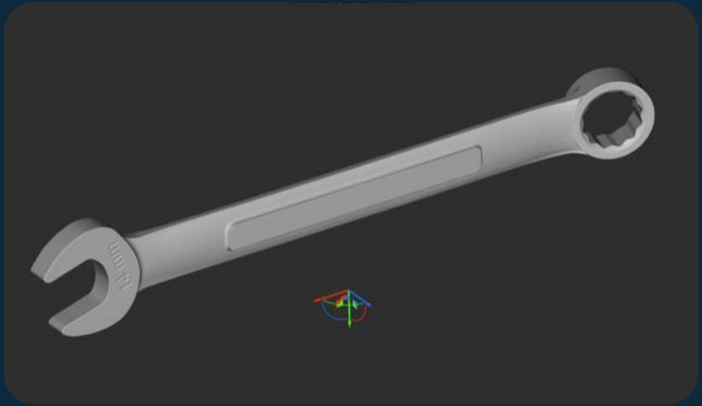
Conclusions from Physical Tests

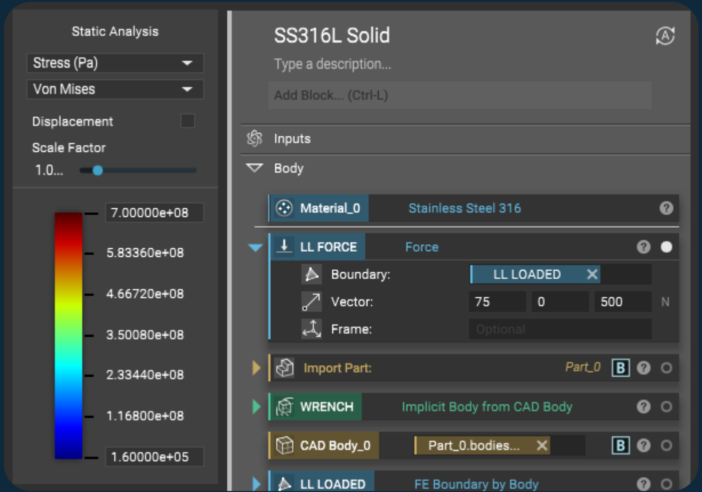
- ◇Continue utilizing nTopology modeling & simulation capabilities
- ◇Internal lattice geometries alone do not reach yield strength of solid materials with low strength material
- ◇Adding shells to lattice geometries increases part strength
- ◇Print the strongest lattices in stronger materials for more accurate results
  - Diamond, Gyroid, Schwarz

SS316L Solid

Von Mises Plot

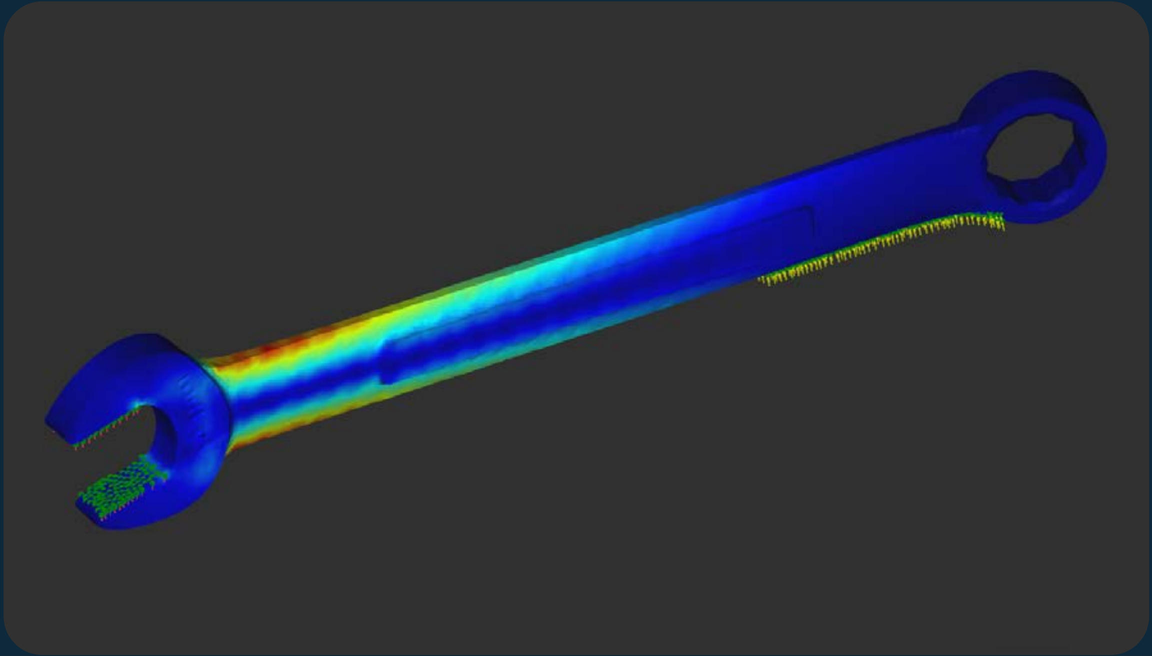


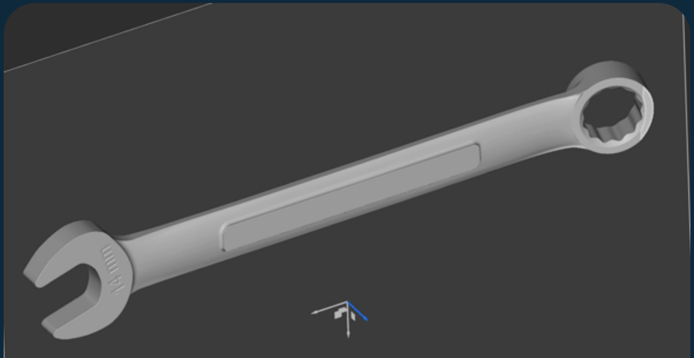




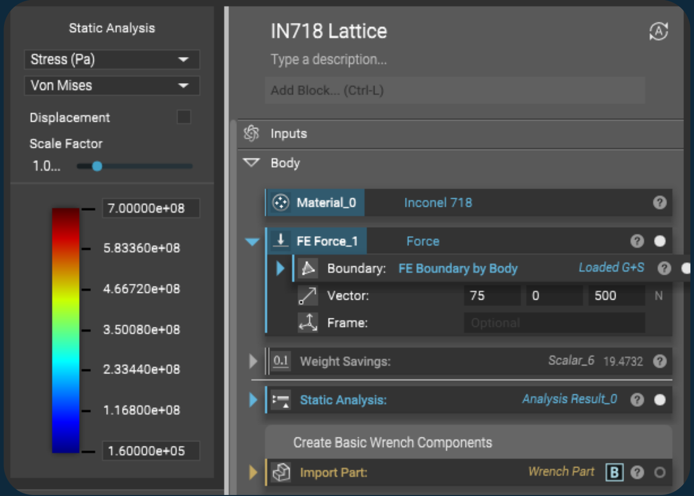
IN718 Gyroid/Shell

Von Mises Plot



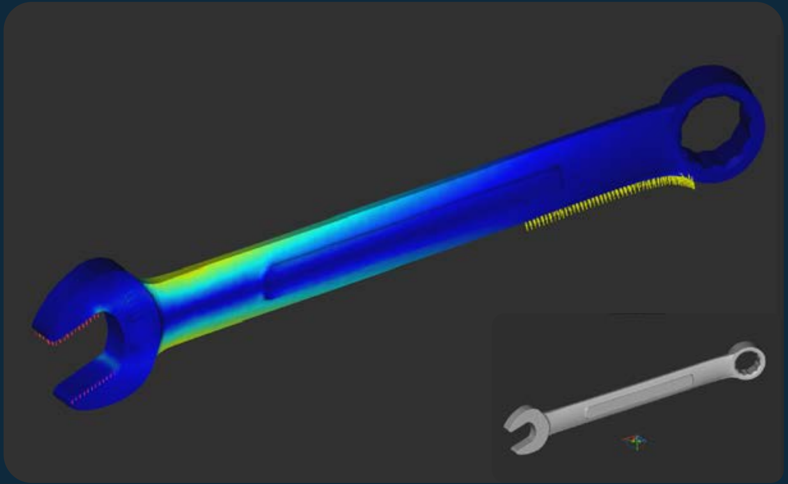


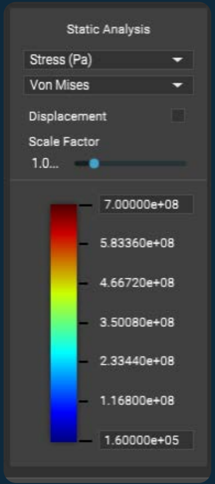
19.47% less material volume

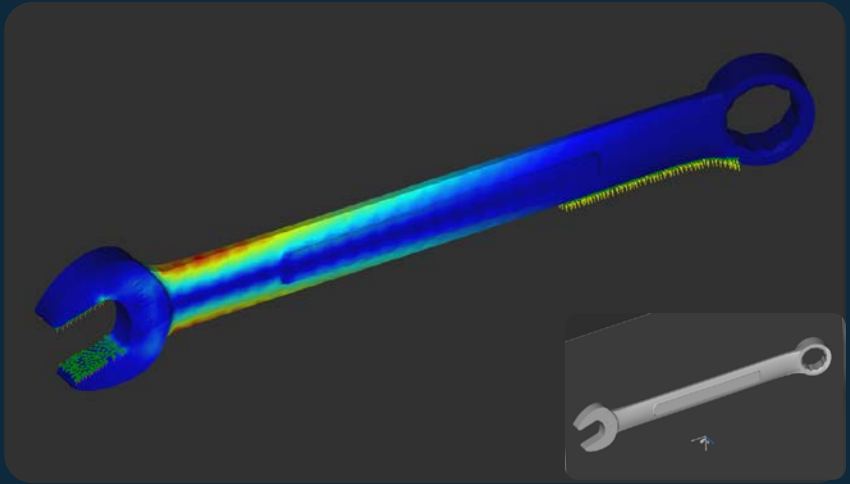


SS316L Solid

IN718 Gyroid/Shell





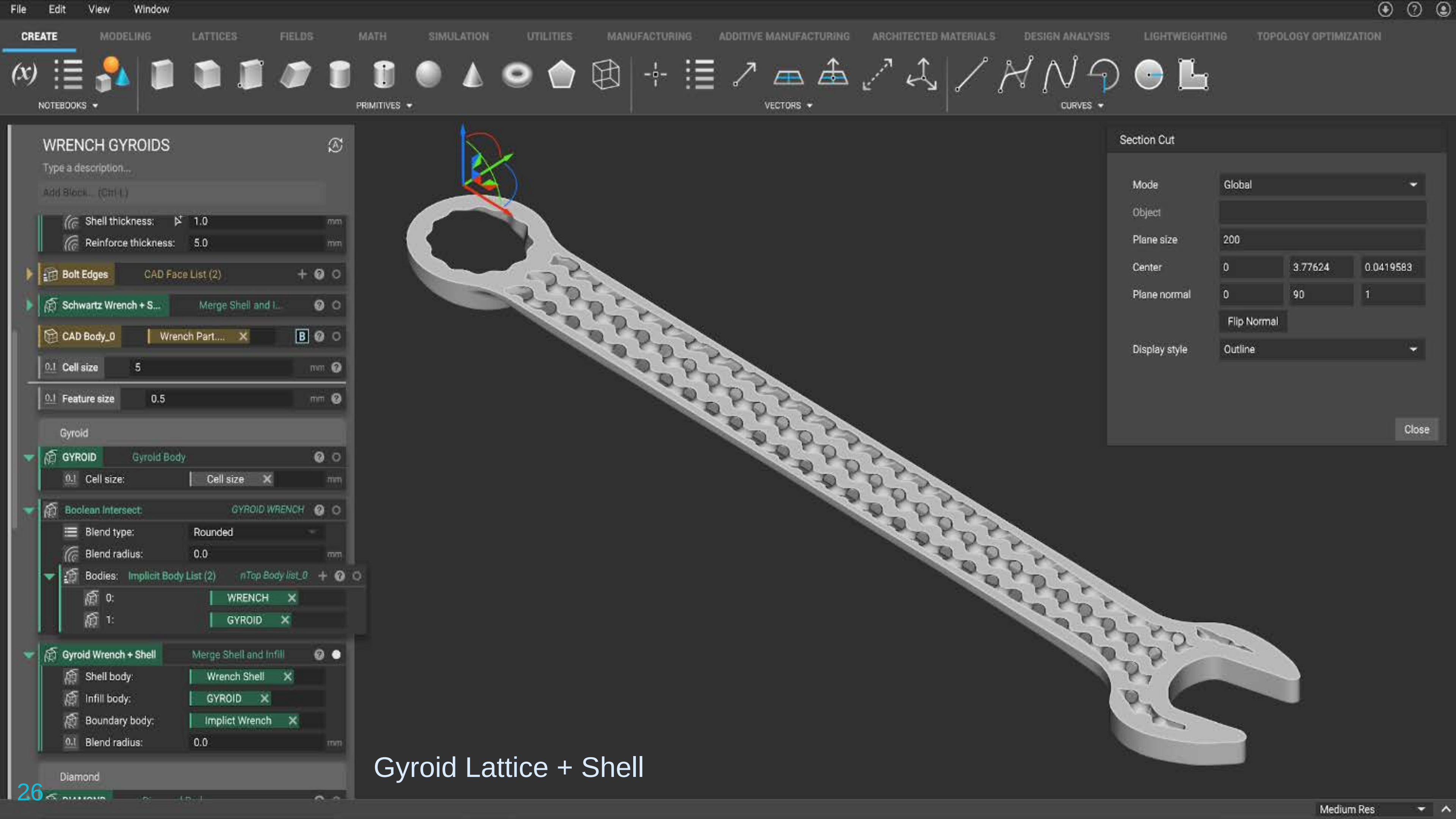


- ◇Young's Modulus - 180 GPa
- ◇Ult. Tensile Strength - 510 MPa
- ◇Maximum stress ≈ 400-500 MPa

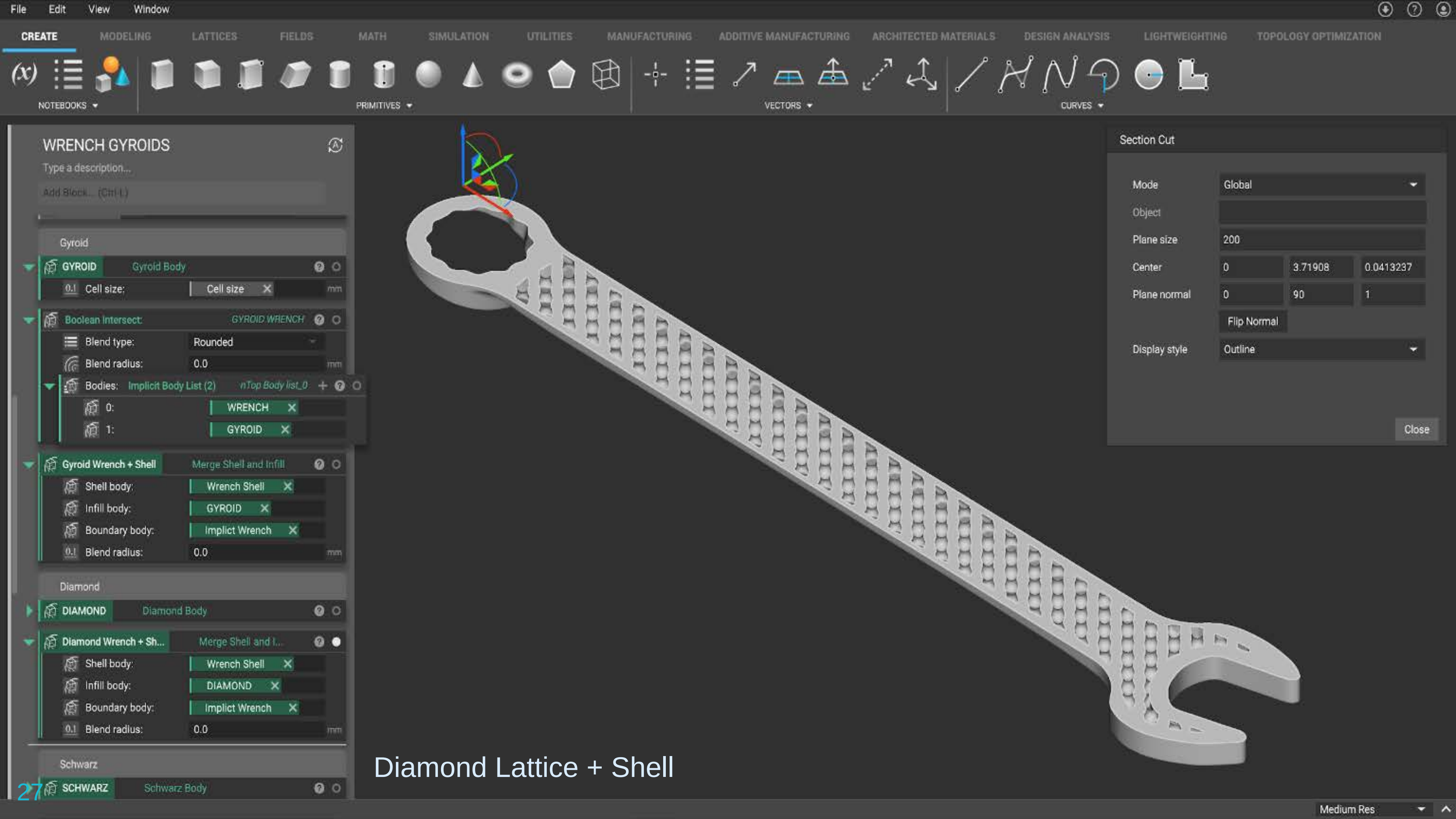
- ◇Young's Modulus - 220 GPa
- ◇Ult. Tensile Strength - 940 MPa
- ◇19.47% less material volume
- ◇Maximum stress ≈ 700-800 MPa

Objective 3

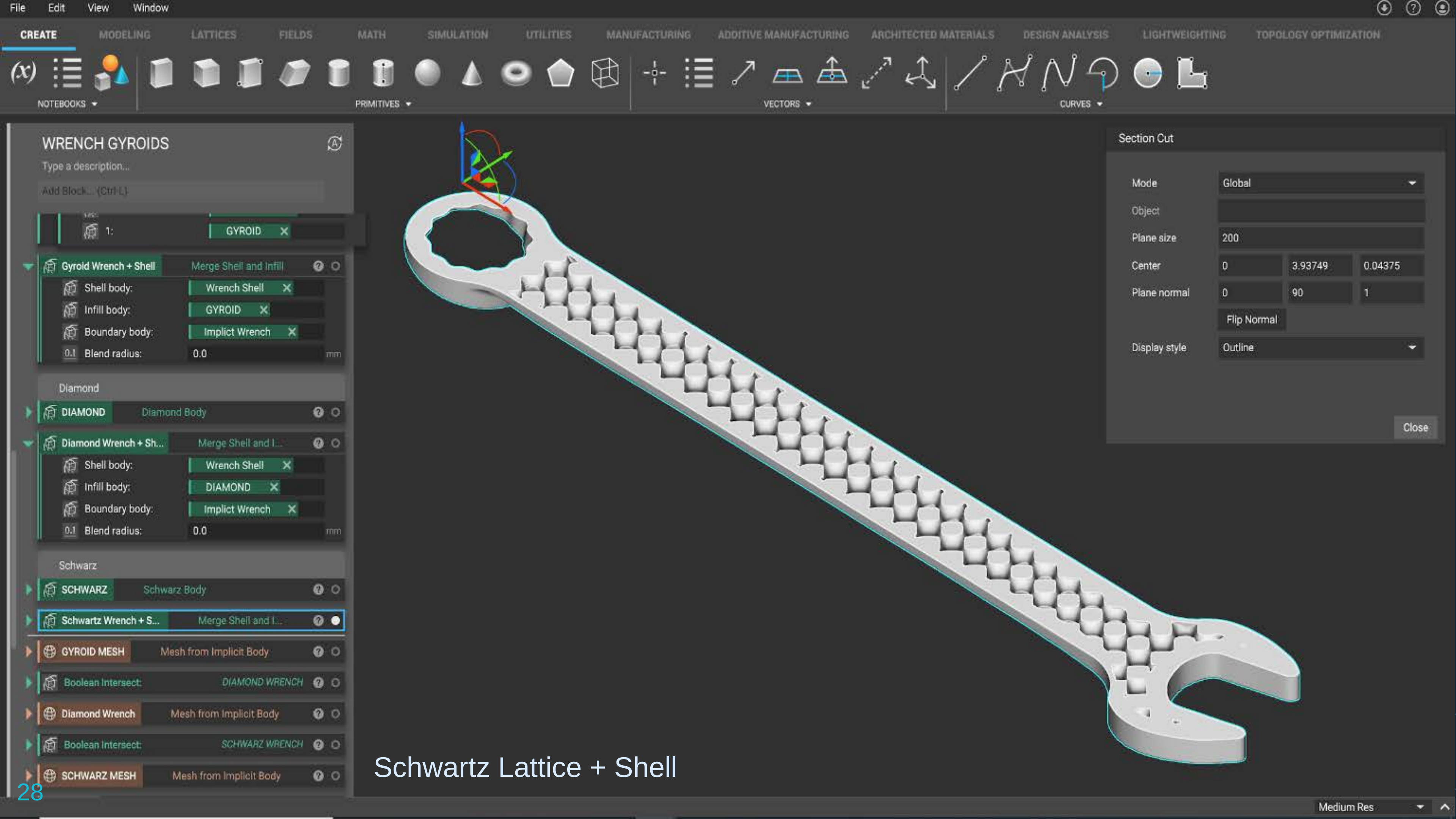
Create 3 iterations of wrench part with varying internal lattices



Gyroid Lattice + Shell



Diamond Lattice + Shell



Schwartz Lattice + Shell

Weight Reduction (PLA)

Wrench Infill*	Weight (g)	Percent Difference
Unmodified Wrench	16.09	~
Gyroid	7.91	50.82%
Diamond	8.05	49.98%
Schwarz	7.98	50.41%
Gyroid + Shell	12.95	19.47%
Diamond + Shell	13.06	18.81%
Schwartz + Shell	13.65	15.16%

*Assuming 100% infill of PLA with density 0.00124 g/mm3, no support added

Objective 4

Provide manufacturing process steps and settings for making part

Post-Processing Instructions

- Initial material is chosen for part
  - Polymers will require support material removal
  - Metals will require debinding and sintering
- These steps can be saved in the database for each material
  - Users can identify post-processing before printing the part

Objective 5

Redesigned parts meet 100% of relevant NASA standards

Compliance to NASA Standards

- There are no NASA standards directly governing this process
  - Redesigning existing parts with less material
- Our goal was to meet original part requirements
  - Strength, temperature, etc.
  - We do not know requirements for off-the-shelf parts
- Our efforts reflect similar standards outlined in Wohler & Associates Design for Additive Manufacturing Best Practices & MSFC-SPEC-3716 & 3717

Objective 6

Provide research results on varying material type when modeling and analyzing part

Materials Research

- Researched variety of material properties
  - **Polymers:** ABS, PLA, Thermax, Polymax PC, Polylite PC
  - **Metals:** Stainless Steel, Aluminum, Inconel, Titanium, Ultrafuse
  - **Carbon Fiber:** Markforged Filament
- Determined strength-to-weight ratios for materials

Sources of Error

- Values taken from filament spec sheets
- Tolerances not taken into account
- Isotropic values assumed from spec sheets
  - Inaccurate - Does not account for layer direction / height
  - Impossible to account for 3D printing properties without physical testing
- Carbon Fiber Filament - Traditionally used as reinforcement to other polymer filament

Materials Research

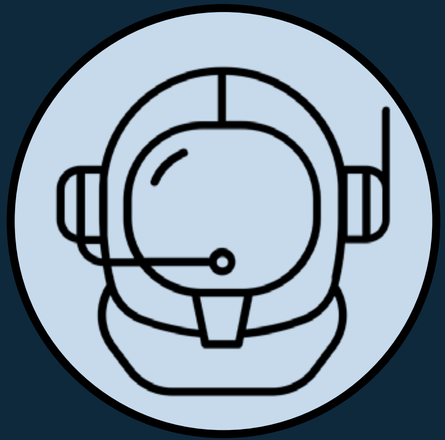
Material	Category	Density (kg/m^3)	Ultimate Tensile Strength (Pa)	Young's Modulus (MPa)	Cost ($/kg)	Strength to Weight Ratio
Acrylonitrile Butadiene Styrene (ABS)	Polymer	1,098.75	39e+6	1,618.5		35,494.96
PolyLactic Acid (PLA)	Polymer	1,246.91	49.5e+6	2,347		39,698.07
THERMAX PSU	PolySulfone	1,240	52e+6	2,100		41,935.48
PolyMax PC	**Polycarbonate**	**1,180**	**59.7e+6**	**2,048**		**50,593.22**
PolyLite PC	**Polycarbonate**	**1,190**	**62.7e+6**	**2,307**		**52,689.08**
Stainless Steel (SS316L or 1.4404)	Metal	7,910	510e+6	180,000		64,475.35
Ultrafuse 316L (Commercial FIlament)	Metal	7,850	561e+6			71,464.97
Aluminum (AlSi10Mg)	Metal	2,590	250e+6	70,000		96,525.10
Inconel IN718	**Metal**	**8,070**	**940e+6**	**220,000**		**116,480.79**
Titanium Ti6Al4V	**Metal**	**4,360**	**900e+6**	**110,000**		**206,422.02**
Markforged	**Carbon Fiber**	**1,400**	**800e+6**	**60,000**		**571,428.57**

Database Design

Customer Needs: Database

Minimizes Data Envelope

Contains Part Information

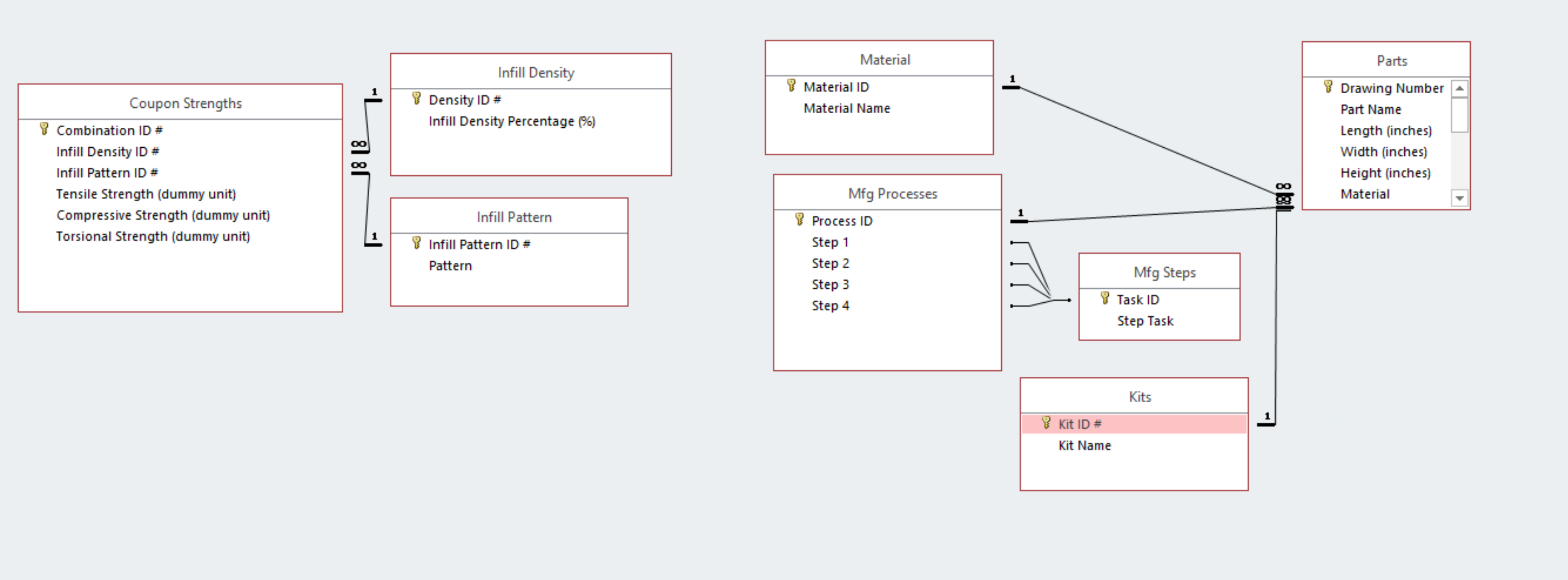


User-Friendly GUI

Chosen Database

- Microsoft Access Selected
  - Relational database
  - Small learning curve
  - Frontend and backend capability
  - Has the ability to support a more complex database

Relationships



Objective 7

Populate database with manufacturing instructions for redesigned part

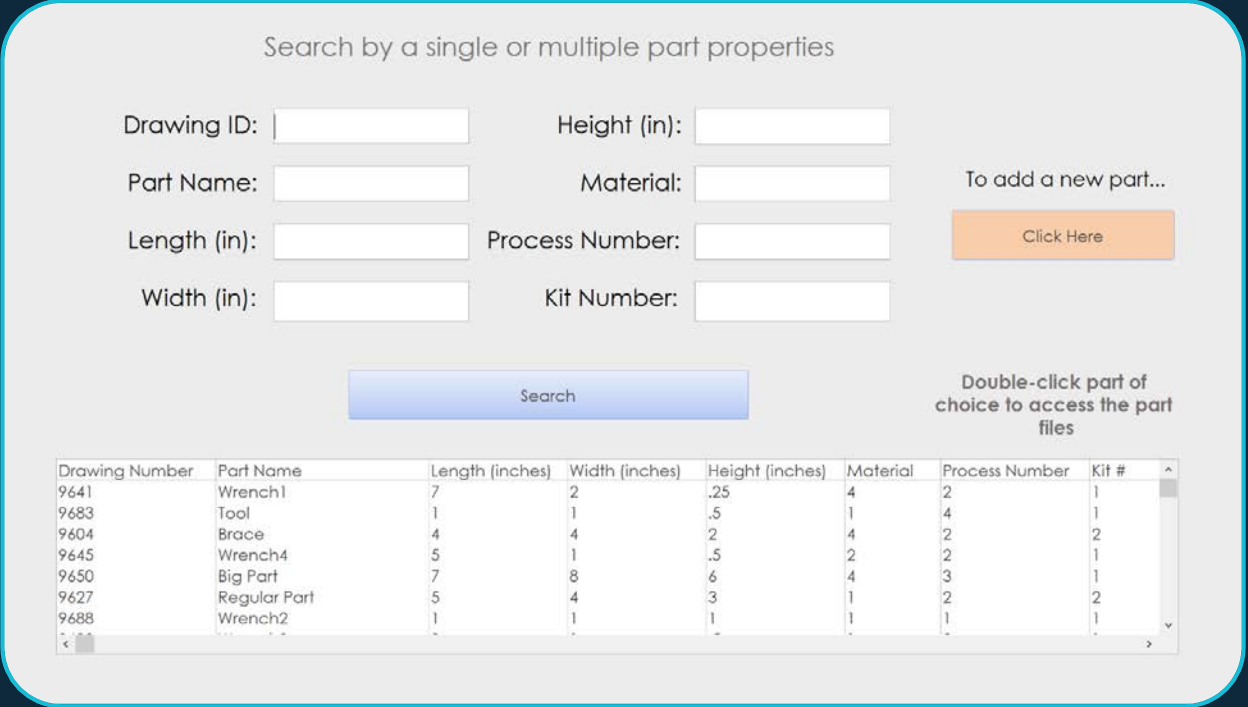
Manufacturing Steps

Task ID	Step Task	Click to Add
1	Remove Excess Material by Hand	
2	Sand in Vacuum Chamber	
3	Soaking	
4	Heat	
0		

Objective 8

Provide at least 1 search feature for each entry in the Part ID table

Search Features



Drawing Number	Part Name	Length (inches)	Width (inches)	Height (inches)	Material	Process Number	Kit #
9641	Wrench1	7	2	.25	4	2	1
9683	Tool	1	1	.5	1	4	1
9604	Brace	4	4	2	4	2	2
9645	Wrench4	5	1	.5	2	2	1
9650	Big Part	7	8	6	4	3	1
9627	Regular Part	5	4	3	1	2	2
9688	Wrench2	1	1	1	1	1	1

Objective 9

Database provides hyperlink to nTopology software

Direct Link to nTopology

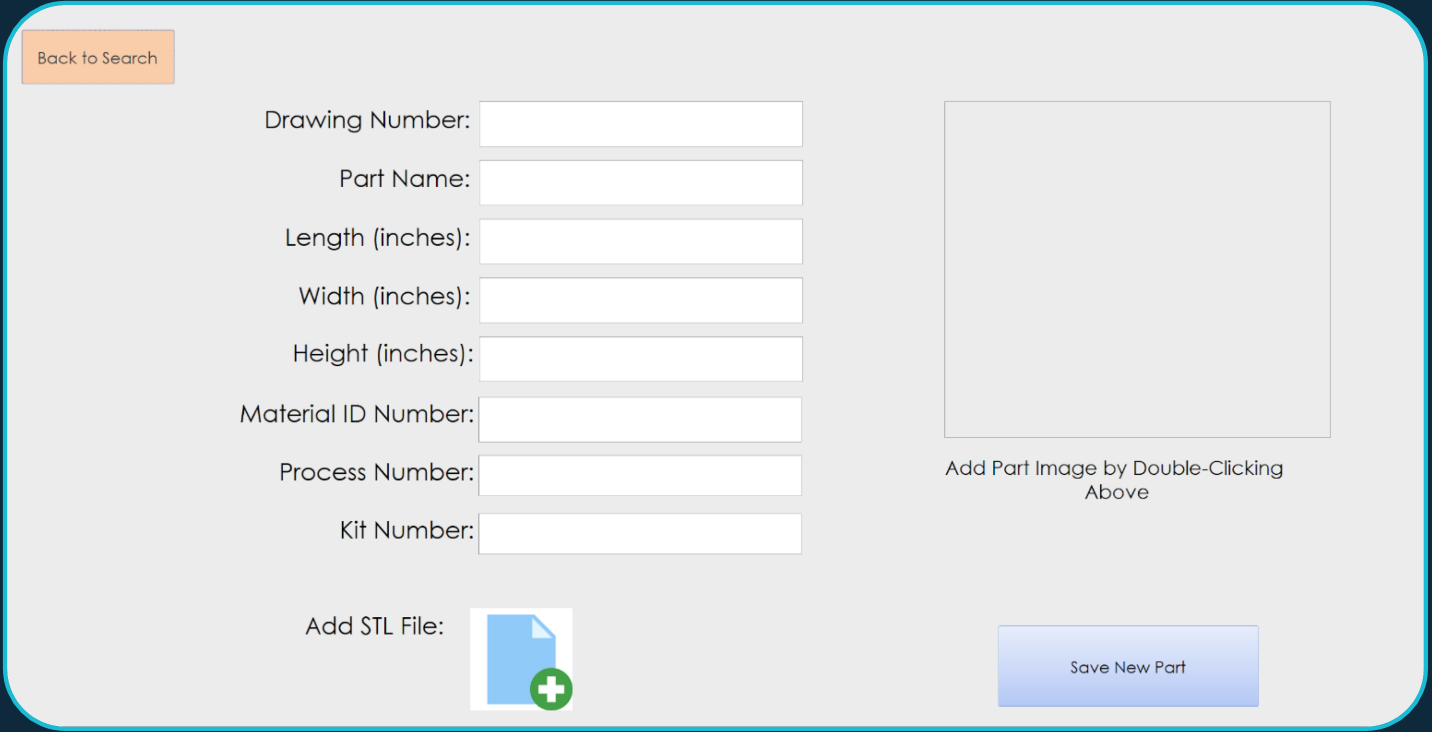
Drawing Number	9641
Part Name	Wrench1
Length (inches)	7
Width (inches)	2
Height (inches)	.25
Material	4
Manufacturing Process Number	2
Kit #	1
Open in Slicer	

Edit

Objective 10

Create 1 input form for each table in the database

Input Forms



Back to Search

Drawing Number:

Part Name:

Length (inches):

Width (inches):

Height (inches):

Material ID Number:

Process Number:

Kit Number:

Add STL File:

Add Part Image by Double-Clicking Above

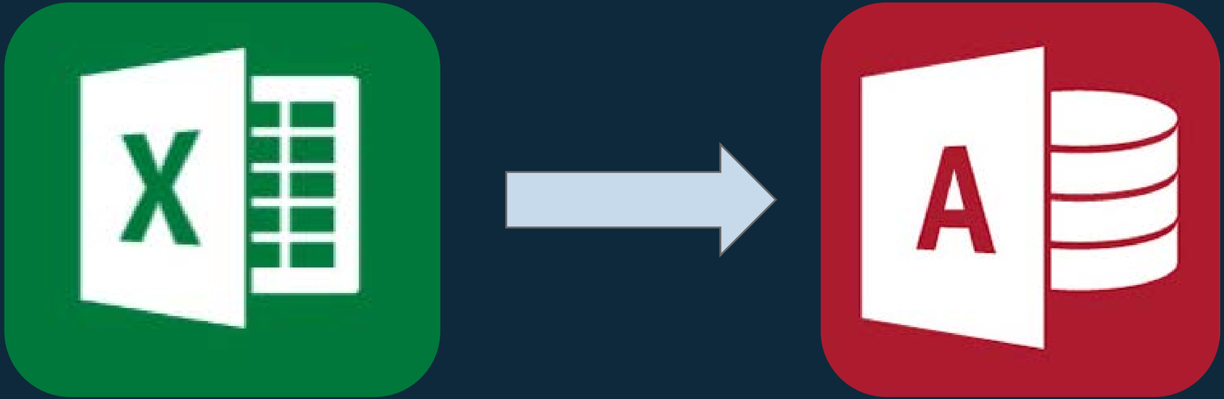
Save New Part

Objective 11

Maintain cost of software(s) to operate database

Software Cost

- Access comes with Microsoft Office Suite
  - Microsoft Office is already used by NASA team, so cost is comparable if nothing



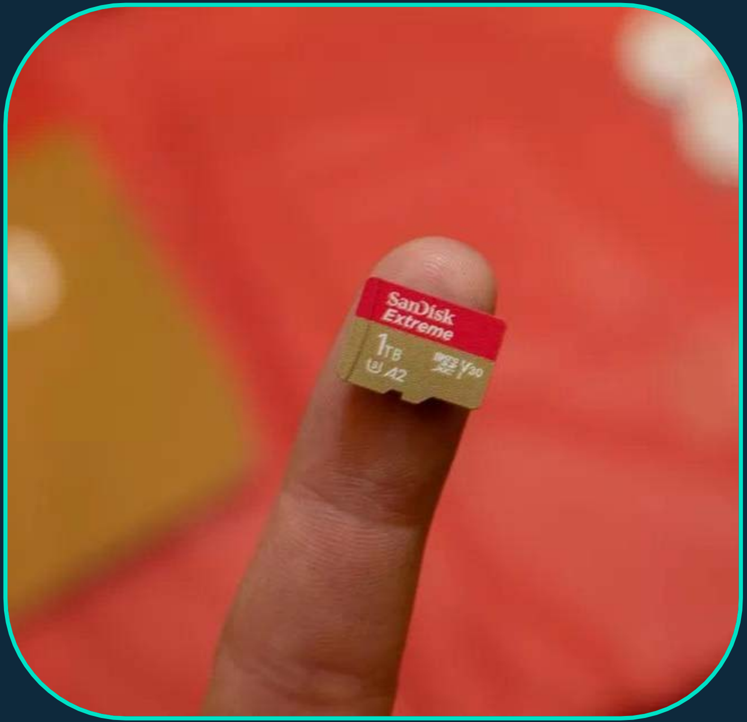
Objective 12

Average package size is equal to or less than 4.5MB specification

File Package Size

◇ **Negligible**

- Current database - 500 parts,
  - If avg ~4.5MB ea, ~2.3GB total
  - If avg ~100MB ea, ~50GB total
- Scale by 100 - 50,000 parts,
  - If avg ~4.5MB ea, ~230GB total
  - If avg ~100MB ea, ~5TB total



Objective 13

Database meets 100% of technical standards

Compliance to Regulations

◇No specific regulations governing this project

- Currently a non-flight project
- No specific database development regulations

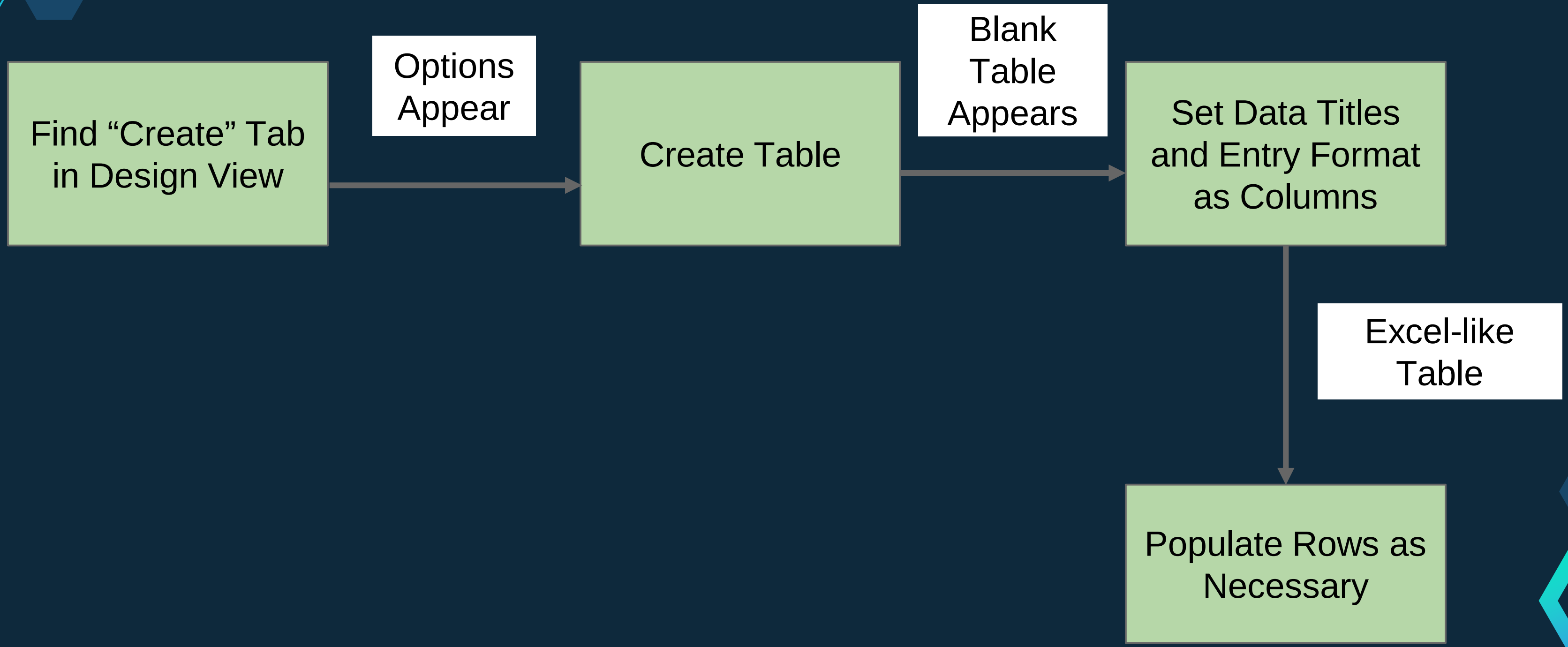
Objective 14

Maintain 1 -to-1 ratio between tables and part information. Provide instruction template for users to create and enter table information for future use.

Objective 14: 1-to-1 Ratio

- Examine the database to ensure no redundant or repeated information
- Use of relationships helps to apply one type of information to multiple parts without need for repetition

Objective 14: Creating Table



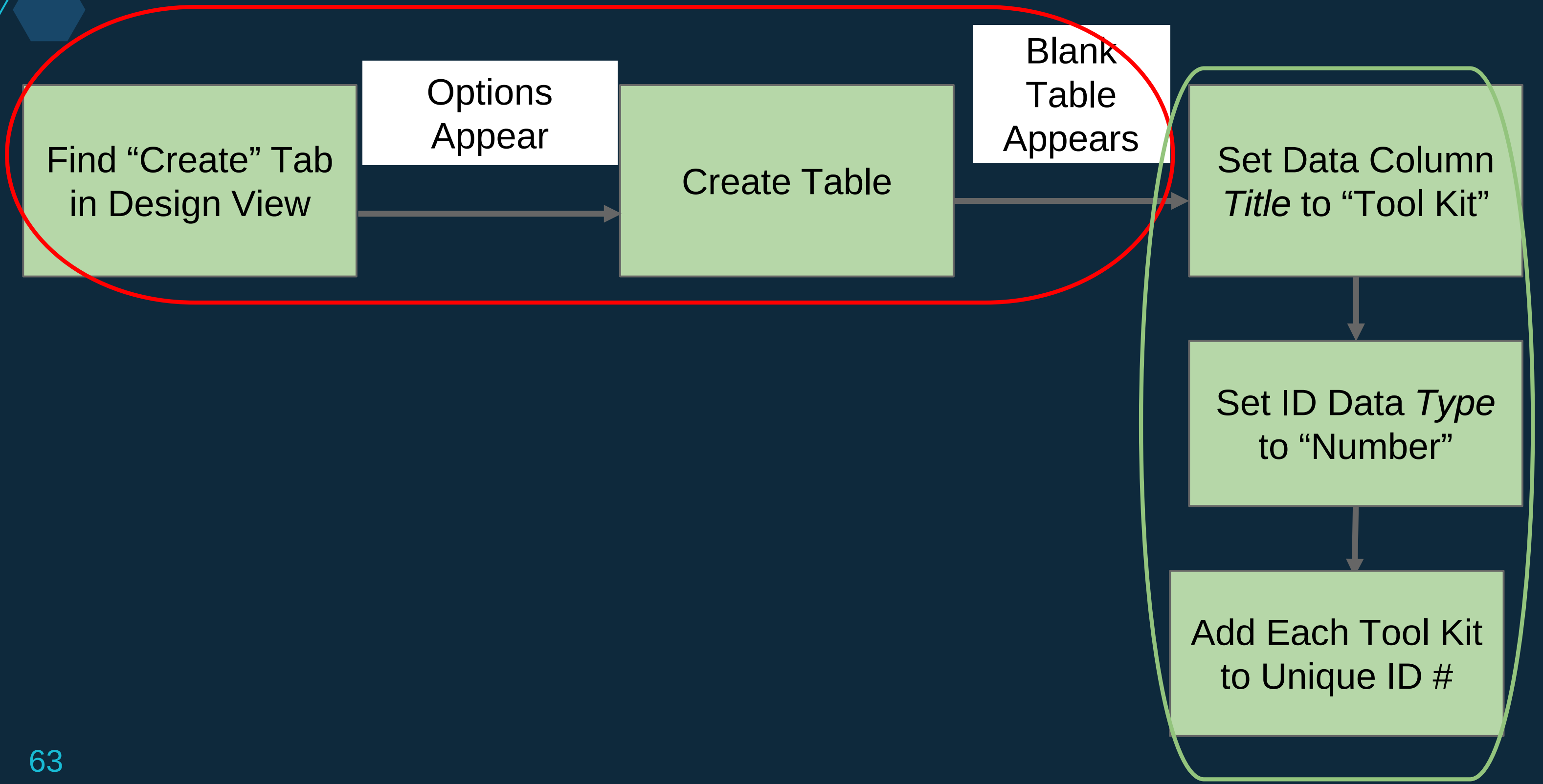
Objective 15

Provide instruction template for new users to create a tool kit table and input information

Objective 15

- Simply Obj. 15 with a purposed application
  - Follow same steps, entries for each row will be tool kits

Objective 15: Tool Kit Table



Future Work

Wrench Optimization

- Deeper Dive into nTop Capabilities
  - New software - constantly updating & adding new features
  - Explore how modifying feature settings affect part strength
  - Investigate topology optimization features
  - Optimize other part files
- Continue pursuing multiple topography analysis methods (Solidworks, nTop) to strengthen relevant parts of material
  - Can use FEA results to thicken lattices in nTopology

Physical Testing

- Print wrenches in metal / polymer materials as used on ISS
- Test analogous parts to determine
  - Test tension, flexion, compression, etc.
  - Use material testing equipment to handle large loads
  - Reduce need for scaling part strengths between materials

Materials Testing

- Utilize initial materials research
- Print modified wrench designs
- Physically test to compare material strengths
  - Markforged Carbon Fiber
  - Titanium Ti-6Al-4V
  - Inconel IN718
  - Polylite PC
  - PolyMax PC

Database Remaining Objectives

- Maintain an 85% success rate in locating part in < 15 seconds
- Provide 1 new photo for each part that failed in Cycle 3 Photo survey
- Achieve 85% success rate in photo identification
- Simplifying pop -up window for opening CAD software directly from database

Database Testing

- Provide copy of database to NASA staff for user testing
  - Obtain feedback and provide instruction for future development

Document Deliverables

- A series of documents will be submitted Wednesday, May 6th
  - Final Report
  - Bill of Materials, LBM
  - Engineering Drawings
  - Product Safety Analysis
- Otherwise, we are always available via email
  - livelongandprinter@gmail.com

Conclusion

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- Proved concept for optimizing 3D printed parts for in-space manufacturing
  - Possible to reduce material use while maintaining part strength
  - This approach can be utilized for polymer & metal materials
- Developed user-friendly database for astronauts
  - Improved ease of accessing & printing parts
- Imperative to give astronauts the right tools for success

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- **NASA Engineers:** Norman Chaffee, Bernard Rosenbaum, Renee Lance, & Lonnie Jenkins

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