Optimized Pathology Sample Storage System

Final Report

Team 20:
Derek Johnston
Kathryn Olson
Justin Sawkin
Keith Vander Putten

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Instructor: Professor Jwo Pan

ABSTRACT

Every day, the Pathology Department at the University of Michigan Hospital generates and receives a large quantity of anatomic pathology samples in the form of glass slides for light microscopy. The slides are used by pathologists to arrive at diagnoses for patients who have undergone diagnostic biopsies or surgical excisions of a variety of tissues or organs. These slides are currently stored in a very primitive drawer system that has not changed for decades. Our project was to modernize this system by optimizing the slide storage density, fixing current design problems, and designing to allow for easy adaptation to an automated slide retrieval system. Through our engineering analysis, we were able to determine the best shape and size to maximize the density based on set ergonomic and material constraints. For the fabrication of our prototype we decided to use low carbon steel sheet and angle steel.

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INTRODUCTION

We have been given the task of developing an improved storage system for microscope slides. The slides are created by the pathology department at the University of Michigan Hospital and contain thin slices of biopsies from patients. The current storage system for these slides has many structural and operational issues. The partitions separating rows of slides from each other as well as the handles tend to break, which mixes up the slides and makes them hard to access. The drawers do not slide on tracks, but instead sit on top of a piece of sheet metal, meaning that the static friction between the two metals has to be overcome to open the drawer. Also, when the drawer is pulled out it hangs down at an angle making it very hard to automate the system in the future. Therefore, we have been asked to create a storage system that removes all of these issues. Other important constraints are that the system has to have a higher density of storage and be compatible with an automated retrieval system. We will be working with our sponsors Professor Albert Shih, a professor in both the mechanical and biomedical engineering departments, and Doctor Peter Lucas, a professor in the pathology department of the medical school. Also assisting in our project development will be Professor Jwo Pan, a professor in both the mechanical engineering and applied mechanics departments.

Figure 1: Current Storage System for Microscope Slides

INFORMATION SEARCH

Before generating potential designs for our project, we consulted our sponsors and hospital personnel to determine the issues with the current storage system and customer requirements for the new design. We conducted web-based research to determine if any products existed in the market that could be adapted for the hospital's needs, or if there were any patents we would need to work around. We also researched the technical benchmarks that currently exist for a microscope slide storage system. Several products already on the market are similar to the current storage system, and several different types of automated storage systems currently exist that could be considered a starting point for the design of an automated slide storage system.

Our sponsors informed us there is no automated storage system for microscope slides in use at the University of Michigan Hospital or any other hospital to their knowledge. The automated storage systems that are currently on the market are typically on a much larger scale and are not easily converted to handle something as small as a slide. Some examples of systems we found on the internet are shown below in Figures 2-3. However, we could integrate ideas from these systems into a design to determine an efficient way to optimize space and time. As a team, we would need to generate a design with specific dimensions and electronic components that can successfully store many slides.

Figure 2: PFS Container Carousel [1]

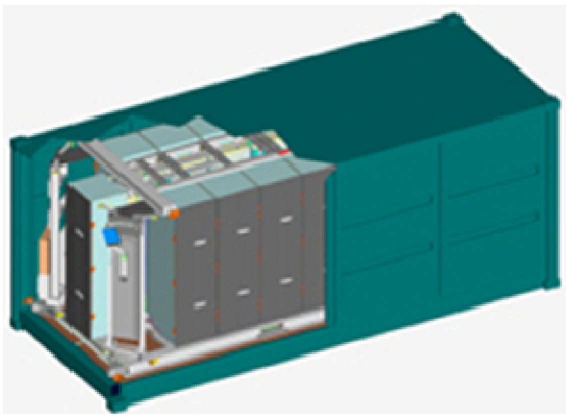
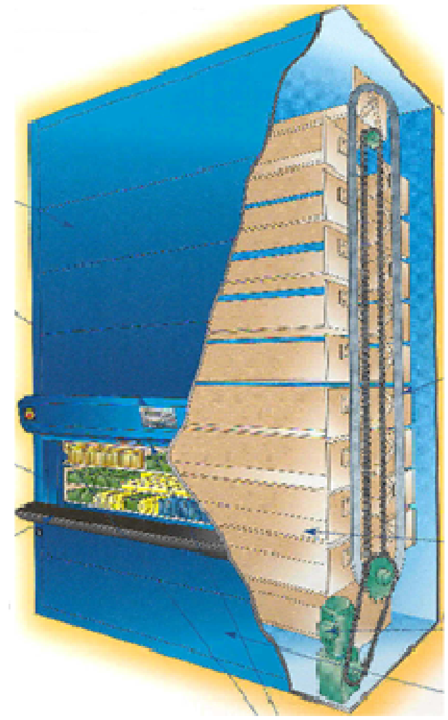


Figure 3: MegaStation Vertical Carousel [2]



The missing information for an automated storage system would be determined through analysis and testing. Engineering principles and calculations would determine: the frictional forces between a slide and the surface it rests on; the torque and gear ratios required from a motor and transmission; the momentum of a varying amount of slides rotating; etc. To aid these calculations, we would also need to do space optimization analysis to determine how many slides one storage system would hold, as well as how many slides one “bin” or “track” of slides might hold.

An automated system will not maximize the density of slides because components such as motors and gears will take up storage space. When paired with a program that will keep track of where each slide is located within the system, the time needed to retrieve a slide and human error will be significantly reduced. By reducing the manual labor required to retrieve slides, an automated system could reduce the long term cost to the hospital. However, the hospital personnel have put a greater emphasis on maximizing density than on reduced cost due to the high volume of slides received each year.

Several of the currently advertised brands of storage drawers, such as Fisher Scientific, Boekel Scientific, and Tissue Tek, are extremely similar. They all involve removable drawers with one or two rows which hold slides back to back. The brand we focused on and redesigned is Fisher Scientific, the one most often used by the University Hospital. A single unit can hold up to 4500 slides and contains six drawers with two rows of slides and a central support beam located between the two inner most drawers, as seen in Figure 4 below. A metal casing houses these drawers and contains simple “tracks” (Figure 5,) to keep a drawer in its proper position. The unit does not use any sort of sliders or bearings: drawers simply slide along the painted surface of the casing, which also allows the drawers to hang at an angle when pulled out completely. Multiple units can be vertically stacked on top of one another to save space, and are attached via a thin sheet metal hook in the back of the unit.[3]

Figure 4: Stackable Fisher Scientific Slide Storage Drawers

Figure 5: Simple Metal Tracks Used by Fisher Scientific to Restrain Movement of Drawers

While documenting the design of the current storage systems, we measured all the dimensions of the Fisher Scientific and Tissue Tek drawers, the forces needed to open both empty and full drawers, and the weight of empty drawers. This information can be found in Table 1 on page 8.

Table 1: Benchmark Specifications

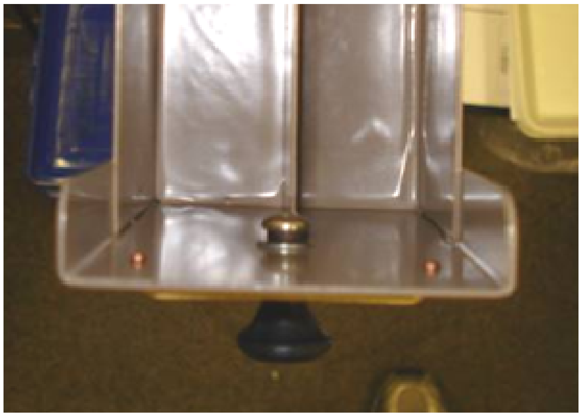
		Fisher Scientific	Tissue Tek
	Material	Metal	Metal
	Drawers per Unit	6	14
	Rows per Drawer	2	1
Unit Dimensions	**Height**	125 mm	139 mm
	Depth	477 mm	484 mm
	Width	403 mm	484 mm
Drawer Dimensions	**Overall Height**	95 mm	107 mm
	Inside Height	53 mm	44mm
	Overall Depth	453 mm	466 mm
	Overall Width	60 mm	27 mm
	Drawer Width	56 mm	27 mm
	Row Width	27.5 mm	27 mm
	Mass of Empty Drawer	822 g	369 g
	Maximum Force Required to Open Drawer	31.2 N	26.7 N

After speaking with the slide librarian at the University Hospital and lab technicians at other hospitals, we discovered that several problems exist with the current drawer systems. Since the drawers do not pull out all the way, it is difficult to reach slides in the back of the drawer, therefore the users do not fill the drawers completely; this results in wasted storage space. Furthermore, when the drawers are not full, the slides have room to fall over and can become unorganized. Foam "stoppers" can be used to hold up slides when drawers are not full, but these can be easily misplaced or lost. Since entire drawers are able to be removed from the unit, they are sometimes left sitting out, causing disorganization of the drawers as seen in Figure 6 on page 9. Whenever plastic is used for drawers or handles, these parts tend to break easily. Fisher Scientific also uses a round bolt to hold the handle onto the front of their drawer, shown in Figure 7 on page 9; slides in the front of the drawer may come into contact with this bolt and break, causing a safety issue for the user.

The hospital's ultimate goal is to eventually automate the entire process of storing and receiving slides. Since the drawers simply slide along the surface of the casing, they are able to hang at an angle when nearly or fully extended. This feature will make automation difficult. The foam stoppers also force the slides to be stored vertically, requiring a tedious effort to lift an individual slide out of the row to view the label; it would necessitate great dexterity and very tight tolerances for a robotic arm to achieve this task, meaning more expensive systems.

Figure 6: Drawers Left Out of the Unit

Figure 7: Bolt Used to Attach Drawer Handle



Our goal was to redesign a storage drawer system that will optimize space, attempt to solve all the problems discussed above, and take a step towards automation of the system. To determine the best solution, we have applied our knowledge of engineering principles such as statics and behavior of materials, or dynamics and controls. Our design has ultimately created a more user-friendly storage system that has maximized slide density while minimizing safety concerns and the need for re-organization of slides. The development of potential designs and the selection process are discussed in detail in the following sections.

CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

In the Quality Function Development (QFD) as seen below in Figure 8 on page 12, we worked with our sponsors to develop customer requirements and weigh them appropriately. These requirements focused on increasing the density and ease of use while keeping in mind the ability for the storage system to be automated. A high density of storage is needed since the pathology department gets over 300,000 slides per year. By eventually having an automated process it will limit the human task and error of retrieving the slides as well as allow a computer to store the information of when a slide is checked out and by whom.

Other priorities from our sponsors are to develop a reliable product of reasonable size which allows for quick and ergonomic slide retrieval. Reliability and accuracy are necessary requirements because misplacement or mishandling of a patient's slides could have serious consequences.

These customer requirements were translated into engineering requirements which can be seen in Table 2 on page 11. The size of the unit is directly related to the number of slides we could fit in the unit, the volume per unit, and the weight of each unit. With a larger size it could create a larger distance between the user and the slide causing longer slide retrieval time, as well as most likely use more components and require a thicker steel thickness.

The customer requirement of a high density of storage was also directly correlated with the number of slides, the length of time to retrieve a slide, steel thickness, and weight of unit. This is because with an increased density there will be more slides in the unit resulting in more weight, thicker steel, and more time to move slides and get the one requested. We also expected that with more slides/volume it could increase the force needed to pull out a drawer and may cause more wear and tear on the system possibly limiting its lifespan. As the storage density increases, the volume for a set number of slides decreases.

The cost of the final product will increase with the number of components placed in the unit and the greater expected life of the unit since better/more materials will have to be used. Additional materials could also be needed for an increase in slide density or volume. However, with the purchase of better materials the unit's weight could decrease.

In order to have quick access to a requested slide the drawer will have to open and close quickly, meaning that the force needed to accelerate the drawer will have to be minimized. However, if the user opens or closes the drawer too quickly, the impact will lower the life expectancy of the system.

The manufacturability will be increasingly more difficult with the number of components used and require more precision with a long expected life of the unit. In order to make the product more user friendly, lowering the time to retrieve slides as well as the force needed to pull out the drawer will be required. The engineering specifications that could be used to keep the machine safe would be to keep the unit light weight and require small forces. With these specifications an accident would result in minor or no injury to an individual operating the system.

Having a higher number of slides per unit increases the chance of grabbing a wrong slide. Because of this the accuracy and reliability of the unit will be affected. Also, with a greater number of components a larger risk of failure is present, further reducing the accuracy and reliability.

By keeping a fewer number of slides, components, and less volume the unit will be easier to clean and maintain. A clean and maintained unit will extend the life.

The ability to automate the system will depend on how many slides are in the unit and how they are organized. The more slides that are in the unit, the more complex the retrieval device would have to be requiring more components and volume for these components.

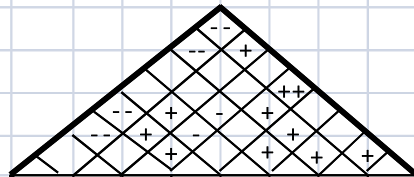
The stability of the unit will depend on its weight distribution and volume. How much force is being used to pull the drawers out and how quickly the slides are accessed can also affect the stability.

Table 2: Engineering Requirements

Engineering Specifications:	More/Less is Better
Number of slides per unit	(+) more is better
Number of components	(-) less is better
Length of time to retrieve slides	(-) less is better
Volume per unit	(-) less is better
Expected life of unit	(+) more is better
Force needed to pull out drawer	(-) less is better
Steel thickness	(-) less is better
Weight of unit	(-) less is better

Figure 8: Quality Functional Development (QFD)

Quality Function Development (QFD)



(+) => more is better
(-) => less is better

	Weight*	Number of Slides per Unit (+)	Number of Components (-)	Length of Time to Retrieve Slide (-)	Volume of Unit (-)	Expected Life of Unit (+)	Force Needed to Pull out Drawer (-)	Steel Thickness (-)	Weight of Unit (-)	*Current Out-Dated System* (Benchmarks)		
Size	9	9	3	1	9			1	9	5		
High Density of Storage	10	9	1	1	1	3	3	9	9	5		
Cost of Final Product	5	3	9		1	9	1	3	1	4		
Quick Access to Requested Slide	9	3		9		3	1			1		
Manufacturability	4		9			1		3		4		
Ease of Use	8		1	3			9			1		
Safety of Use	6						1	1	1	3		
Durability	8	3	1			9	3	9		3		
Ease of Cleaning/ Maintenance	4	1	9		1	1			1	3		
Reliability	9	1	9			9				3		
Ability to Automate	10	3	3		3		3			1		
Stability of Unit	7				1		1	3	9	5		

Measurement Unit	#	#	min	m^3	yr	N	mm	kg
Target Value	4500	40	5	0.02	50	3.2	1	10
Importance Rating	**10**	**5**	**10**	**8**	**7**	**5**	**6**	**4**
Total	280	281	124	137	263	183	225	249
Normalized	0.16	0.16	0.07	0.08	0.15	0.11	0.13	0.14
Current Out-Dated System	4200	47	120	0.02	50	2.2	1	10

Key:
9 => Strong Relationship
3 => Medium Relationship
1 => Small Relationship
(blank) => Not Related

CONCEPT GENERATION

In order to come up with some initial concept designs we used the FAST diagram (Figure 9 below) and morphological chart (Table 3 below). From these we created three different categories of concepts: automated storage and retrieval systems, automated storage systems, and optimized storage systems. Within these categories we came up with multiple concept designs. One design for each category is discussed below.

Figure 9: Fast Diagram

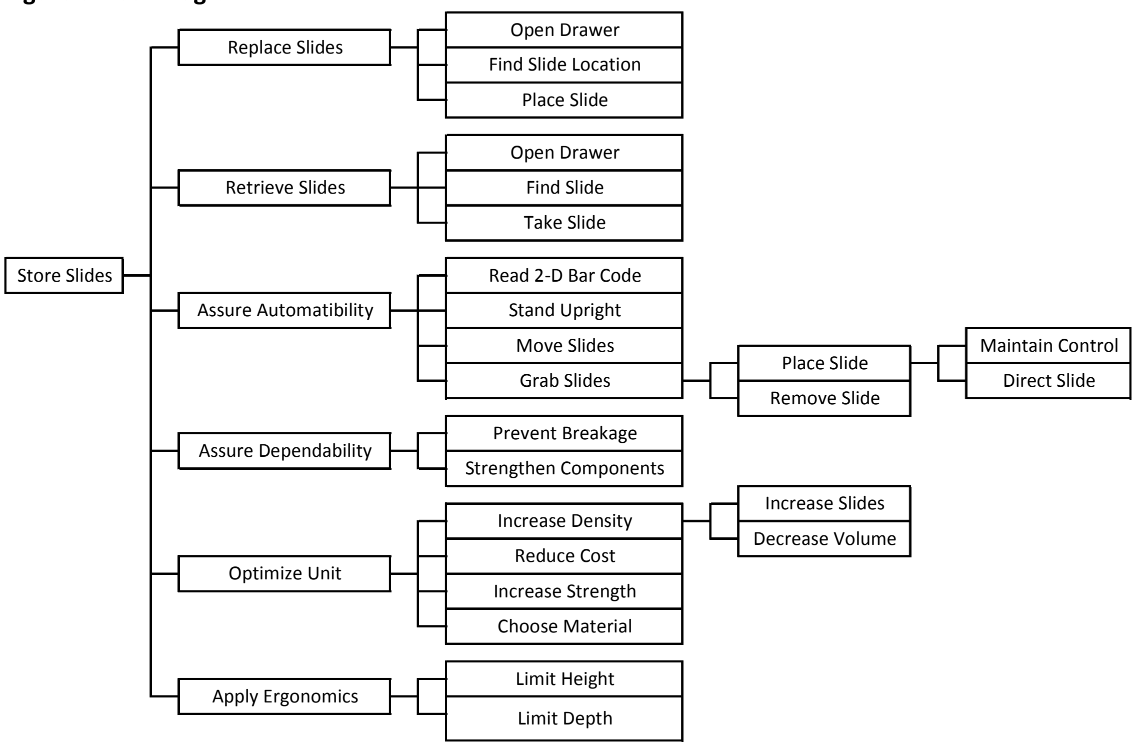


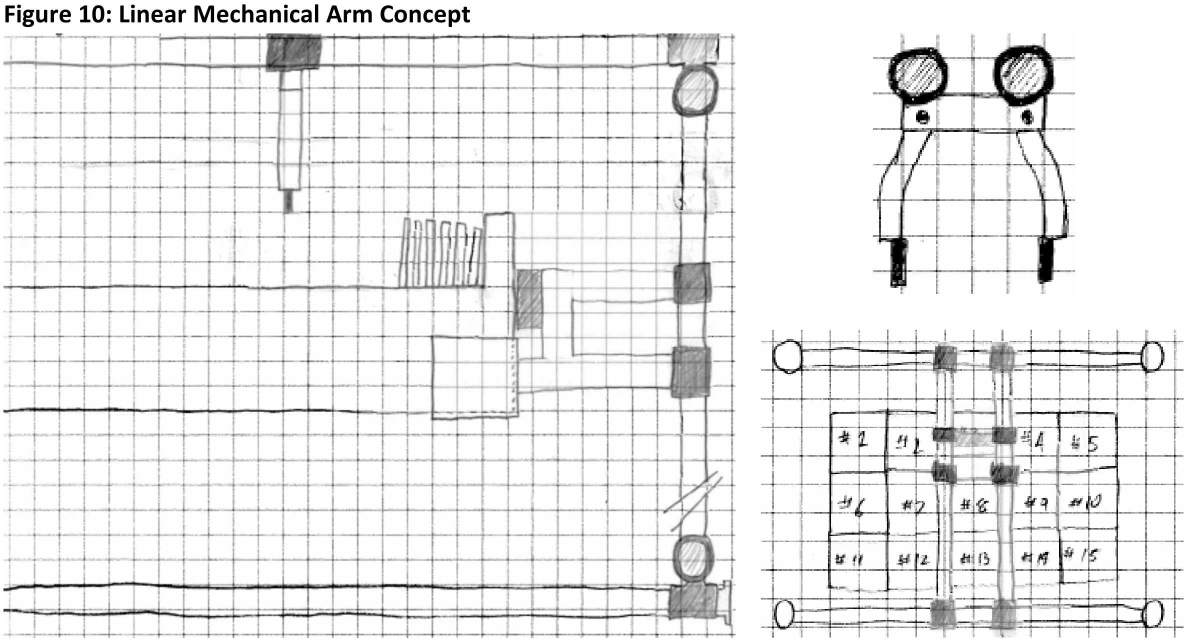
Table 3: Morphological Chart

Function	**Option 1**	**Option 2**	**Option 3**
Store Slides	Drawer System	Horizontal Carousel System	Vertical Carousel System
Replace Slides	Human	Mechanical Arm	Conveyor Belt
Retrieve Slides	Human	Mechanical Arm	Conveyor Belt
Assure Automatability	Create separation between each slide	Slides at constant angle	
Assure Dependability	Structural reinforcement	Thicker metal	
Optimize Unit	Drawers with two rows	Drawers with greater than two rows	
Apply Ergonomics	5th Percentile Female		

Automated Storage and Retrieval Systems: Linear Mechanical Arm

This system, seen in Figure 10 below, involves a mechanical arm attached to a drawer system. The arm could move along tracks in the x, y, and z directions. The drawers could be pulled out by activating an electromagnet that would attach to an individual drawer which would then be pulled out by the arm. Once the drawer was open the mechanical arm could then grab the slides with a form of pinchers. The slides, however, would have to have an assigned position and be spaced apart from each other. This whole system would be controlled by a computer program. This system allows for both storage and retrieval to be automated. At the same time it decreases the density of the slide storage by at least 50% and has to be very precise. Any error in the slide selection could prove disastrous for the hospital. This system would most likely be very expensive and would require a fair amount of time to design and build.

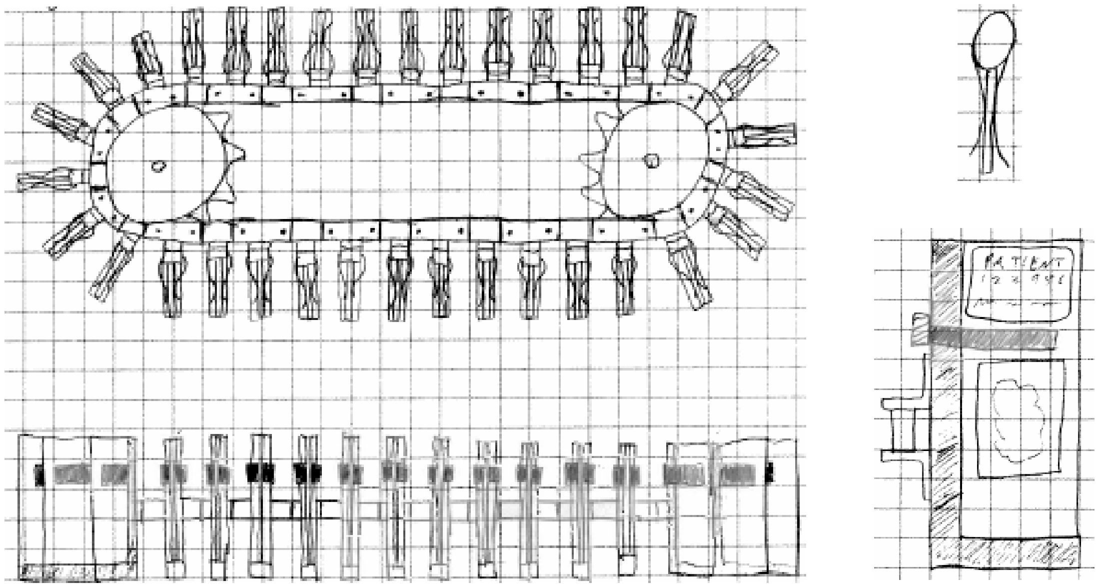
Figure 10: Linear Mechanical Arm Concept



Automated Storage Systems: Horizontal Slide Carousel

This system holds the slides on a type of carousel track and is shown in Figure 11 on page 15. Slide holders with a spring clip that provided enough friction to hold the slides in place would be attached to a special kind of chain that has built in mounting points. The chain would in turn run on sprockets which were attached to a motor. This system would be controlled by a computer program that would rotate the carousel system so that it brought the selected slide to the front. This system allows for quick retrieval of slides but decreases density by 80 – 90%. It would also be very hard to create and use the controls necessary for this system to function properly.

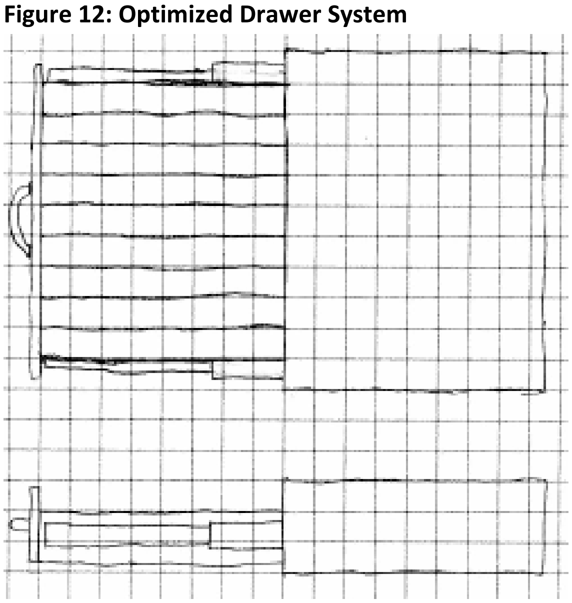
Figure 11: Horizontal Slide Carousel



Optimized Storage Systems: Optimized Drawer System

This system holds the slides in a similar, but optimized drawer system. As shown in Figure 12 below, Instead of having multiple drawers per unit this will have one drawer, eliminating the wasted space between the drawers. Also, it will be attached to sliding bearing tracks allowing for the drawers to be easily opened and keeping them level. The size of the drawer will be determined by the strength of the steel used and dimensions appropriate for the 5^{th} percentile female. Metal partitions between the rows of slides will be used so that they no longer break and mix the slide and a new metal handle will be chosen so that it doesn't easily break and distributes the pulling force of opening the drawer.

Figure 12: Optimized Drawer System



CONCEPT EVALUATION AND SELECTION

After we formulated our preliminary designs we had to evaluate them in order to find the best one. We focused on the top customer requirements- having a high density of storage and the ability to automate, while keeping the lesser customer requirements in consideration. We narrowed our selection down to our two top designs. The first design was chosen from the carousel designs. We chose the horizontal carousel because we felt that there would be less wasted space and since there is a vertical ceiling limit, the vertical carousel design as seen in Figure A.1 of the appendices would not be optimized. The other design we choose did not incorporate an electrical power requirement and focused more on the optimization of slide storage.

In order to compare these two designs we formulated a Pugh Chart which can be seen in Table 4 below. The optimization design was calculated to be the best choice using the Pugh chart because it proved to have a higher density; less size restrictions; and was more durable, cheaper, and easier to manufacture due to the less moving parts and precision components. While the slide carousel design would require less human power, the density of storage would decrease from the current storage system to about one tenth of the current Fisher Scientific. In addition to these reasons, our team also thought that slide carousel design did not use the same amount of engineering principle since with the available parts on the market; the components would not be at a high stress relative to their absolute strengths. The design focused more on the appearance of an entertaining design and less on the functionality and engineering behind a quality design that would better fit our customers.

In order to make sure that we were making the proper design selection, our group visited the hospital and met again with our sponsors, and the secretaries, nurses, and doctors who have direct contact with the current system. They agreed that the density of storage had the higher priority and felt like the horizontal carousel design would not benefit them as much. In addition to this they also gave us a list of specific problems and benefits with the current system which we would later use when refining our optimization design. We wouldn't have been able to implement these if we chose to use the horizontal carousel design.

Table 4: Pugh Chart Comparing Top Two Designs

	Weight	**Datum**	**Option 1**	**Option 2**
Evaluation Criteria		Current Fisher-Scientific Design	Slide Carousel	Optimization
Density	10	0	-	+
Ability to Automate	10	0	+	+
Size	9	0	-	0
Reliability	9	0	-	0
Durability	8	0	-	0
Stablitity of Unit	7	0	0	+
Safety of Use	6	0	-	0
Cost of Final Product	5	0	-	0
Easy of Use	4	0	+	+
Manufacturability	4	0	-	-
Total		0	-37	27

SELECTED CONCEPT

The design we have selected will be the most beneficial as well as provide the easiest transition as a replacement for the current storage system used by the University Hospital; it solves all of the issues communicated by our sponsors and the users of the system. Figures 13-15 below show a preliminary CAD model of our complete storage drawer.

Figure 13: Preliminary CAD Model of the Selected Concept

Figure 14: Bottom View of the Selected Concept, Close-Up on "Hook" Feature

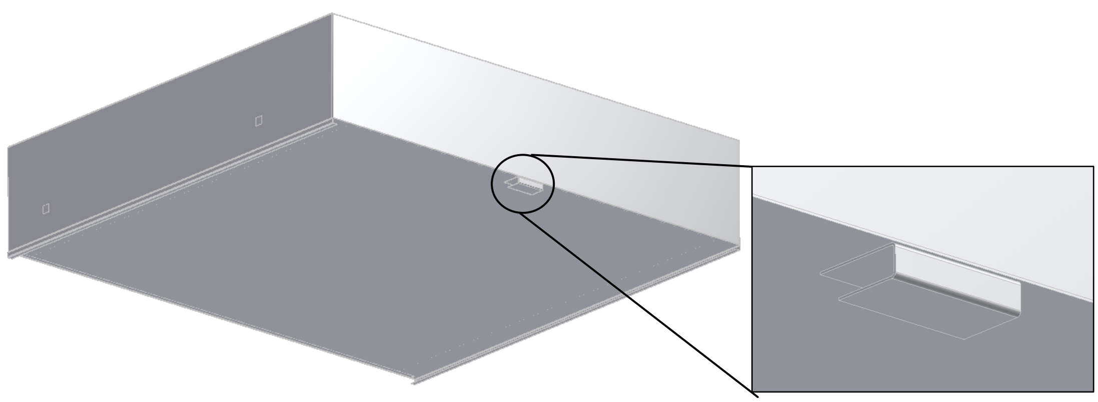
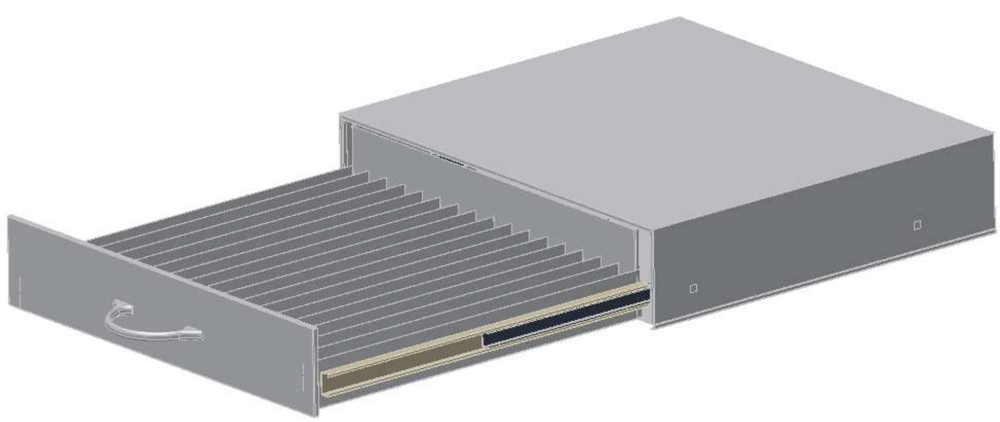


Figure 15: Selected Concept with Drawer Fully Extended



This model shows some of the major changes that have been made to the current design. We increased the density of slides by removing the central pillar and using one large drawer instead of six small ones. The use of slider bearings (see Figure 18, page 19) counters the added weight and keeps the maximum force required to open the drawer equal to the force required in the current system. Also, the sliders support the drawer in a horizontal position, reducing required human interaction (no need to hold the drawer upright) and increasing the system's ability to become automated. The "hook" on the back of the unit has been redesigned to be strong enough to prevent the unit from tipping or rotating towards a user when a full drawer is completely extended, and is now less deformable, making assembly and disassembly of the structure easier. We have also incorporated a device that will force the slides to lie at a angle. This provides some space to allow users to more easily flip through slides, and will ease the transition to an automated system in the future.

To develop dimensions for the frame, drawer, and hook structure, we had to consider the engineering principles we have learned. The thickness of the material and the overall width of the drawer have been determined by analyzing the properties of materials available and determining bending moments caused by the added weight of multiple rows of slides. When the drawer is filled with slides and fully extended, it will cause the back of the unit to rotate upwards; we have designed a hooking mechanism that can withstand this force and keep the unit safely in place during use.

Figures 16-17 show partially dimensioned drawings for our CAD model with all dimensions given in millimeters. All dimensions given are estimates, and any missing dimensions had not been determined yet at this stage of our design; all are dependent on the engineering analysis of our system. We set up an Excel file which contains all of the relevant equations and constraints needed to determine the critical dimensions for our design, and have used Solver to help us determine final dimensions for our unit.

Figure 16: Dimensioned CAD Drawing of the Frame

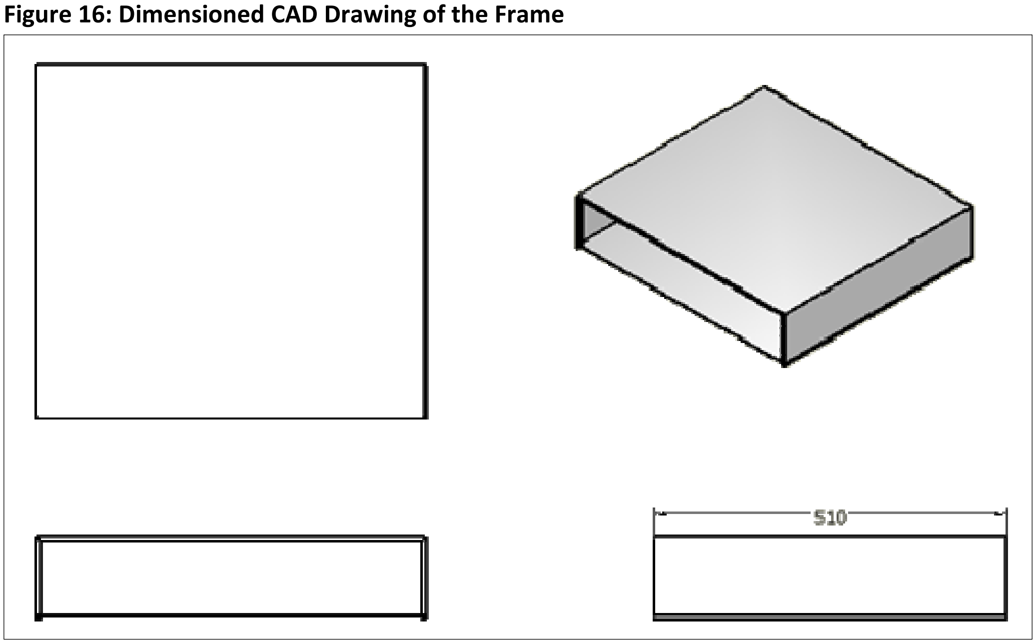
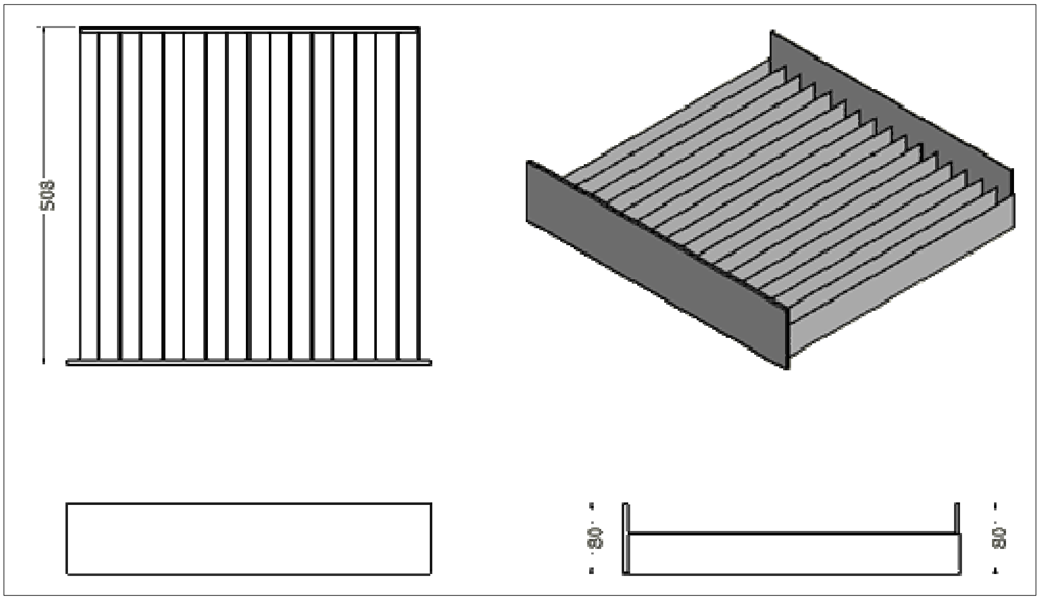


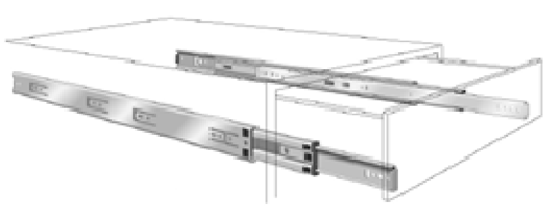
Figure 17: Dimensioned CAD Drawing of the Drawer Structure



The dimensions shown were decided based on ergonomic and safety issues. The overall depth of the drawer structure is limited to 508mm, which is approximately the reach of a 5th percentile adult female; this limitation will ensure that any person will find this design easy and comfortable to use. The overall depth of the frame is slightly larger at, ensuring that the drawer does not come into contact with the frame while closing; this will help increase the life of the unit by preventing excessive fatigue to the frame. The overall height of the drawer is constrained to be at least 80mm, which is slightly higher than the longest side of a microscope slide. This is a safety feature for our unit, and will ensure that if a user inadvertently closes the drawer while the slides are vertical, the slides will not accidently catch between the drawer and frame, preventing breakage.

Our prototype is comprised of both hand-made and store bought parts. The frame and drawer structure are made out of low-carbon steel sheet. We have considered which type of steel would best suit our needs for ease of fabrication; the sheet metal was bent and welded into the final design in the ME450 machine shop. The drawer slides were purchased from a supplier; since our drawer depth is 508mm (20 in.), we chose a drawer slide of an equal length with full extension, ensuring the entire drawer is clear of the frame when open. An example of this component can be seen in Figure 18, below. An ergonomically appealing handle that can withstand the force required to open the drawer was chosen from a supplier.

Figure 18: Example of a Drawer Slide to Be Used in Selected Concept



ENGINEERING ANALYSIS

Variable Optimization

Some key variables in designing our prototype were the dimensions of our unit and the choice of materials, components, and suppliers. Because the hospital personnel that used the current system had a very negative feeling about the use of anything plastic in the unit, we decided to fabricate the whole unit from metal. After researching other storage systems on the market, we decided to use a low carbon steel, unpolished AISI 1006-1018, because we wanted to maintain a low cost and steel has proven to be useful with our competitors. Since the project is short-term and we need materials quickly, we chose McMaster-Carr as our key metal supplier because of their fast delivery time and available in-stock items. Because the steel supplier has limits on their available steel thickness, we choose a range of thicknesses from the company and ran them through our solver to find the one that best maximized our density with keeping a low cost, which was 0.76 mm.

Since our sponsors stressed the importance of the ease of use, we chose to set the depth of the drawer to the arm reach of the bottom 5th percentile female, which was 20” or 508 mm. The height of the drawer was set to be slightly larger than the slide height. This was because if the height was smaller than the slide there would be a high possibility of breaking the slide while closing the drawer and too large of a height would decrease the storage density. To set the width of our drawer, we had to analyze the internal bending moments on the drawer. We calculated the bending moment to reassure that the maximum stress induced by the weight of the slides was not going to exceed the yield stress of the metal that we decided to use. By assuming that the dividers within the drawer provided minimal weight in comparison to the slides, the dividers were neglected. The weight of the slides was assumed to be a distributed load determined by the maximum number of slides a row could hold. The slider bearings were assumed to support the drawer similarly to a simply supported beam, allowing for beam theory to be used. This assumption needed to be made since plate theory is out of the discipline of undergraduate studies. These assumptions provided the equations:

$$M_{Max} = M\left(x = \frac{r * w_b}{2}\right) = \frac{m * s * g}{w_b} * \frac{r^2 * w_b^{\,2}}{8} \qquad \text{Eq. 1}$$

$$\sigma = \frac{M * y}{I} = M_{Max} * \frac{t}{2 * I} \leq \frac{\sigma_Y}{2} \qquad \text{Eq. 2}$$

where M is the internal bending moment, m is the mass of a slide, s is the number of slides in a row, g is the gravitational constant, 9.81 m/s^2, r is the number of rows in the drawer, w_b is the width of a row, σ is the stress due to the moment, t is the steel thickness, I is the second moment of area of the cross-section, and σ_Y is the yield stress of our steel.

Along with the moment analysis, the maximum deflection found under the load needed to be limited. The deflection was set to be less than 2 millimeters so that it would not exceed the space between the drawer and the outside unit. The angle of deflection was also examined since a large angle will cause the row dividers to sit at an angle similar to that of the angle of deflection. This would cause the width of the row to be reduced at the top of the dividers, potentially clamping the slides and damaging them. This change in row width needed to be less than 2 millimeters, the difference between the width of a row and a slide. The equations for this analysis are seen below.

$$v(x=\frac{r*w_b}{2})=v_{Max}=-\frac{5*m*s*g*(r*w_b)^4}{384*w_b*E*I} \qquad \text{Eq. 3}$$

$$\theta=\frac{dv}{dx}_{Max}-\frac{dv}{dx}(x=w_b)=\frac{m*s*g}{w_b*E*I}*\left(\frac{4*w_b^{\,3}-6*r*w_b^{\,3}}{24}\right) \qquad \text{Eq. 4}$$

In these equations, *v* is the deflection, *E* is the Young's modulus of our steel, and *ϑ* is the difference between our largest angle of deflection at the ends and the angle of deflection one row away from our max. For a more detailed explanation of how we reached these equations, look at Appendix B, C, and D.

Another design constraint that we needed to satisfy was to develop a system that would adequately hold the back of the unit down and prevent it from flipping. This would be a large issue when the drawer is fully loaded with slides and pulled completely open. We found the force needed to hold the back down with Eq. 5. To satisfy this constraint we used two captive fasteners that were made to handle shear loads up to 5400 N.

$$N=\frac{(W_d-W_f)}{2}+\frac{m*g*s*r}{2} \qquad \text{Eq. 5}$$

The variables used for our engineering analysis and their constraints are shown in the table below. A safety factor of 2 was used in all constraints. These values were placed in an optimization solver in Microsoft Excel to determine the optimal values that remained under the limits of the constraints while maximizing the density of storage. Please see table below for specific values. . The optimal width of the drawer to maximize the storage density was found to be 760 mm, which allows for 26 rows of slides.

Table 5: The equations, functions symbols, and constraints in our optimization solver

	Variables	Values	Constraints
Depth	D	508 mm	<= 508 mm
Height	H	78 mm	>= 76 mm
Width	W	26 rows = 760 mm	
Steel Thickness	t	0.76 mm	Set by availability
Max Stress	*σ*	1.29 MPa	< 193 Mpa
Max Deflection	*v*	1.000 mm	< 1 mm
Max Angle of Deflection	*ϑ*	0.000031 rad	< 0.082 rad
Slide Density	ρ_s	9126 slides/unit	> 4500 slides/unit
Force on Back	*N*	442 N	< 2700 N

From our solver, the constraint that was first to limit our design was the maximum deflection of the center of the drawer. This reached one millimeter before any other constraint became an issue. Through using this optimization, we were able to produce a slide density of 8681 slides per unit, an increase of 32.5% of slides per volume.   The solver used to determine the optimal values can be found in Appendix E.

Finite Element Analysis

Using beam theory as a mode of engineering analysis, we were able to calculate estimated values for the expected stress and deflection for our drawer and subsequently determine the dimensions for our final design. However, since the drawer is made out of a large rectangular steel sheet with dividers acting as "ribs" for reinforcement, it may not behave exactly like a beam. Therefore, we decided to employ finite element analysis (FEA) software to verify that our fully loaded drawer will not fail.

We used Altair HyperMesh 8.0 software to develop a finite element model (FEM) for a simplified version of our final drawer design. The FEM consists of the drawer's bottom panel, its folded sides, and each of the 26 folded dividers. Sharp 90° angles were used at any point where there would be a bend in the metal: this gives us a "worst case scenario" model, since stresses should be greater on sharp corners than they would be on a curved bend.

Both the bottom and the dividers were modeled with a material of thickness 76 mm, a stiffness factor of 190 GPa, and a Poisson's ratio of 0.3. The dividers rest on the top surface of the drawer bottom and are "spot welded" in place by fusing only certain points together within the program. Since in reality a weld will be stronger than the material around it, this technique gives us a good representation of the stresses and displacements around these weld spots.

After generating a model, we added proper forces and constraints to the components. Individual point forces were added for every 5 slides in a row: with 400 slides per row and 26 rows, this yielded a total of 510 N distributed force across the surface of the dividers and bottom. Several points along the left and right sides of the drawer were constrained from translation in the X, Y, and Z directions to simulate the reaction forces applied by the drawer sliders, which will be attached to the drawer at specific points. Since these sliders move along roller bearings we did not constrain any degrees of freedom corresponding to rotation of the drawer at these points.

We also did a stress analysis on each model and discovered that due to the gaps between the folded sides of the bottom panel, a stress concentration develops in the corners of the bottom panel that contains very large stresses, with a maximum of 325 MPa, as seen in Figure 19. Although this is below the yield stress of our material (386 MPa), we still want to apply our safety factor of 2. Therefore, to reduce this stress, we have designed a front and back panel for the bottom that will connect all of the folded sides together via spot welds. This will prevent our drawer from bending or cracking at the corners and will minimize these high stress concentrations.

One of our main concerns in the generation of our design is the amount of deflection the drawer will experience. Since the dividers add structural strength to the bottom panel of the drawer, we have used our FEM to determine how many spot welds we should use along the touching surfaces. Since our design will only allow for a 2mm deflection, we need to apply our safety factor of 2 and deduce that our model should not deflect more than 1mm when fully loaded. A comparison of the deflections in three models is shown below. The first, second, and third model represent a drawer with three, four, and five spot welds along each divider, respectively (Figures 20, 21, and 22). As you can see from the images, the last model in Figure 22 shows a fairly evenly distributed maximum deflection of approximately 1mm along the entire bottom of the drawer. Therefore, we have decided to consider five spot welds as the minimum safe number of welds when attaching our dividers to the bottom panel of the drawer.

Figure 19: Contour Image of Stresses (Maximum Stress = 325 MPa < Yield Stress = 386 MPa)

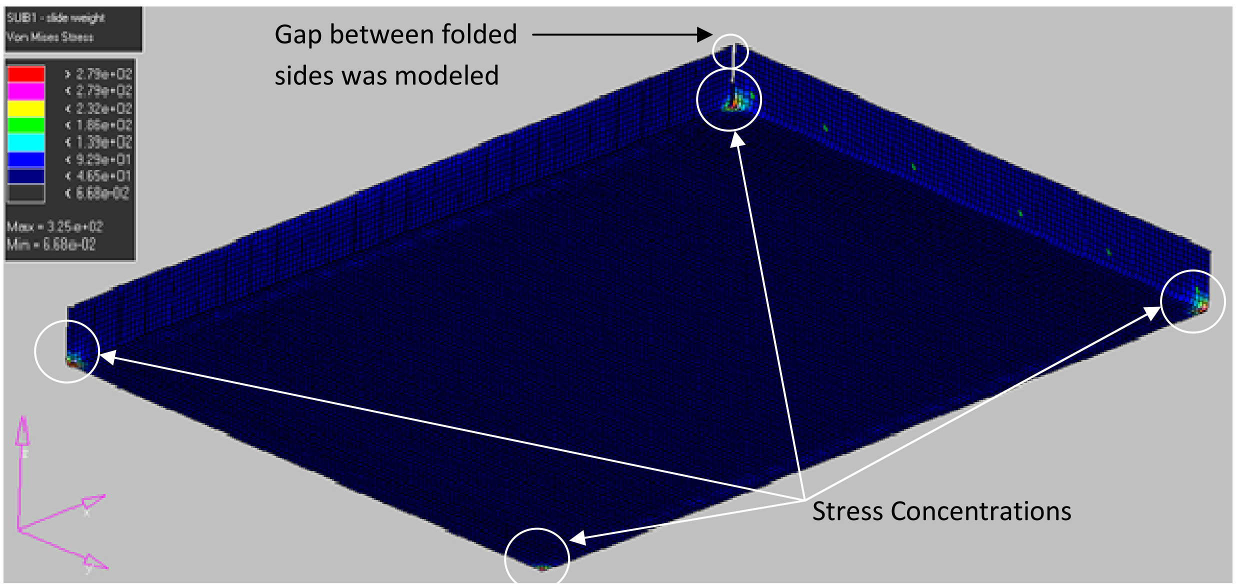


Figure 20: Bottom View: Contour of Deflections with 3 Spot Welds along Divider (Max = 1.27mm)

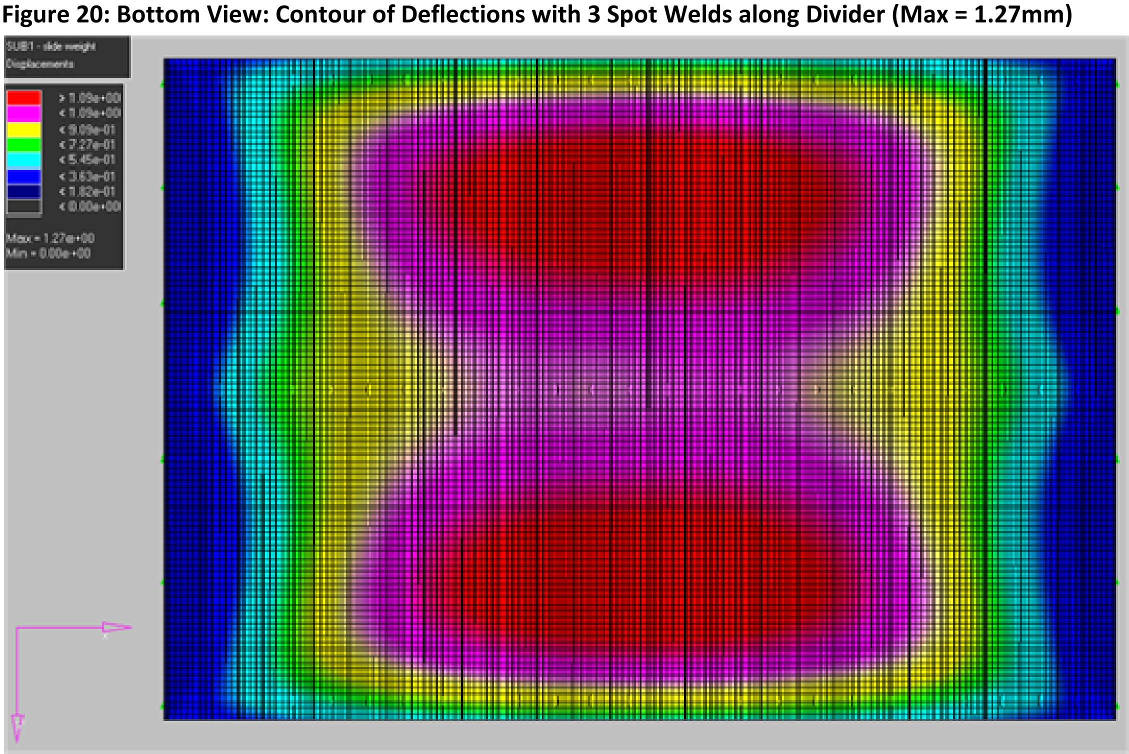


Figure 21: Bottom View: Contour of Deflections with 4 Spot Welds along Divider (Max = 1.13mm)

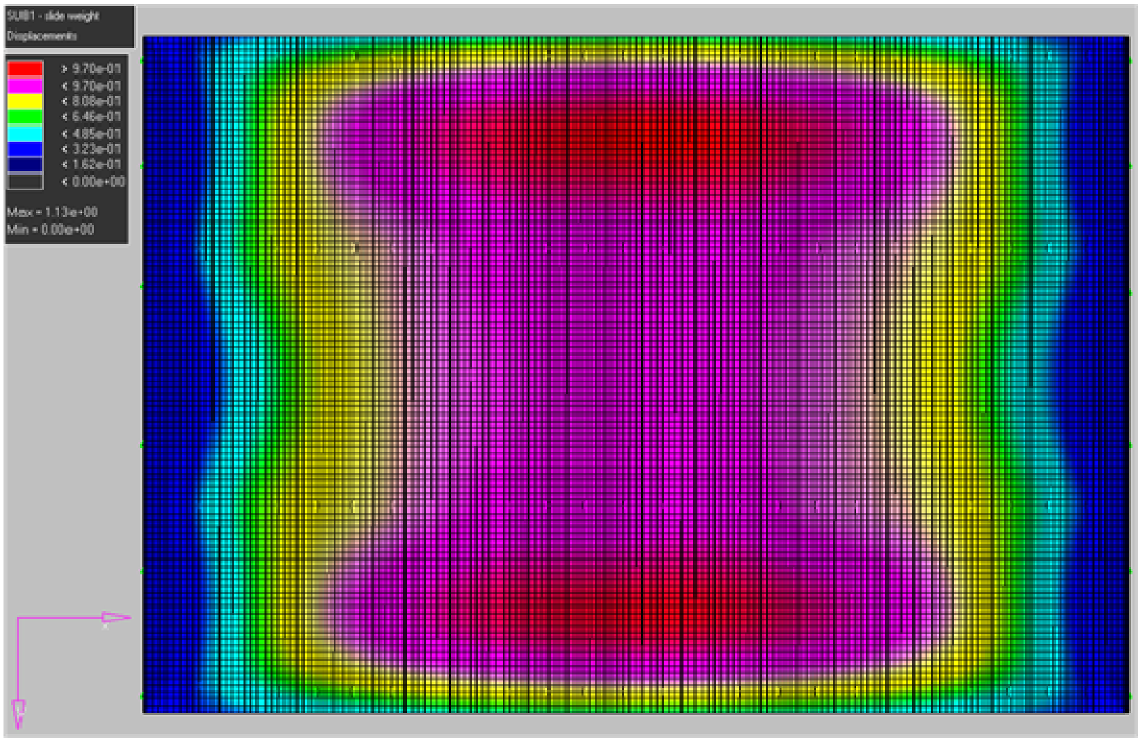
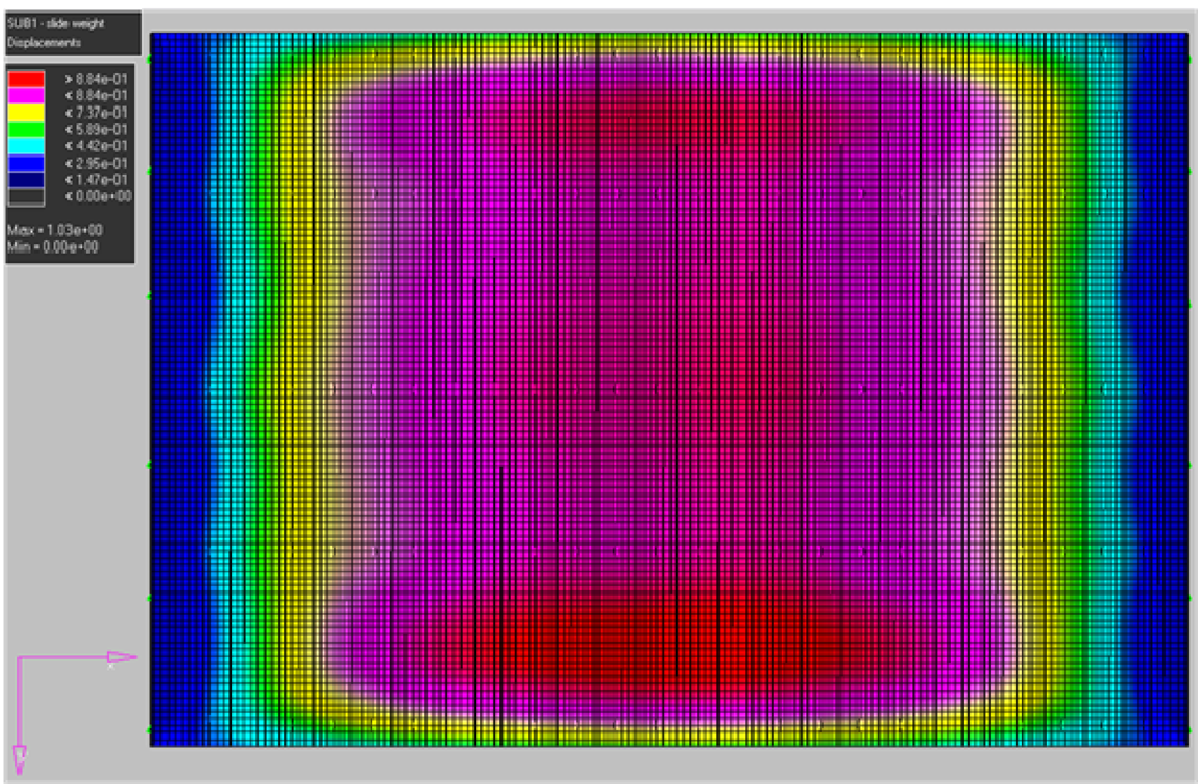


Figure 22: Bottom View: Contour of Deflections with 5 Spot Welds along Divider (Max = 1.03mm)



FINAL DESIGN

After considering ergonomic and manufacturing limitations and applying engineering analysis to our selected concept, we have developed the final design of our optimized pathology sample storage system. A CAD drawing for our entire assembled mock-up prototype of our final design, is shown below in Figure 23.

Figure 23: CAD Model of Final Design (Closed and Open Respectively)

Fully dimensioned CAD drawings for each part are discussed below and are located in Appendix F. [Note: Any references to scales are intended for original drawings printed on 8.5"x11" paper only, and may be slightly skewed.] The included sheet metal bend radii apply only to the prototype and will be smaller for mass production due to different fabrication techniques.

We fabricated a working mock-up prototype, shown below in Figure X, to give our sponsors and others a visual, interactive representation of our final design. However, it is not a true prototype, since we had to make some sacrifices in our final design due to limitations in manufacturing process. For example, our mock-up is much heavier than our final design is intended to be due to excess material that would not be incorporated in the production version. All of the differences between our proposed final design and the actual mock-up created will be explained in detail in the following sections.

Figure 24: Fabricated Mock-Up of Final Design

Drawer

The drawer sub-assembly shown in Figure 25 was fabricated entirely of sheet metal and presented at the Design Expo. Figure 27 also shows an explosion of how the parts fit together (all of the dividers except for one have been removed for visual clarity). It contains 26 rows separated by dividers which can each hold approximately 334 microscope slides if filled to maximum capacity (including the slide support described in the following sections). We added support to the bottom panel of the drawer by attaching extra front and back pieces that hold the folded sides together and remove any material gap generated from bending. The drawer's weight is supported above the bottom panel of the frame on both sides by slider bearings, discussed in the next section, which allow the drawer to easily roll open and closed. To improve aesthetic appeal, an extra piece is attached to the front which is wide enough to cover these bearings.

Figure 25: Drawer Sub-Assembly

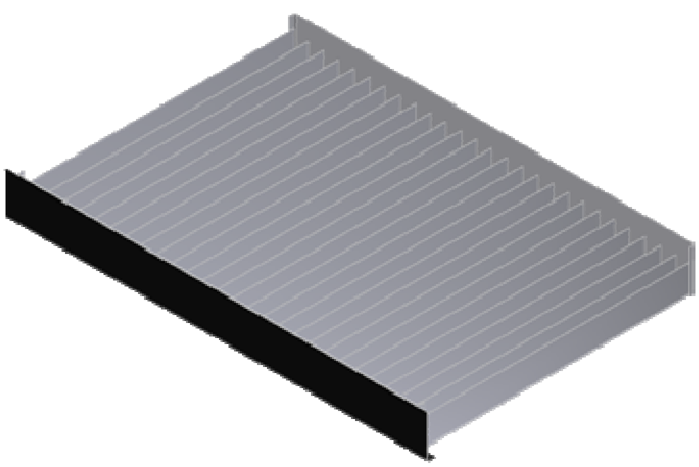
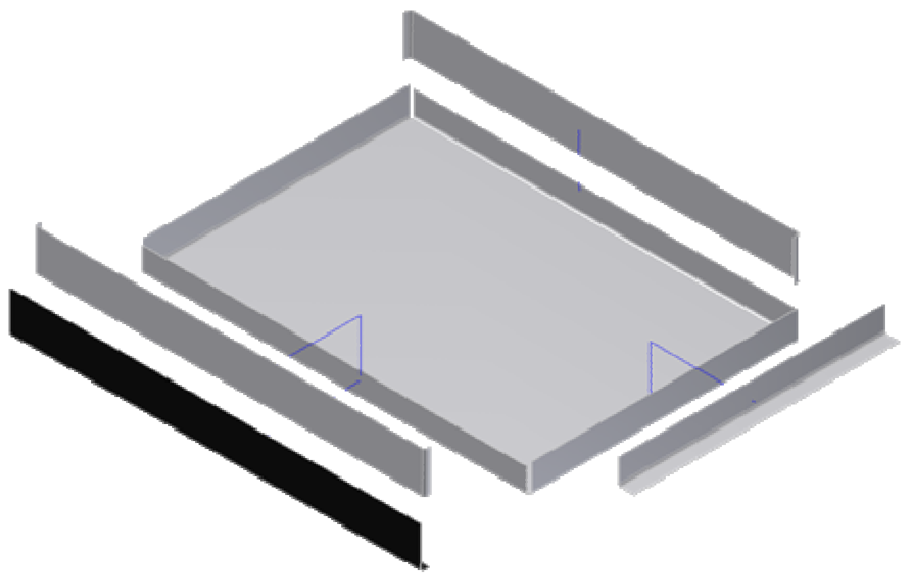


Figure 26: Mock-Up Version of Drawer (with some slides)

Figure 27: Explosion View of Drawer Sub-Assembly



Due to the large bending radius incorporated in fabrication of our mock-up, small gaps exist between the dividers and the front/back folded sides of the drawer, which slides can become stuck in. The large radius also caused some of our dimensions to be slightly larger than desired, resulting in a drawer longer than the 20” long slider bearings: this meant the mock-up drawer cannot be pulled completely out of the frame, and it would still be hard to retrieve a slide at the back of the drawer. These characteristics are not intended for our final design: when using stamped metal, the bend radius will be much smaller, eliminating this hazardous gap from our product and returning the drawer to the correct size.

Slider Bearings

The slider bearings we will be using in our final design have been purchased from CabinetParts.com, and are shown in Figure 28. They are labeled as "full extension" sliders and should allow the drawer to pull out and clear the frame completely. This feature ensures that all slides are easily accessed, including those in the very back of the drawer. A small catch at the end of these slides prevents the drawer from rolling open on its own.

Figure 28: Purchased Slider Bearings, 20" Long with Full Extension

Frame

The frame sub-assembly shown in Figure 29 is what we built specifically for presenting purposes and for the Design Expo; it is unique to our mock-up and was designed due to manufacturing constraints. Ideally, we would have liked to fabricate the frame using a mold and a press to create a "box" of sheet metal. To avoid bending and welding various sheets together due to lack of precision, we had to improvise to maintain an aesthetically pleasing appearance. As seen below in Figure 30, the frame was created using steel angle parts welded together to form 90° angles, and steel sheet "panels" which attached to the surfaces of the steel angle structure via steel rivets.

Figure 29: Prototype Mock-Up of Frame

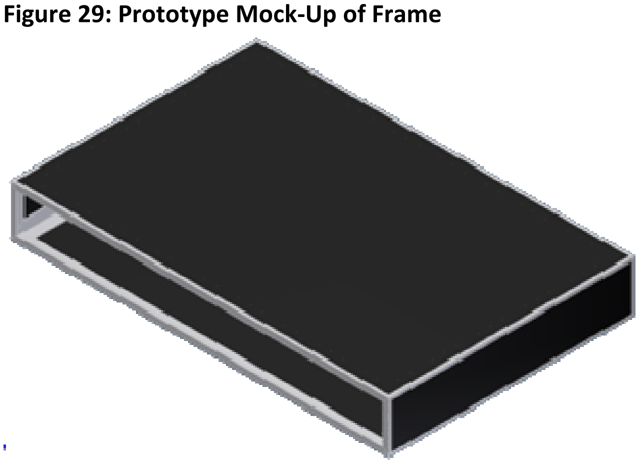
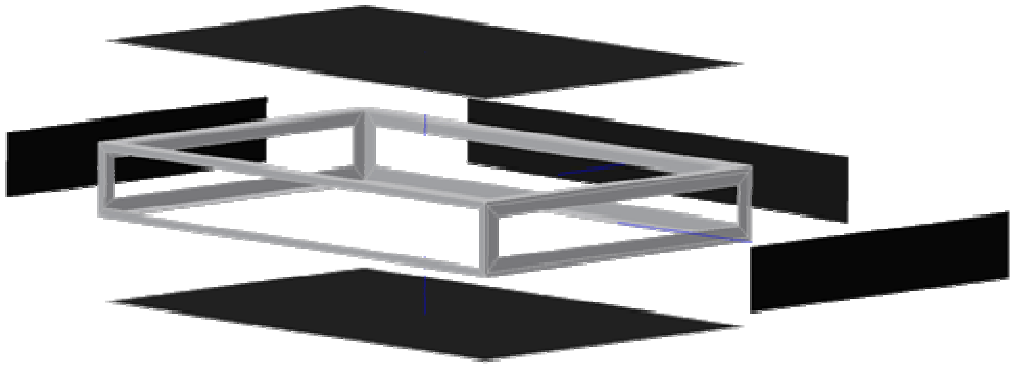


Figure 30: Frame Structure and Shell Explosion

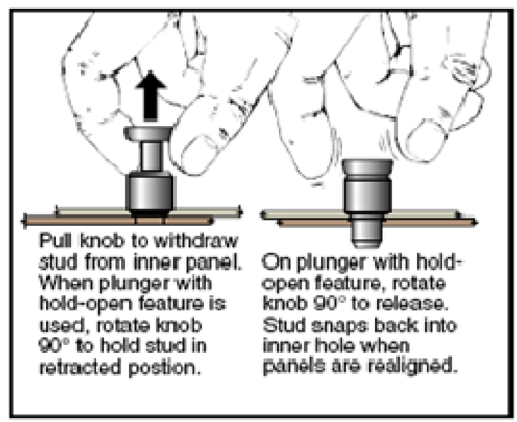


New Features

In the case that a customer wants to stack multiple units on top of one another, we have incorporated spring loaded fasteners to reduce the hassle in safely attaching a drawer to the one below it. The plungers purchased from SouthCo, shown below in Figure 31, will remain open when twisted 90°, and will snap back in place when twisted another 90°. An illustration of this movement is shown in Figure 32.

Figure 31: Spring-Loaded Fastener Chosen

Figure 32: How to Use the Fasteners



These fasteners allow the user to open the plungers, use both hands to place the drawer system in the correct location, and then close the fasteners to lock the system in place.

Figure 33: Close Up of Plunger Assembled in Drawer Unit

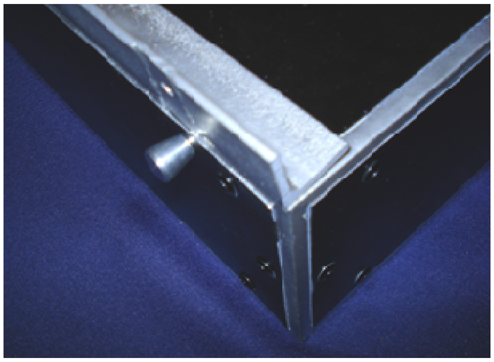
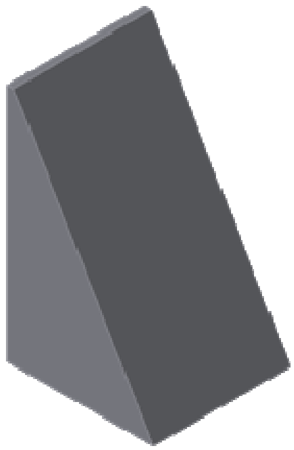


Figure 34: Back View of Mock-Up Drawer with Attached "Simulated" Bottom of Second Drawer

Included as an accessory to the drawer sub-assembly is the “slide support” shown in Figure 35 on the left. This part will be used to force the slides to lie at an angle of 60°, which allows about 0.6mm of the top edge of each slide to be visible (see Figure 37). The angle will increase the user-friendliness of the drawer system, since viewing the label of any individual slide will be much easier. Instead of having to pull a slide vertically out of the row in order to view the label, a user can “flip” through slides to find the one he/she is looking for. For simplicity, a mock-up of this feature was created using a single piece of bent steel sheet, as shown in Figure 35 on the right: a magnet was placed on the bottom to prevent the weight of the slides from moving the support out of place, and will also be incorporated in the final design.

Figure 35: Slide Support to Hold Slides at a 60° Angle – Left, Final Design – Right, Mock-Up



The final improvement in the drawer sub-assembly is the “case divider”, shown in Figure 36. Due to the 32.5% increase in density of slides per storage space we have achieved with our design, we have justified incorporating a part that will physically divide up individual patient cases. The divider is 2 millimeters longer than a microscope slide, and will help to reduce the time required to find a specific slide. Approximating each case as 15 slides, we would need to replace about 579 potential slide spots with a divider: therefore, even with dividers, our density remains about 23.7% greater than our baseline, the Fisher Scientific system.

Figure 36: Case Divider

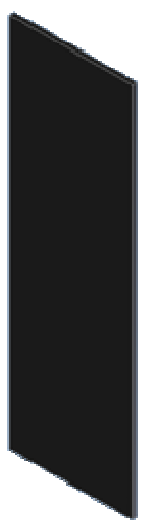
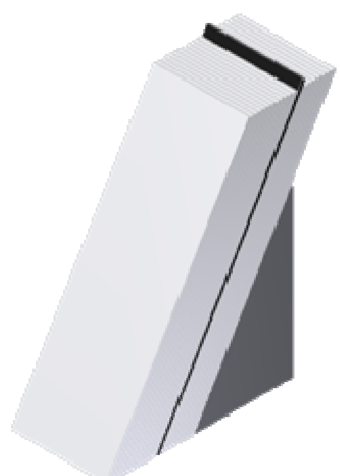


Figure 37: Slide Support and Case Divider in Use



Bill of Materials

The materials and components purchased for the fabrication of our prototype are shown below, in Table 6. The total expenses of our prototype added up to be $402.06. This placed us only $2.06 over our budget.

Table 6: Bill of Materials

Part	Description	Ordered From	Part No.	Quantity	Nominal Price	Tax/Shipping Cost	Total Price
Unit Panelling	Low carbon steel sheet, .036" thick x 48" x 48"	McMaster-Carr	8943K26	1	$54.20	$53.51	$107.71
Drawer Dividers	Low carbon steel sheet, .0299" thick x 48" x 24"	McMaster-Carr	6544K19	2	$21.76	$11.25	$54.77
Drawer	Low carbon steel sheet, .0299" thick x 36" x 24"	McMaster-Carr	6544K17	2	$18.33	$8.50	$45.16
Drawer Slides	20" full extension, max load 200 lb, zinc	Cabinet Parts.com	KV-880020	1	$32.55	$10.57	$43.12
Unit Frame	A-36 steel angle, 8' by 1"x1"x1/8"	Metals Depot	A11118	3	$9.60	$18.86	$47.66
Unit to Unit Fasteners	3/16" Lock Hold Captive Fastener	Southco	56-10-301-20	20	$0.00	$0.00	$0.00
Paint	Spray, S-G Black	Carpenter Brothers	N/A	1	$4.79	$0.29	$5.08
Paint	Spray, Aluminum	Carpenter Brothers	7715-830	1	$4.79	$0.29	$5.08
Rivets	Rivet,Stl3/16x1/4	Carpenter Brothers	N/A	1	$2.99	$0.18	$3.17
Rivets	3/16" Aluminum Rivets	Carpenter Brothers	N/A	1	$2.99	$0.18	$3.17
Rivet Gun	Tool, Rivet HD	Carpenter Brothers	MR55C5	1	$19.99	$1.20	$21.19
Clear Coat	Spray, Clear	Carpenter Brothers	7701-830	1	$4.79	$0.29	$5.08
Handle	Pull <A>	Home Depot	22788797835	1	$4.99	$0.30	$5.29
Bearing Grease	White Lithium Grease	Home Depot	N/A	1	$3.49	$0.21	$3.70
Handle Screws	#8-3/8" Screws	Home Depot	N/A	1	$1.29	$0.08	$1.37
Painter's Tape	Scotch Long Mask Tape	Carpenter Brothers	2090-2	1	$10.99	$0.66	$11.65
Magnets	7/8x7/8x3/8 Blokmg	Carpenter Brothers	N/A	1	$2.49	$0.15	$2.64
Primer	Spray, Primer Gray	Carpenter Brothers	1268	1	$3.49	$0.21	$3.70
Packing Supplies	Box, Lydn Wrdrbe, 3.3 CF 36x21x10	U-Hual	LW	1	$5.95	$0.36	$6.31
Packing Supplies	Roll, Enviro Bubble, 8 mm 12"x100	U-Hual	BP8	1	$19.95	$1.20	$21.15
Paint	Silver	Jack's Hardware Store	N/A	1	$4.79	$0.29	$5.08
						Spent:	**$402.06**
						Remaining:	**-$2.06**

To manufacture our prototype, three parts were purchased: a set of plungers from Southco, a set of bearing sliders from Knape & Vogt, and a handle from Knob Hill. All of the other parts were manufactured in-house from various purchased materials. The bottom and sides of the drawer, as well as the front and back will be made from 0.030" thick low carbon steel sheet. Drawer dividers will be made from 0.029" thick low carbon steel sheet. And the frame of the unit will be made from 1" x 1" x 0.125" low carbon angle steel, while the paneling will be made from 0.036" thick low carbon steel sheet. All of the sheet metal was purchased from McMaster Carr and the angle steel was purchased from Metals Depot. All of the steps for manufacturing and assembly are shown in our process plan, figure X, in the appendices.

For mass production the manufacturing process will change. In the prototype, angle steel was is used to make a 90 degree corner that we would be unable to get through metal bending. For production the sheet metal would be stamped into form, eliminating the need for angle steel. Metal stamping will reduce the number of parts needed as well as the amount of sheet metal. It will also reduce the manufacturing time per unit. This will dramatically decrease the cost per unit while increasing the strength and life of the unit.

TESTING

In order to make sure our final prototype matched the required specifications, some tests needed to be conducted. We wanted to verify the force needed to open the drawer, the moment on the back of the drawer, and how much weight the drawer can hold before deflecting enough to make contact with the frame. The outcomes of our testing can be seen in Table 7 below. These tests were done by evenly distributing weights up to 289 N, the loaded weight at which point the bottom of the drawer began to touch the frame, and measuring the forces with a Chattilon scale. The force needed to open the drawer, though not far below the 32 Newton limit we set, is increasing slow enough with increased load that we feel that it will remain under that limit with a full load. The force of the moment on the back of the drawer is far below the 5400 N limit as set by the maximum shear the plunger fasteners can withstand. However, as mentioned, the drawer made contact with the unit when the force of the load was 289 N, below the approximated 490.5 N force of a full load. We have attributed this to error in manufacturing. Welding the frame together caused the individual pieces of angle steel to warp inwards, significantly decreasing the amount of space between the drawer and the frame. Also, some of the spot welds in the drawer broke before testing, allowing the drawer to flex more than expected. We feel confident that with a more precise manufacturing process these problems will be eliminated and that our system will pass this part of the testing. Our final test found that the drawer first begins to tip over when the load is equivalent to a 41 N force at the center of the drawer.

Table 7: Results of testing show force need to open drawer and force on back to be within set values

Force Needed to Open Drawer (N)	Force on back (Moment) (N)	Weight Loaded in Unit (N)
24.53	0	0
24.53	0	40.79
24.53	73.58	222.49
26.98	117.72	289.23

DISCUSSION FOR FUTURE IMPROVEMENTS

We were not able to include all of our ideas for improvements into our prototype due to material choice, manufacturing restrictions, and time constraints. We recommend that for the final design these suggestions are taken into consideration. We were pleased that the handle was changed from plastic to metal and still only required one hand to open the drawer, however, we would have liked to attach the handle to the drawer with pan head bolts to protect the slides inside the drawer. Another improvement would be to weld the slider bearings to the drawer instead of attaching them with screws. We were unable to do this because the bearings we chose were zinc plated and cannot be welded in the shop. By welding the bearings, there will be more space to store the slides and the structural integrity will be increased.

For the frame of the unit we would have liked to fabricate it completely out of stamped sheet metal, but we were limited by the equipment available. Instead, we resorted to using angle steel to create a frame which the sheet metal was riveted to. By using stamped sheet metal, angle steel would no longer be needed, greatly reducing material cost and manufacturing time.

A possible safety concern with our prototype arises when multiple units are attached to each other. If enough drawers are open at the same time, the moment on the system could be large enough to cause it to tip towards the user. For the final design we would recommend putting in a locking system that would prevent users from being able to open more than one drawer at a time.

Another important feature that we would like to have implemented is the use of a base skirt for the unit. This would help protect the bottom unit and slides from damage which could occur from sitting on the floor (flooding, ground level impact, etc.) and would provide the weight to prevent a single unit from tipping over (if the user did not attach the units to each other, we found that we would need a base unit weight from Equation 5 to counteract the moment on the back of the unit caused when the drawer is opened).

Figure 38: Visualization of Multiple Stacked Drawers

After showing our final prototype to the people at the hospital who have direct interaction with the system, we were able to get more suggestions for future improvements. Some of these improvements included, attaching wheels with locks to the base of the unit so that the unit would be able to move around easily. Another suggestion was to have a label holder in the front so that the user could see what case numbers where in each row before opening and searching for it. Since the drawer’s weight is significantly increased, a final suggestion was to have removable row dividers so that the user could easily take out one or more rows of slides from the drawer for moving purposes.

Finally, we would recommend that our sponsors continue to try to automate the system. We were able to move the current system towards being automated by keeping the drawer parallel to the ground, combining the six drawers into one easy to pull out drawer, and creating angle slide stoppers so that the slides rest at an angle that makes them easy to read and allows for them to be flipped through with little effort.

CONCLUSIONS

The Pathology department at the University of Michigan's hospital asked our group to design a new sample slide storage system that would better fit their needs. The current system by Fisher Scientific lacks the high density of storage needed to accommodate the large number of slides the hospital is required to store each year. Other specific complaints from the users include the amount of time needed to retrieve a slide, slides and components breaking, and not being able to reach the slides in the back of the drawer. To solve these problems and come up with a new design we decided to run an optimization that would optimize the density of the unit while taking a number of engineering constraints into consideration. Once dimensions were determined, we verified our engineering calculations and found the most favorable manufacturing practices through finite element analysis. Our final all metal design has a 26 row wide drawer which slides on a set of bearings with keeps the drawer parallel to the floor, requires little force to pull out, and extends far enough out to reach the slides in the back of the drawer. It uses captive fasteners, rated to withstand a 5400 N shear force, to attach the units to each other. The time needed to find a slide has been shortened by making the slides easier to read and retrieve through the implementation of the case dividers and angle slide stoppers. The new final design increases the density of storage by 23.7%, is more user friendly, and is on track to being automated in the future.

TEAM BIOS

Derek Johnston is currently in his fourth year of Mechanical Engineering here at the University of Michigan. He plans to graduate in May 2008 and hop right into the work force and eventually return to get a masters. Ever since he was a little young lad he has enjoyed fixing and building things. To this day he can still be found taking little kids Legos and K'nex toys. He is from a town north of Detroit, Michigan called Harrison Township. In his spare time he enjoys playing sports, being outdoors, and watching “How It’s Made” on the Discovery Channel.

I am Keith Vander Putten, a current senior graduating at the end of this semester. I am from Warren, Michigan, which is just outside of Detroit. As a kid, I played with Lincoln Logs, Legos, and K’Nex. Combining this early interest in construction with a strong background in mathematics and the sciences developed in prior education led me to the pursuit of an undergraduate degree in Mechanical Engineering from the University of Michigan. I have currently applied and intend to continue my education with a Master’s degree in Mechanical Engineering in the direction of Dynamics and Vibrations. After achieving my master’s degree, I intend to enter private industry. Eventually I plan to get an M.B.A. to expand my business knowledge. This will help me in developing my own business. Along with my studies, I am involved in a number of extracurricular activities. I am a member of Pi Kappa Phi fraternity, treasurer of Alpha Kappa Housing Corp., teammate in a number of intramural sports and an indoor soccer league, and juggler.

Justin Sawkin is a fourth year mechanical engineering student at the University of Michigan. He is from Clinton Township, Michigan a city in the southeast portion of the state. He plans to graduate from the undergraduate program in December 2008 and continue on to biomedical engineering graduate school to do research and obtain his masters and possibly a doctorate. Ever since Justin was young he has enjoyed taking apart and fixing things while trying to understand how they work. He is hoping to put this understanding to use in creating new technology in the biomedical field. Justin enjoys spending his free time reading, playing sports, and being in the company of his friends and family.

Kathryn (Kati) Olson is from the city of Rochester Hills, an hour northeast of Ann Arbor. As a child, she enjoyed creating unbelievably tall but incredibly unstable towers out of Legos and racing Hot Wheels cars down her driveway rather than playing with Barbies or creating new hairstyles. These tendencies eventually led her down a path paved with math and science. Currently pursuing a Mechanical Engineering degree with a minor in Mathematics at the University of Michigan, Kati is in her fourth year and plans to graduate in December 2008. After graduation, she plans to work at or near a ski resort in the western United States for the remainder of the winter season, spending her free time slicing through powder on a snowboard. She will begin a career in engineering starting in the summer of 2009, possibly also working towards a Master's degree in engineering or business. Kati enjoys outdoor activities and doesn't discriminate against the seasons; some of her favorites are picnicking, camping, bike riding, snowball fights, or an occasional game of croquet.

ACKNOWLEDGEMENTS

We would like to thank our sponsors, Professor Albert Shih and Doctor Peter Lucas, and our section instructor, Professor Jwo Pan, for helping us to determine the specifications and goals for our senior design project. Thank you to Professor Greg Hulbert for guidance in developing our finite element model. A special thanks to Rebecca at the University of Michigan Hospital and Ilene from the Stanford University Hospital for helping us generate the list of issues that we addressed to design a more user-friendly product. We would also like to thank Thomas Hosford, from Hosford and Company located in Ann Arbor, for assembling and welding the frame for our casing.

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[4] "Rapid automatic slide retrieval device." Free Patents Online. 2004. 17 Sept. 2007. <http://www.freepatentsonline.com/4793761.html?highlight=4793761&stemming=on>

[5] "Slide archival storage and retrieval system." Free Patents Online. 2004. 17 Sept. 2007. < http://www.freepatentsonline.com/4693373.html?highlight=4693373&stemming=on>

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[7] `"Current Fisher Scientific Drawer." Thermo Fisher Scientific Inc. 2007 < https://www.fishersci.com/wps/portal/!ut/p/_s.7_0_A/7_0_K9/.cmd/ad/.ar/sa.PortletNAVAction/.c/6_0_AJ/.ce/7_0_ABL/.p/5_0_33V/.d/1?ru=http%3A%2F%2Fprodwcsserver%2Fwebapp%2Fwcs%2Fstores%2Fservlet%2FFisherProductDisplay&catalogId=29104&productId=1438062&langId=-1&distype=&isChemical=false&fromCat=yes&catCode=RE_SC&brCategoryId=null&hlpi=&highlightProductsItemsFlag=&fromSearch=Y >

[8] "Ergonomical Workstation Design." International Encyclopedia of Ergonomics and Human Factors. (page 1559) 20 Oct. 2007 http://books.google.com/books?id=lQcgNKKif8oC&pg=RA1-PA1599&lpg=RA1-PA1599&dq=anthropometry+arm+length+5+percentile&source=web&ots=ALLao8oWrG&sig=6f5v4p_KdjnfCsNJPOGqP7phPHI#PRA1-PA1599,M1.

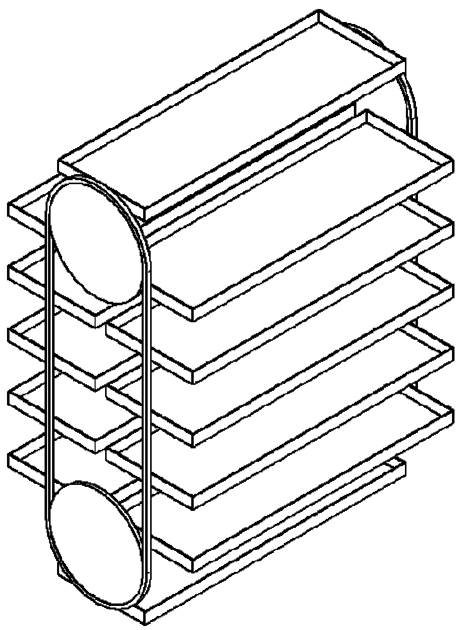
[9] Oberg, Erik; Jones, Franklin D.; Horton, Holbrook L.; Ryffel, Henry H. Machinery's Handbook (27th Edition) & Guide to Machinery's Handbook. Industrial Press. http://www.knovel.com/knovel2/Toc.jsp?BookID=1074&VerticalID=0

APPENDICES

A. Vertical Tray Carousel Concept

A concept that was generated but not fully developed or considered for this project is shown below in Figure A.1. A variation from the horizontal carousel described in the "Concept Generation" section of this report, this concept is a vertical carousel of large trays that each hold many slides. Like the horizontal carousel, this concept is automated and would reduce required human interaction in storing or retrieving slides. We considered integrating the horizontal carousel concept with this idea; each tray could hold a few horizontal carousels. This would create the greatest reduction in human interaction, but would greatly complicate the system, and was consequently beyond the scope of this design course.

Figure A.1: Vertical Tray Carousel Design Concept



B. Moment and Stress Analysis

To develop the moment equation, a number of variables need to be defined. This can be seen in Table B.1.

Table B.1: Variables and their description

Description	Variable
mass of slide	m
Maximize depth of drawer	D
Number of rows in a drawer	r
Moment of Inertia in Y-Z-plane	Ixx
Middle of Drawer	r*wb/2
Yield stress	σY
Young's modulus	E
Normal Force on back of unit	N
Normal Force on bearing track	N_o
Moment	M
Gravity	g
# of slides/row	s
Weight of drawer	Wd
Weight of frame	Wb
Width of bottom of row	wb
Weight of slides	Ws
Width of slide	w

Through force analysis, the normal force on the bearings due to the weight of the slides needed to be calculated.

$$2 * N_O - W = 0; \quad \text{Eq. B.1}$$

$$N_O = \frac{W}{2} = \frac{m * s * r * g}{2} \quad \text{Eq. B.2}$$

By treating the weight as a distributed load, the shear force, *V(x)*, could then be determined.

$$\frac{dV}{dx} = \frac{m * s * g}{w_b} \quad \text{Eq. B.3}$$

$$V(x) = \frac{m * s * g}{w_b} * \left(x - \frac{r * w_b}{2} \right) \quad \text{Eq. B.4}$$

Through the relationship between the shear force and internal bending moment, *M(x)*, we are able to find the moment using the boundary condition for when x=0.

$$\frac{dM}{dx} = -V(x) \qquad \text{Eq. B.5}$$

$$M(x=0) = 0 \qquad \text{Eq. B.6}$$

$$M(x) = -\frac{m*s*g}{w_b}*\left(\frac{x^2}{2} - \frac{r*w_b*x}{2}\right) \qquad \text{Eq. B.7}$$

Since the maximum moment is in the middle of the drawer,

$$M_{Max} = M(x = \frac{r*w_b}{2}) = \frac{m*s*g}{w_b}*\frac{r^2*w_b{}^2}{8} \qquad \text{Eq. B.8}$$

With the maximum bending moment, we can compute the stress, *σ,* created through

$$\sigma = \frac{M*y}{I} = M_{Max}*\frac{t}{2*I} \le \frac{\sigma_Y}{2} \qquad \text{Eq. B.9}$$

To fully compute this, we needed to find the second moment of area, *I*, of the cross-section of our drawer. This is done by computing the second moments of the individual sections (the bottom, front, and back), then summing them around the centroid of the total cross-section using the parallel axis theorem. This is seen below.

$$I_x = \sum(I_c + A*d_c^2) = \left(\frac{b_1*h_1^3}{12} + b_1*h_1*d_{c1}^2\right)_{Bottom} + \left(\frac{b_2*h_2^3}{12} + b_2*h_2*d_{c2}^2\right)_{Front} + \left(\frac{b_3*h_3^3}{12} + b_3*h_3*d_{c3}^2\right)_{Back} \qquad \text{Eq. B.10}$$

$$d_{c1} = x_{c1} - x_c \qquad \text{Eq. B.11}$$

$$x_c = \frac{A_1*x_{c1} + A_2*x_{c2} + A_3*x_{c3}}{A_1 + A_2 + A_3} \qquad \text{Eq. B.12}$$

C. Deflection and Angle of Deflection

Since we are assuming the drawer to be a simply supported beam, we were able to look up the deflection equation in [6]. With this

$$v(x) = \frac{-m*s*g}{24*w_b*E*I}*\left(x^4 - 2*r*w_b*x^3 + (r*w_b)^3*x\right) \qquad \text{Eq. C.1}$$

$$v(x = \frac{r*w_b}{2}) = v_{Max} \qquad \text{Eq. C.2}$$

$$v_{Max} = -\frac{5*m*s*g*(r*w_b)^4}{384*w_b*E*I} \qquad \text{Eq. C.3}$$

We are able to derive the angle of deflection equation and check that the boundary condition at the middle holds.

$$\frac{dv}{dx} = \frac{-m*s*g}{w_b*E*I}*\left(\frac{x^3}{6} - \frac{r*w_b*x^2}{4} + \frac{(r*w_b)^3}{24}\right) \qquad \text{Eq. C.4}$$

$$\frac{dv}{dx}\left(x = \frac{r*w_b}{2}\right) = 0 \qquad \text{Eq. C.5}$$

Finding the maximum angle to be at the ends of the drawer, we can find the difference in the angle between the ends and one row in. This difference will be the angle that the row width will be shortened by.

$$\frac{dv}{dx}_{Max} = \frac{dv}{dx}(x=0) = \frac{-m*s*g}{w_b*E*I}*\frac{r^3*w_b^{\;3}}{24} \qquad \text{Eq. C.6}$$

$$\frac{dv}{dx}(x = w_b) = \frac{-m*s*g}{w_b*E*I}*\left(\frac{4*w_b^{\;3} - 6*r*w_b^{\;3} + r^3*w_b^{\;3}}{24}\right) \qquad \text{Eq. C.7}$$

$$\theta = \frac{dv}{dx}_{Max} - \frac{dv}{dx}(x = w_b) = \frac{m*s*g}{w_b*E*I}*\left(\frac{4*w_b^{\;3} - 6*r*w_b^{\;3}}{24}\right) \qquad \text{Eq. C.8}$$

D. Normal Force

$$Moment\ at\ O = W_b * \frac{D}{2} - W_d * \frac{D}{2} - W_s * \left(D - \frac{s}{2}\right) = M_O$$ Eq.D.1

$$To\ keep\ back\ of\ drawer\ flat, M_O = N * D$$

$$N(s) = (W_d - W_b)\frac{1}{2} + W_s - (W_s * s)\frac{1}{2*D}$$ Eq. D.2

$$\frac{dN}{ds} = 0\ for\ Max/Min$$

$$\frac{dN(s)}{ds} = \frac{m*g}{w} - \frac{m*g*s}{w*D} = 0$$ Eq. D.3

$$Therefore: s = D\ for\ maximum\ Normal\ Force.$$
$$Maximum\ moment\ occurs\ when\ drawer\ is\ full\ of\ slide$$

So the normal force needed at the back of the frame is:

$$N = \frac{(W_d - W_f)}{2} + \frac{m*g*s*r}{2}$$ Eq. D.4

E. Excel Solver to Find Number of Rows (Brown) by Maximizing Density (Green)

Design Constants:			
Average length of slide	l	0.07526	m
Average height of slide	h	0.02528	m
Average width of slide with cover slip	w	0.00122	m
Average mass of slide with specimen/cover slip	m	0.005	kg
Gravity	g	9.81	m/s^2
Angle that slides rest at	ϕ	1.0471976	radians
Width of bottom of row	w_b	0.028448	m
Material: AISI Hot Rolled 1018			
Yield stress	σ_Y	386000000	Pa
Young's modulus	E	1.9E+11	Pa
Material thickness	t	0.000762	m
Density of steel	ρ	8030	kg/m^3

Current drawer systems:		
unit height	0.139	m
unit width	0.484	m
unit depth	0.484	m
Unit volume	0.032561584	m^3
Slides/Unit	4500	slides
Density	138199.665	slides/m^3

Design Variables:			
Unit:			
Unit width	W_u	0.813	m
Unit height	H_u	0.11	m
Unit depth	D_u	0.53	m
Volume of unit	V_u	0.0473979	m^3
Border thickness	b	0.01	m
Weight of frame	W_f	66.24051	N
Width of bearings	w_{bear}	0.01905	m
Volume of material used for frame	V_{sf}	0.0008409	m^3
Drawer:			
Width of drawer front	W_f	0.798322	m
Depth of drawer	D	0.508	m
Height of drawer (front)	H_f	0.07726	m
Height of row	H_r	0.03863	m
Number of rows in a drawer	r	26	#
Width of drawer	W	0.760222	m
Number of slides that fit in a row	s	334	#
Number of slides in a drawer	S	8681	#
Number of slides with case spacers	S_{cs}	8102	#
Weight of slides in a row	W_{sr}	16.377569	N
Weight of slides in a drawer	W_{sd}	425.81678	N
Weight of drawer	W_d	82.138232	N
Second moment of area in Y-Z-plane	Ixx	1.507E-08	m^4
Middle of drawer	r*wb/2	0.369824	m
Volume of material used for drawer	V_{sd}	0.0010427	m^3
Max moment about Y-axis on drawer	M	48.947225	N-m

Functions to optimize:				**Constraints:**
Normal force on back of unit	N_u	-417.8679	N	< 5400 N
Max stress about Y-axis	σ	1.2372492	MPa	< 193 MPa
Deflection	v	-0.000935	m	> -0.001 m
Max difference in angle of deflection	θ	2.931E-05	rad	< 0.04105 rad
Density of slides in unit	ρ_s	183157.48	slides/m^3	>138200 slides/m^3
Percent Increase in density		32.53%		>0%
Density of slides with case spacers	ρ_{scs}	170941.47	slides/m^3	>138200 slides/m^3
Percent increase in density with case spacers		23.69%		>0%

F. DFMEA

DESIGN FAILURE MODE AND EFFECTS ANALYSIS

Design Responsibility: Team 20

Product Type: Drawer

Prepared By: K. Vander Putten

Revision Prepared By: K. Vander Putten

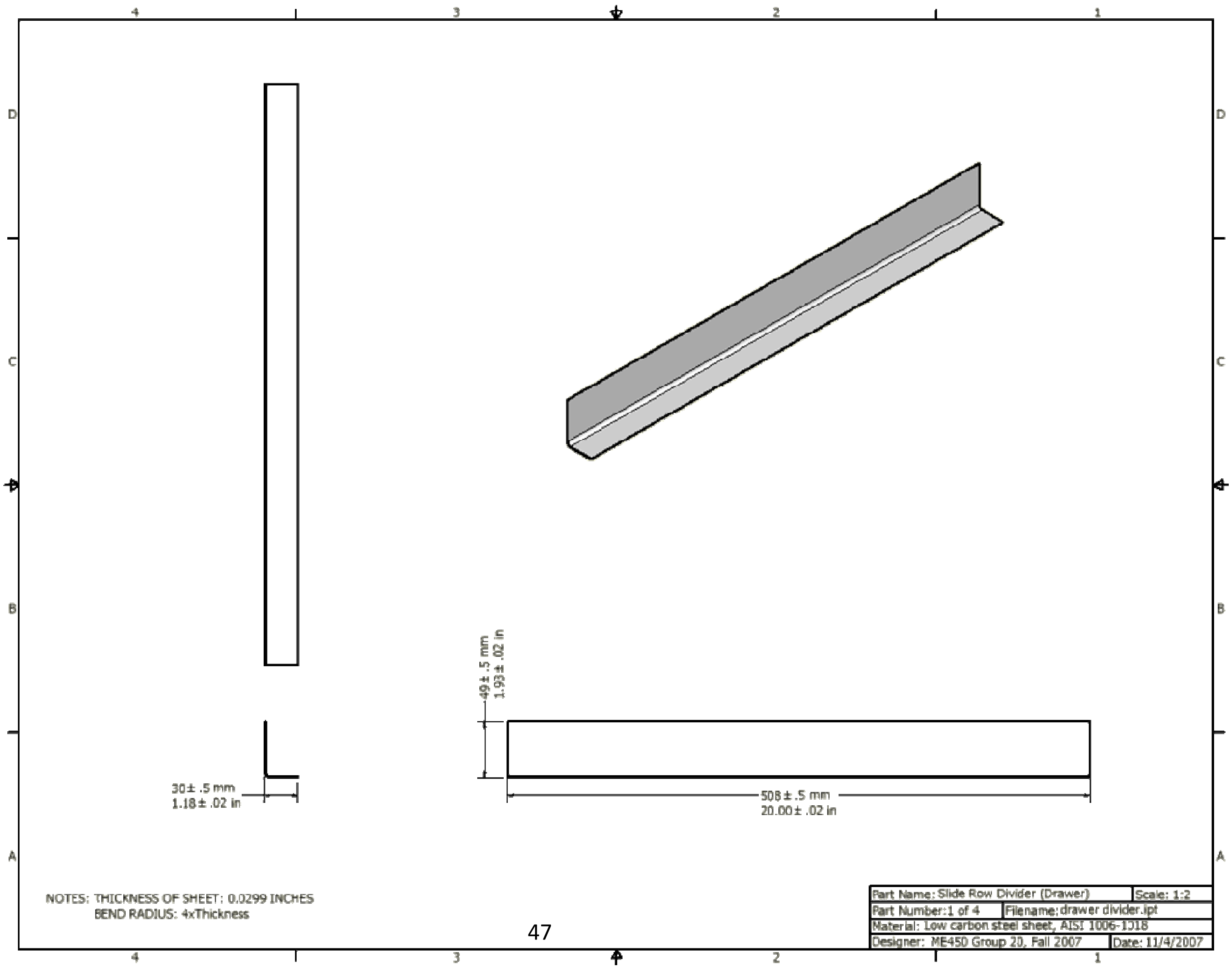
DFMEA Origination Date: 11/11/2007

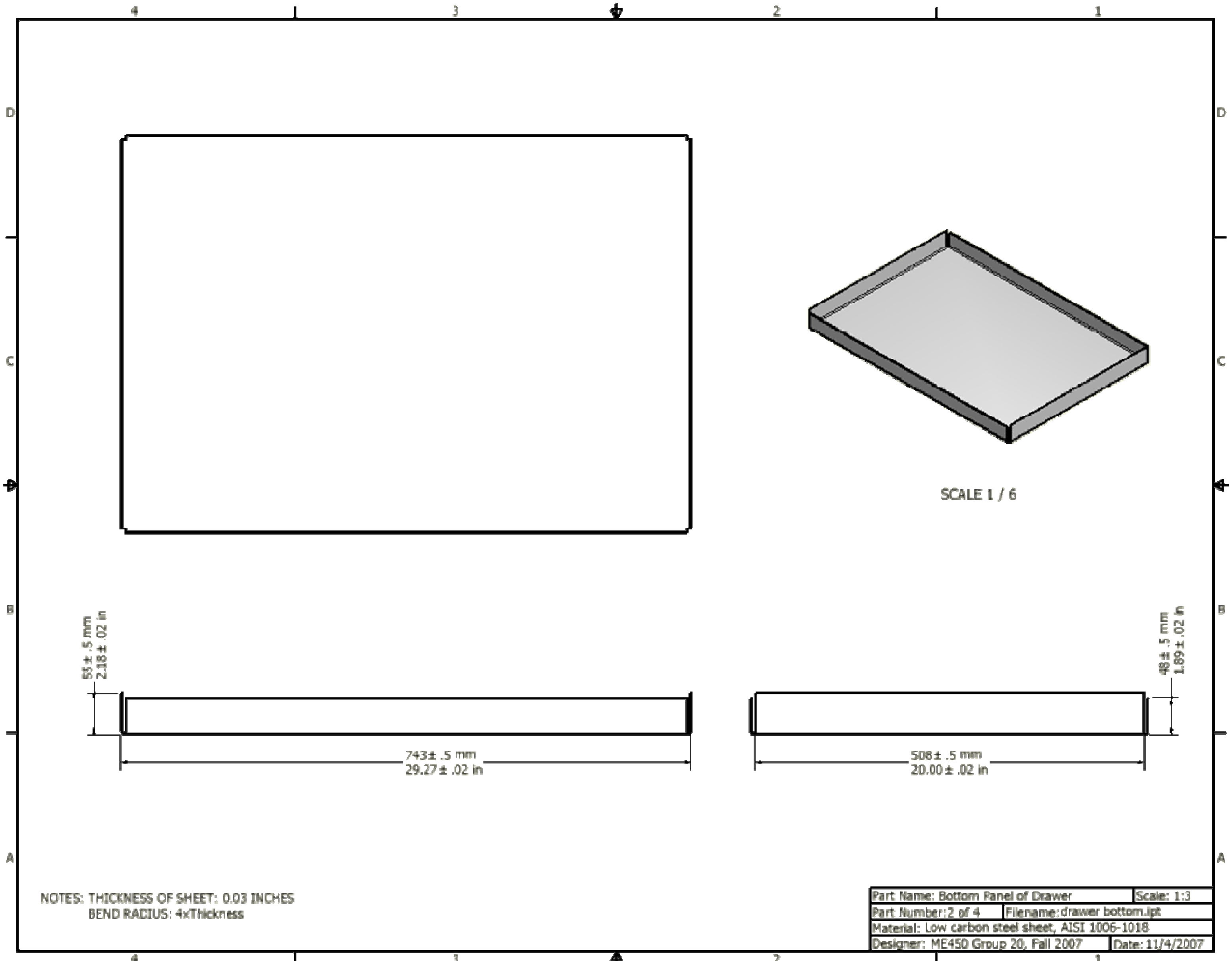
Revision Date: 11/11/2007

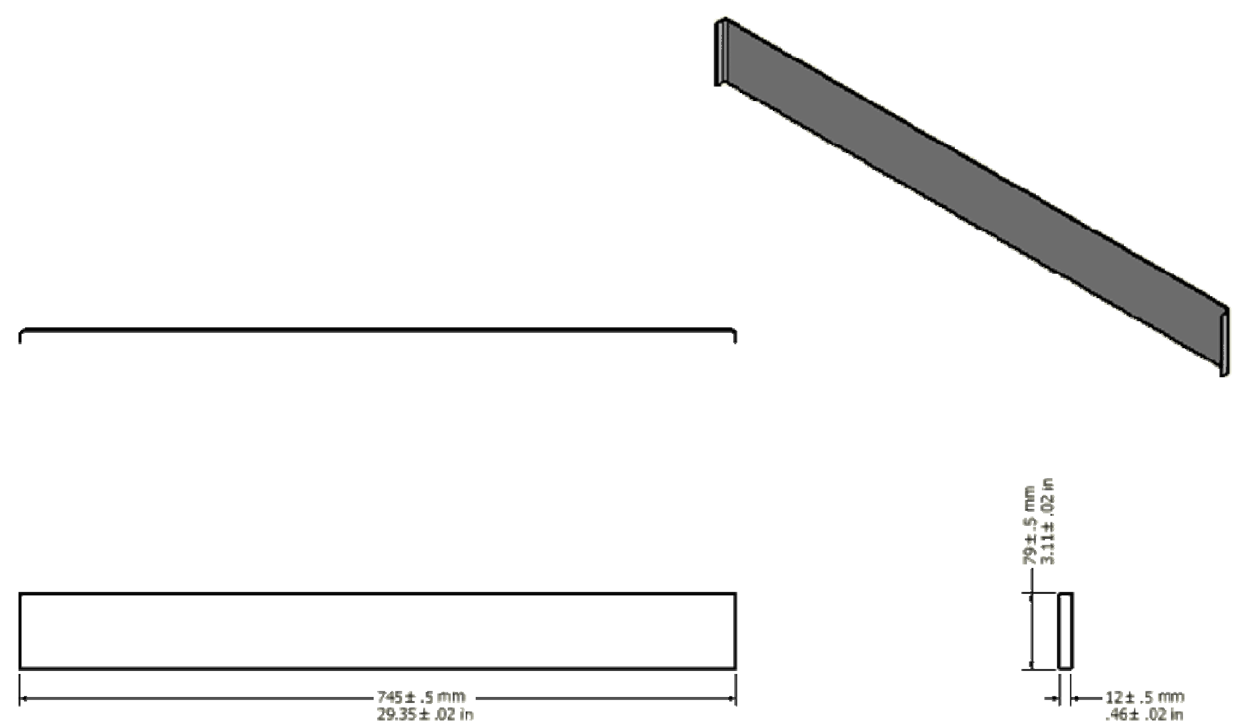
Row #	Part & Functions	Potential Failure Mode	Potential Effect of Failure	SEVER (S)	Potential Causes/ Mechanisms of Failure	OCCUR (O)	Current Design Controls/Tests	DETECT (D)	Recommended Actions	RPN
1	Slider Bearings/ Hold and slide out the drawer	Installed unlevel	Drawer opens at undesired times	3	Back of slider bearings set higher than front	6	Visual examination with a level during installation	4		72
2			Drawer does not remain open	3	Front of slider bearings set higher than back	6	Visual examination with a level during installation	4		72
3			Drawer sits crooked within the frame or does not fit	4	left slider bearing not level with right slider bearing	7	Caliper measurement of slider bearing heights	2		56
4		fracture in welds	Drawer falls off of sliders	9	overload of drawer/ poor weld strength	2	Size of drawer designed to limit weight	6		108
5		Fracture in slider bearing	Drawer falls off of sliders	9	Overload of drawer/ Incorrect strength rating from supplier	1	Size of drawer designed to limit weight	6	Test slider bearings for strength rating before use	54

6	Drawer	Large deflection	Drawer bottom hits frame	4	Too large of a load, weaker material strength than expected	3	FEA of drawer, safety factor of 2 incorporated into design	7	Test material properties of steel	84
7		Drawer yields	Drawer bottom enters plastic deformation	4	Too large of a load, weaker material strength than expected	3	FEA of drawer, safety factor of 2 incorporated into design	7	Test material properties of steel	84
8		shear at metal bends	bottom of drawer falls out	9	Radius of curvature smaller than 2 to 3 times the thickness/ overload/ poor steel properties	3	measurement of radius of curvature, Size of drawer designed to limit load	6	Test material properties of steel	162
9		fracture in welds	Drawer falls apart	9	overload of drawer/ poor weld strength	3	Size of drawer designed to limit weight	6		162
10	Frame	Unit connecting holes are too small	Captive fasteners do not fit into the holes	5	Holes are drilled too small	4	Holes can be drilled larger	1		20
11		crack propagation at holes	Side of frame tears/ Frame structure is weakened	4	fatigue due to shear load applied by captive fasteners	2	Size of drawer designed to limit weight and shear load	4		32
12		fracture in welds	Frame falls apart	9	overload of drawer/ poor weld strength	2	Size of drawer designed to limit weight	6		108
13	Captive Fasteners	Poor Assembly	Captive Fastener falls out	2	Under-torqued nuts	6	Measurement of torque on nuts	3		36
14	Handle	fracture in welds	Handle falls off of drawer	7	overload of drawer/ poor weld strength	2	Size of drawer designed to limit weight	6		84

G. CAD Drawings

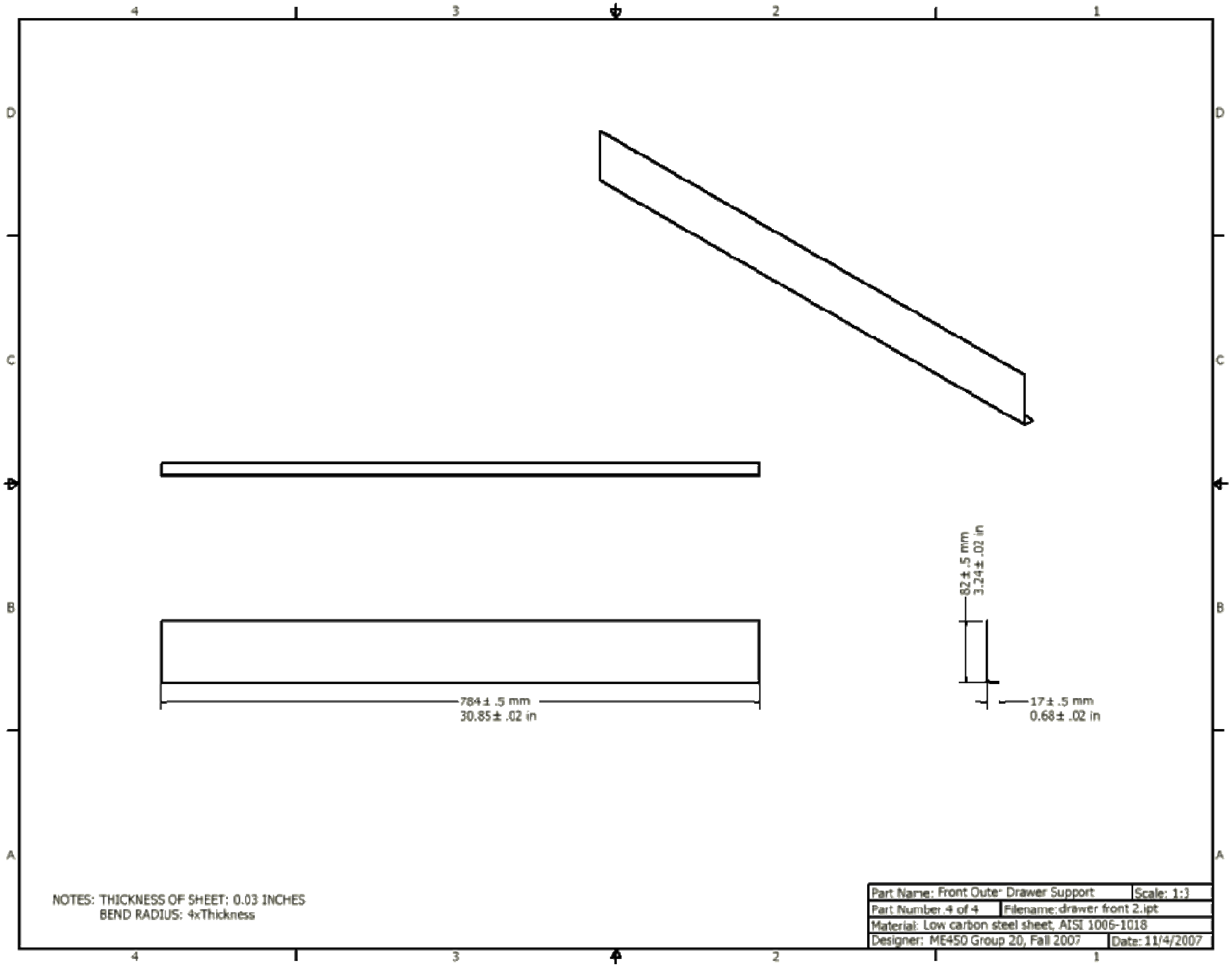



SCALE 1 / 6
55 ± .5 mm
2.18 ± .02 in
743± .5 mm
29.27 ± .02 in
508± .5 mm
20.00 ± .02 in
48 ± .5 mm
1.89 ± .02 in
NOTES: THICKNESS OF SHEET: 0.03 INCHES
BEND RADIUS: 4xThickness
Part Name: Bottom Panel of Drawer
Scale: 1:3
Part Number:2 of 4
Filename:drawer bottom.ipt
Material: Low carbon steel sheet, AISI 1006-1018
Designer: ME450 Group 20, Fall 2007
Date: 11/4/2007

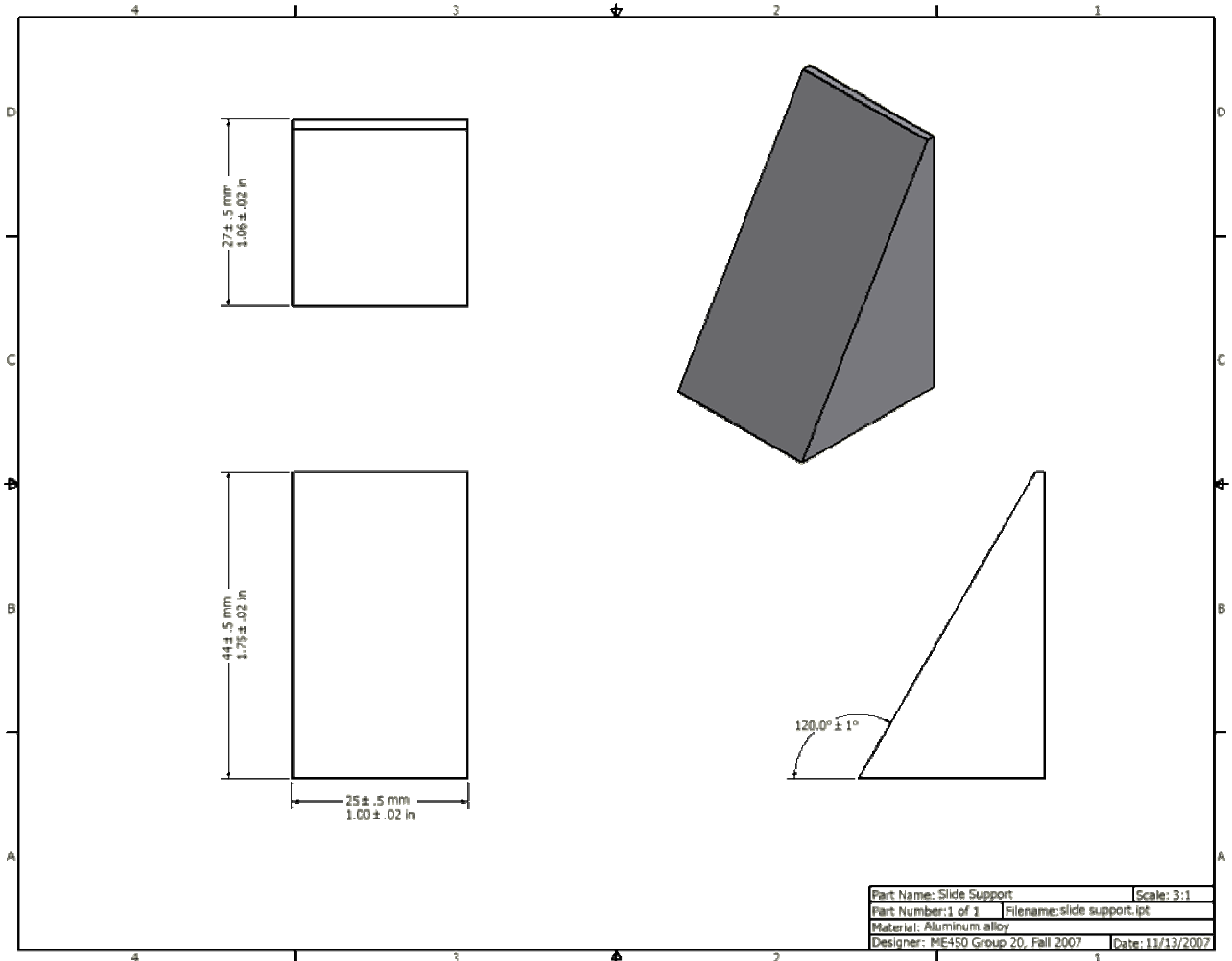


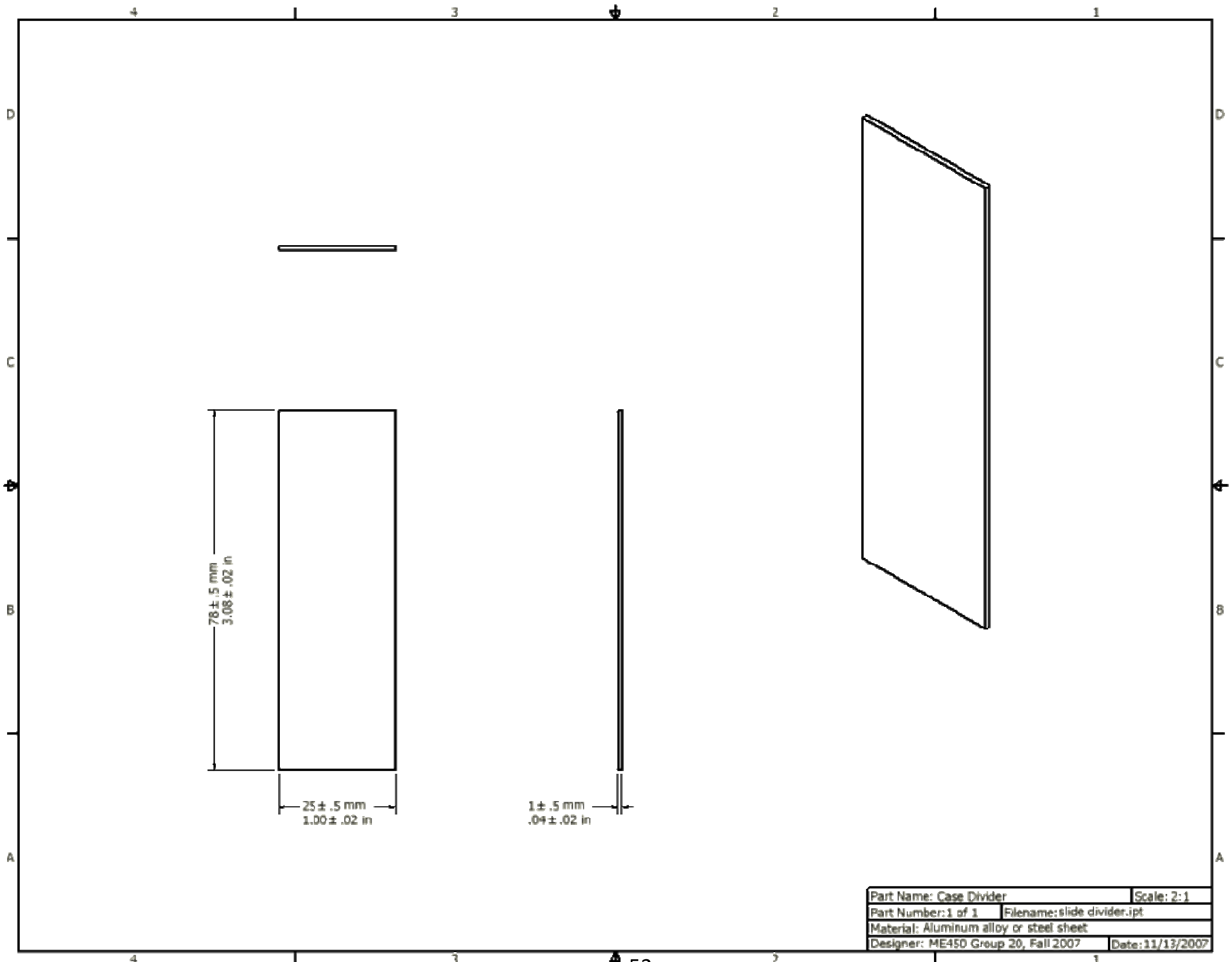
NOTES: THICKNESS OF SHEET: 0.03 INCHES
BEND RADIUS: 4xThickness

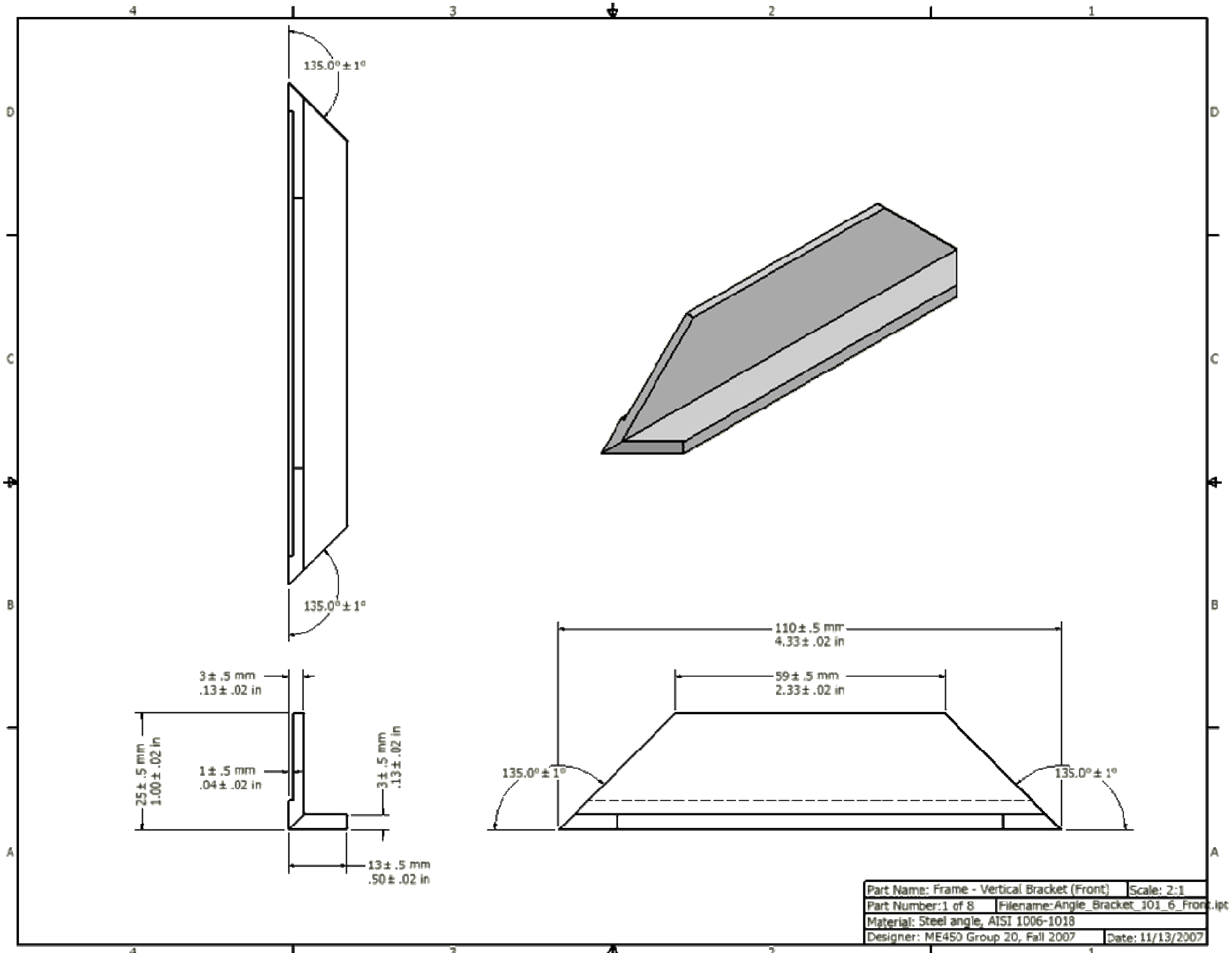
Part Name: Front/Back Drawer Support	Scale: 1:3
Part Number: 3 of 4	Filename: drawer front back 1.pt
Material: Low carbon steel sheet, AISI 1006-1018	
Designer: ME450 Group 20, Fall 2007	Date: 11/4/2007

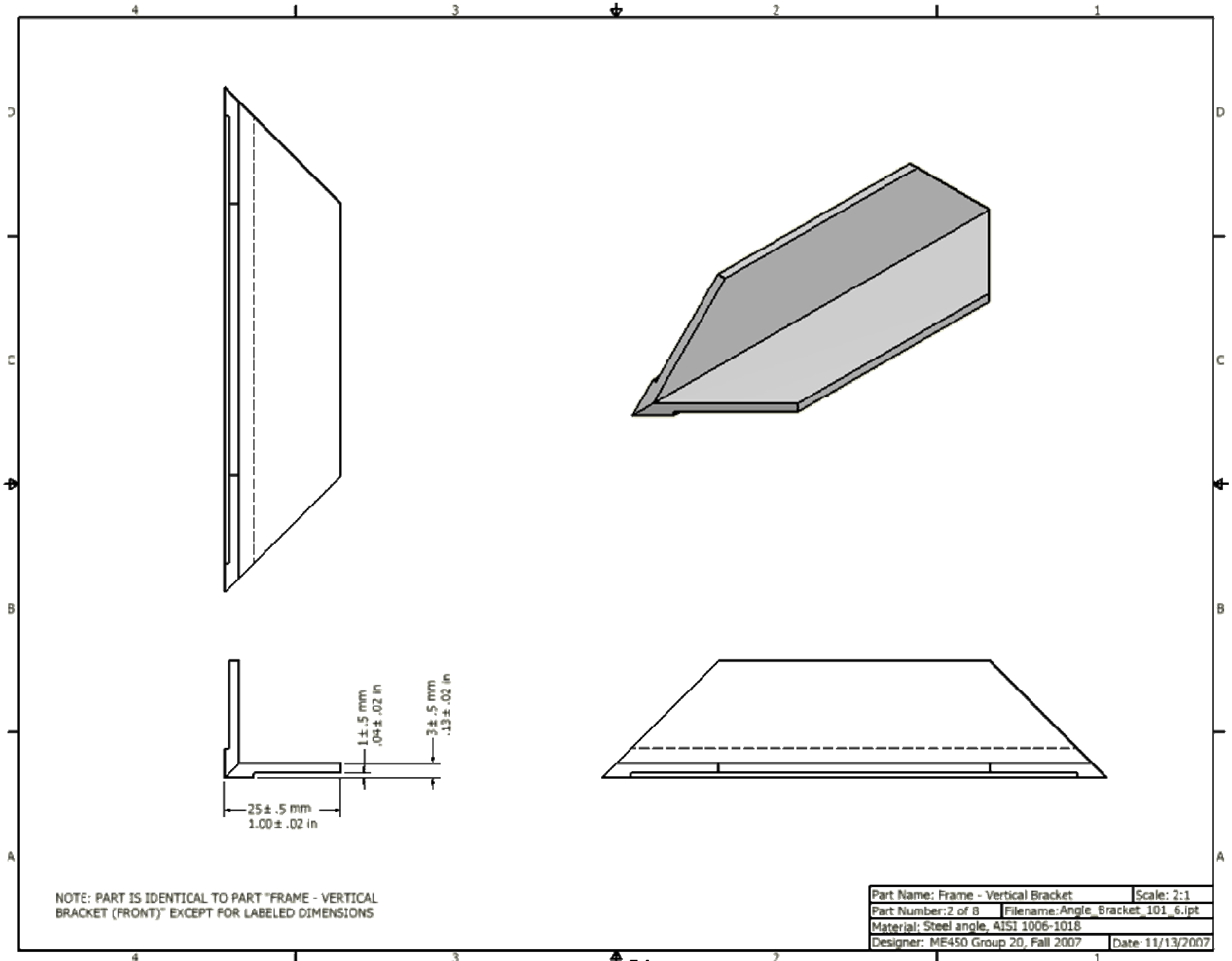


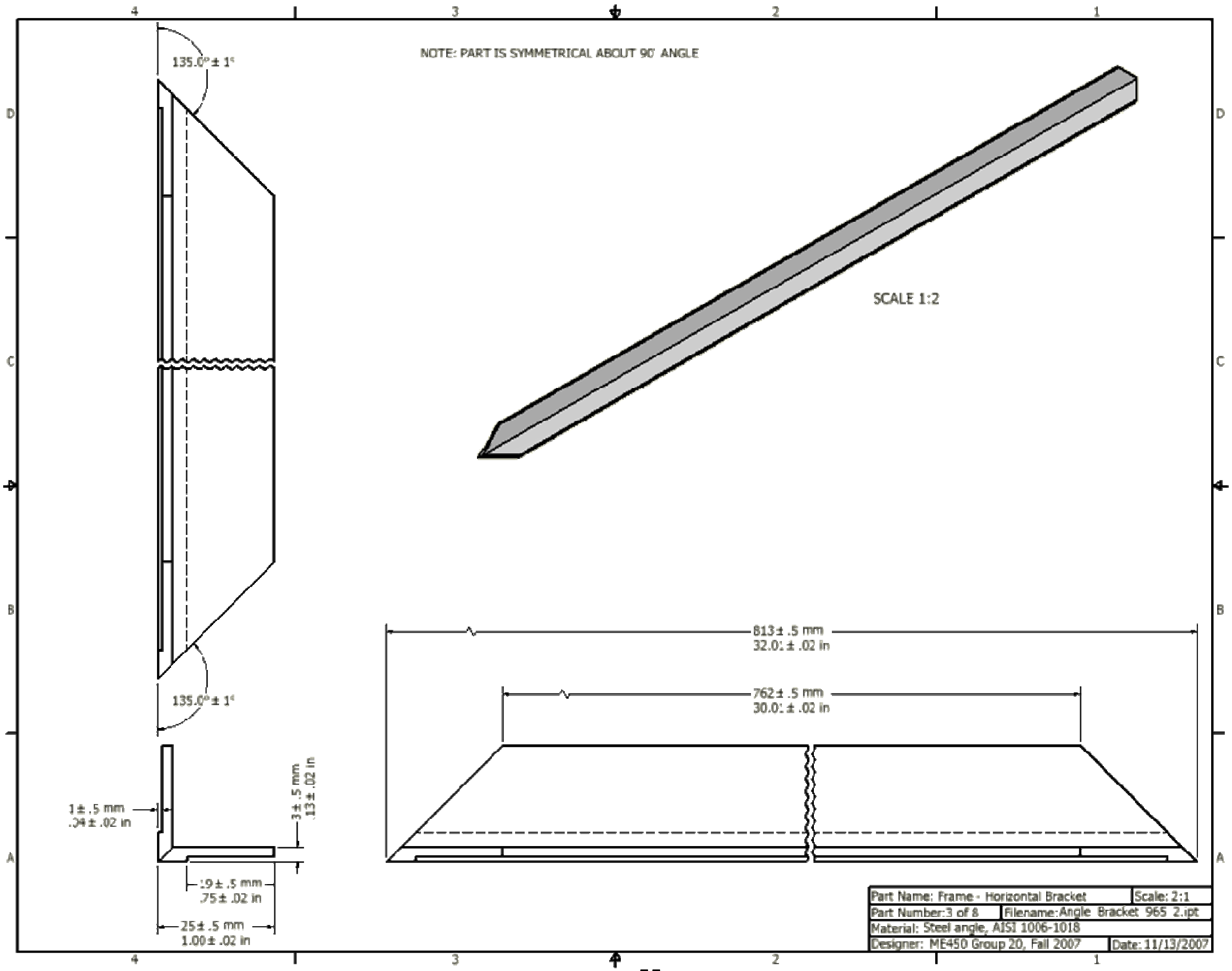
82 ± .5 mm
3.24 ± .02 in
784 ± .5 mm
30.85 ± .02 in
17 ± .5 mm
0.68 ± .02 in
NOTES: THICKNESS OF SHEET: 0.03 INCHES
BEND RADIUS: 4xThickness
Part Name: Front Outer Drawer Support
Scale: 1:3
Part Number 4 of 4
Filename: drawer front 2.ipt
Material: Low carbon steel sheet, AISI 1006-1018
Designer: ME450 Group 20, Fall 2007
Date: 11/4/2007

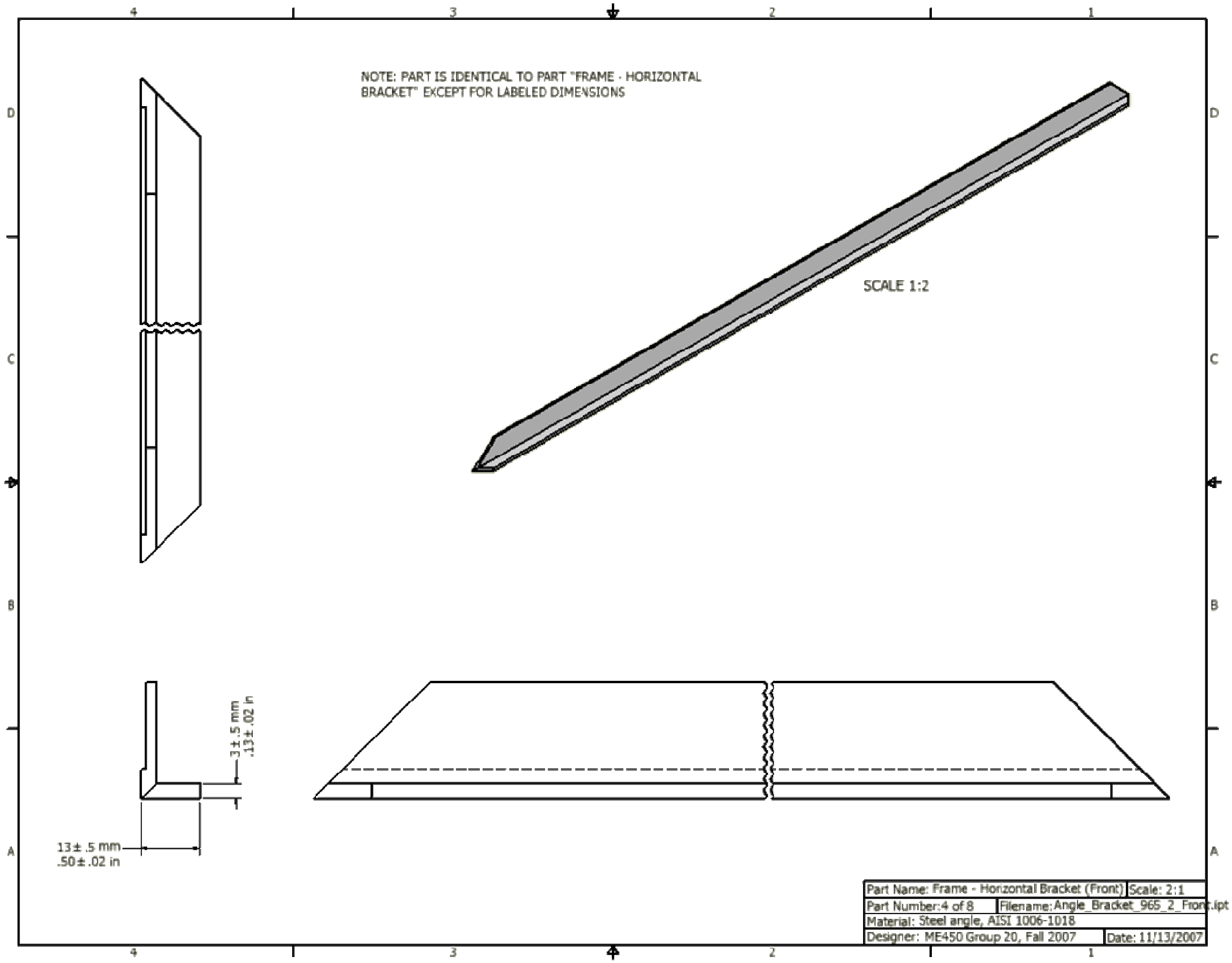

27 ± .5 mm
1.06 ± .02 in
44 ± .5 mm
1.75 ± .02 in
25 ± .5 mm
1.00 ± .02 in
120.0° ± 1°
Part Name: Slide Support
Scale: 3:1
Part Number: 1 of 1
Filename: slide support.ipt
Material: Aluminum alloy
Designer: ME450 Group 20, Fall 2007
Date: 11/13/2007

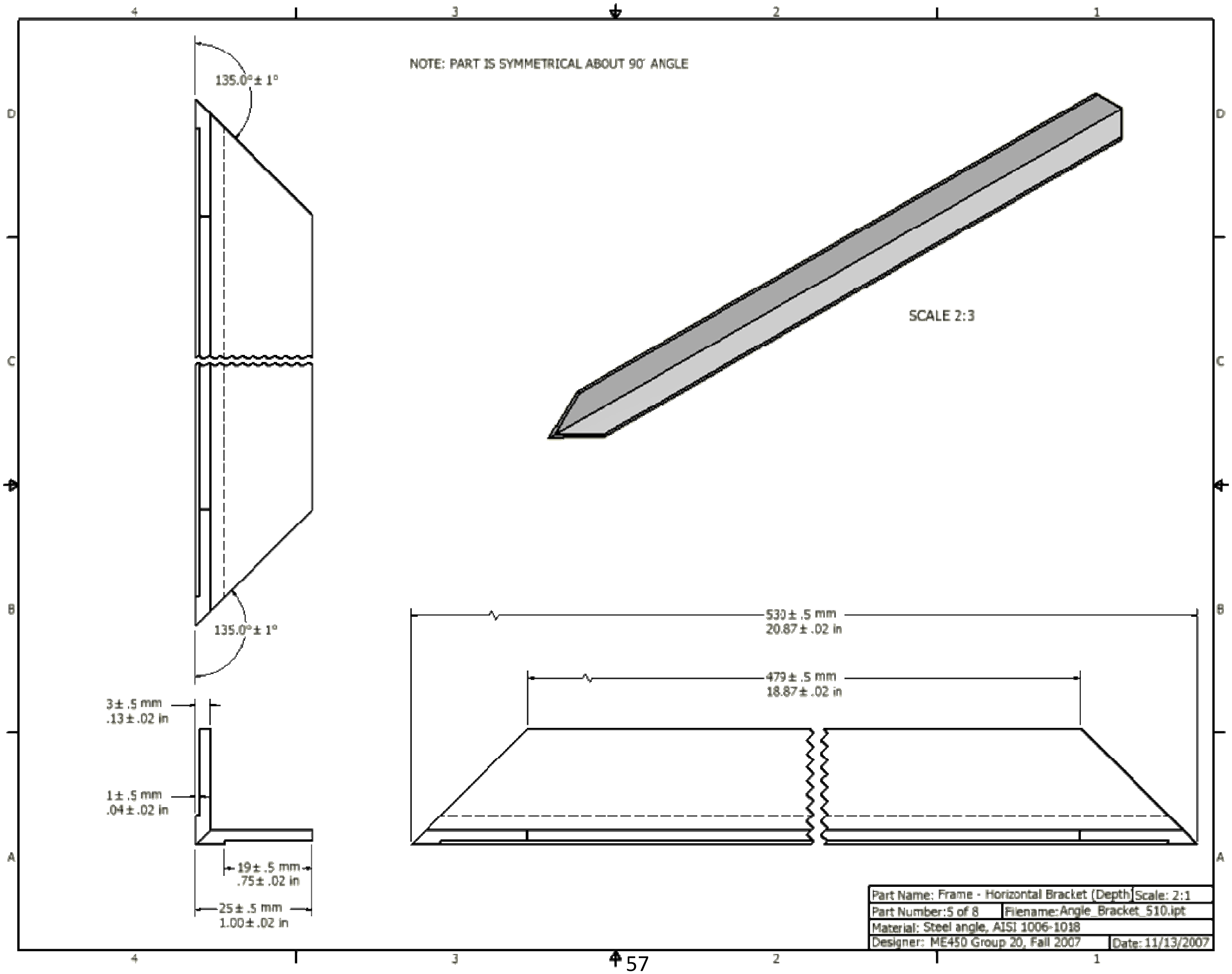

78 ± .5 mm
3.08 ± .02 in
25 ± .5 mm
1.00 ± .02 in
1 ± .5 mm
.04 ± .02 in
Part Name: Case Divider
Scale: 2:1
Part Number: 1 of 1
Filename: slide divider.ipt
Material: Aluminum alloy or steel sheet
Designer: ME450 Group 20, Fall 2007
Date: 11/13/2007

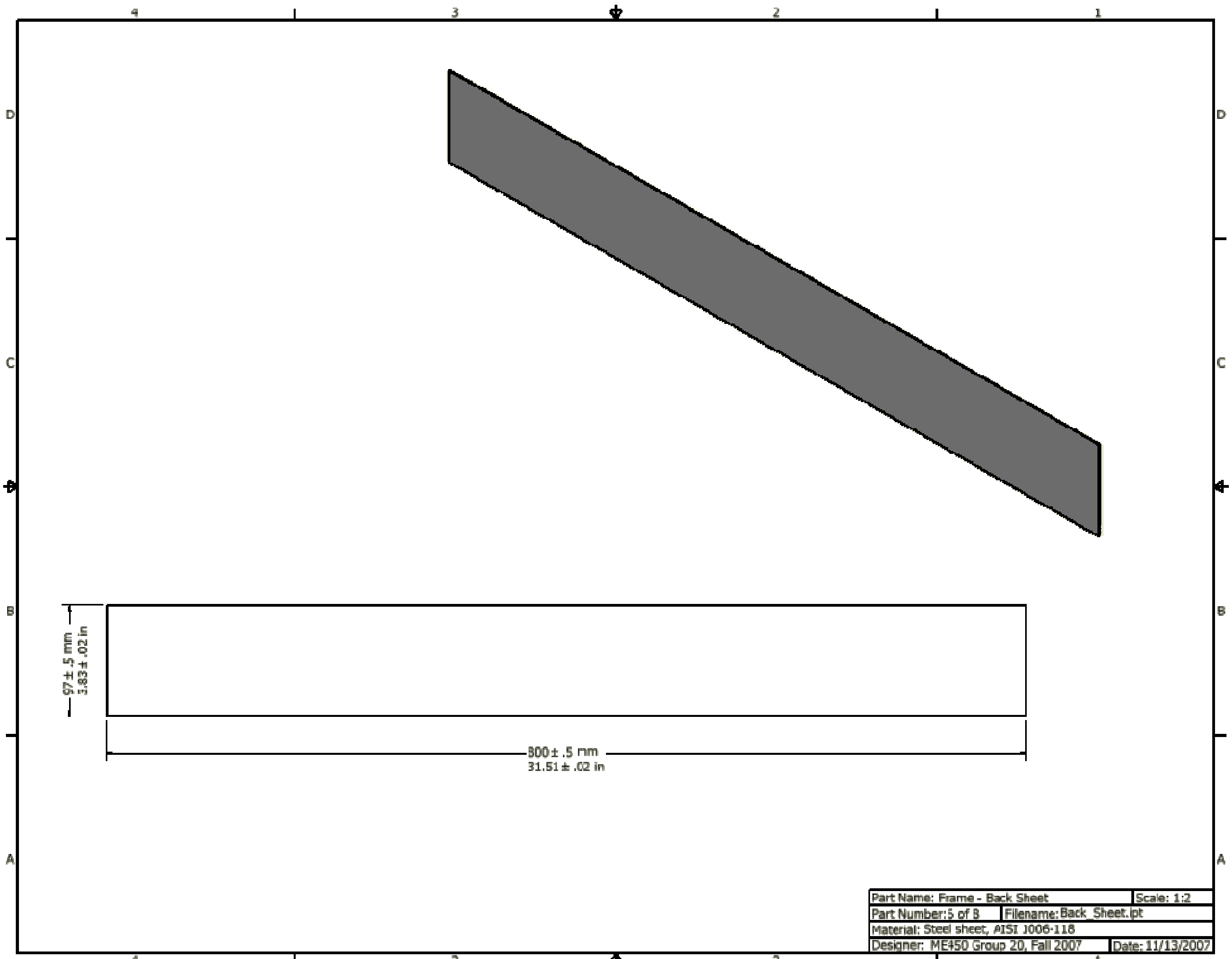

135.0° ± 1°
135.0° ± 1°
110 ± .5 mm
4.33 ± .02 in
59 ± .5 mm
2.33 ± .02 in
135.0° ± 1°
135.0° ± 1°
3 ± .5 mm
.13 ± .02 in
25 ± .5 mm
1.00 ± .02 in
1 ± .5 mm
.04 ± .02 in
3 ± .5 mm
.13 ± .02 in
13 ± .5 mm
.50 ± .02 in
Part Name: Frame - Vertical Bracket (Front)
Scale: 2:1
Part Number: 1 of 8
Filename: Angle_Bracket_101_6_Front.ipt
Material: Steel angle, AISI 1006-1018
Designer: ME450 Group 20, Fall 2007
Date: 11/13/2007

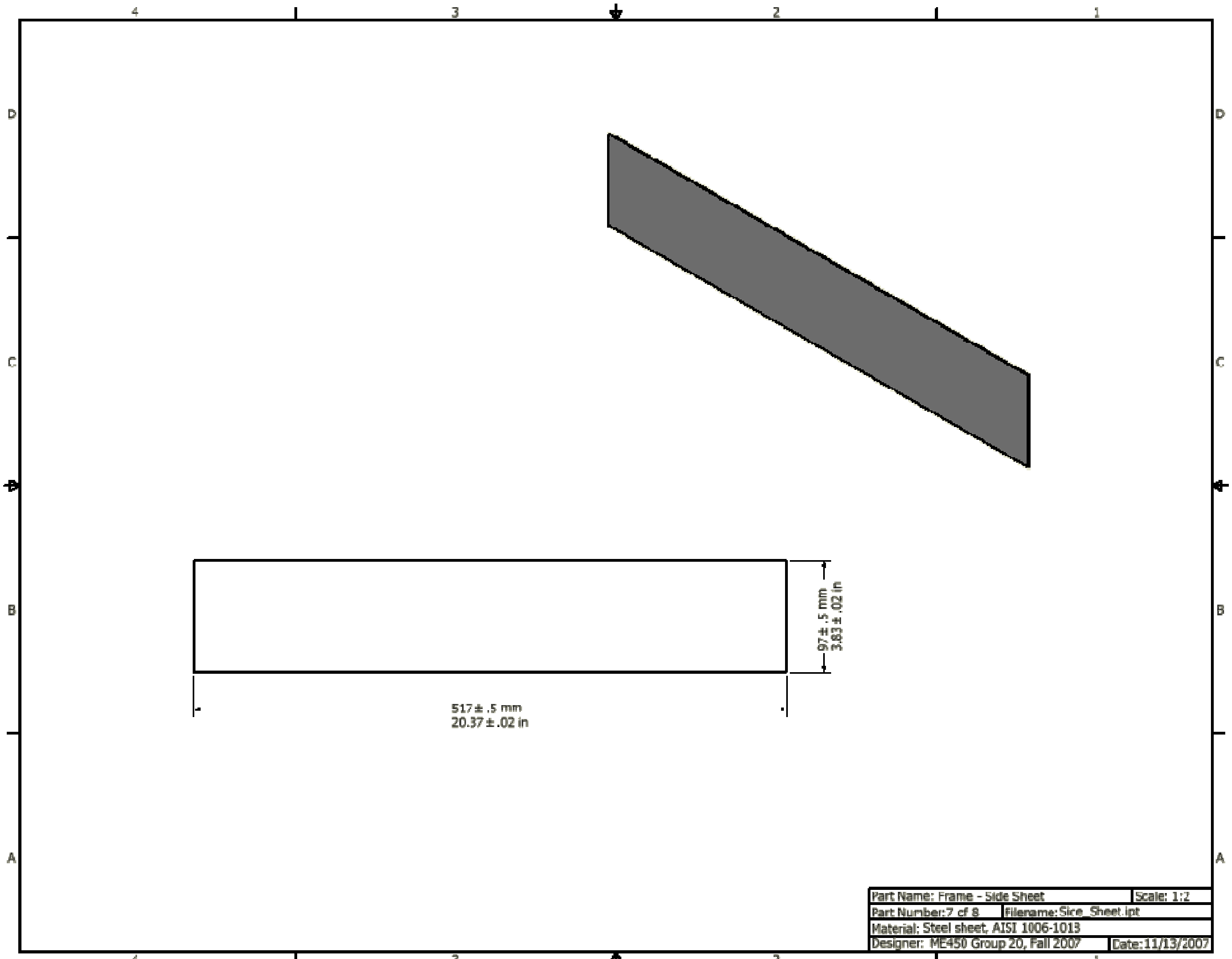

1 ± .5 mm
.04 ± .02 in
3 ± .5 mm
.13 ± .02 in
25 ± .5 mm
1.00 ± .02 in
NOTE: PART IS IDENTICAL TO PART "FRAME - VERTICAL BRACKET (FRONT)" EXCEPT FOR LABELED DIMENSIONS
Part Name: Frame - Vertical Bracket
Scale: 2:1
Part Number: 2 of 8
Filename: Angle_Bracket_101_6.ipt
Material: Steel angle, AISI 1006-1018
Designer: ME450 Group 20, Fall 2007
Date: 11/13/2007


NOTE: PART IS SYMMETRICAL ABOUT 90° ANGLE
135.0° ± 1°
135.0° ± 1°
SCALE 1:2
813 ± .5 mm
32.0: ± .02 in
762 ± .5 mm
30.0: ± .02 in
1 ± .5 mm
.04 ± .02 in
3 ± .5 mm
.13 ± .02 in
19 ± .5 mm
.75 ± .02 in
25 ± .5 mm
1.00 ± .02 in
Part Name: Frame - Horizontal Bracket
Scale: 2:1
Part Number: 3 of 8
Filename: Angle Bracket 965 2.ipt
Material: Steel angle, AISI 1006-1018
Designer: ME450 Group 20, Fall 2007
Date: 11/13/2007


NOTE: PART IS IDENTICAL TO PART "FRAME - HORIZONTAL BRACKET" EXCEPT FOR LABELED DIMENSIONS
SCALE 1:2
3 ± .5 mm
.13 ± .02 in
13 ± .5 mm
.50 ± .02 in
Part Name: Frame - Horizontal Bracket (Front)
Scale: 2:1
Part Number: 4 of 8
Filename: Angle_Bracket_965_2_Front.ipt
Material: Steel angle, AISI 1006-1018
Designer: ME450 Group 20, Fall 2007
Date: 11/13/2007


NOTE: PART IS SYMMETRICAL ABOUT 90° ANGLE
135.0° ± 1°
135.0° ± 1°
SCALE 2:3
530 ± .5 mm
20.87 ± .02 in
479 ± .5 mm
18.87 ± .02 in
3 ± .5 mm
.13 ± .02 in
1 ± .5 mm
.04 ± .02 in
19 ± .5 mm
.75 ± .02 in
25 ± .5 mm
1.00 ± .02 in
Part Name: Frame - Horizontal Bracket (Depth)
Scale: 2:1
Part Number: 5 of 8
Filename: Angle_Bracket_510.ipt
Material: Steel angle, AISI 1006-1018
Designer: ME450 Group 20, Fall 2007
Date: 11/13/2007


97 ± .5 mm
3.83 ± .02 in
800 ± .5 mm
31.51 ± .02 in
Part Name: Frame - Back Sheet
Scale: 1:2
Part Number:5 of 8
Filename:Back_Sheet.ipt
Material: Steel sheet, AISI 1006-118
Designer: ME450 Group 20, Fall 2007
Date: 11/13/2007



Part Name: Frame - Side Sheet	Scale: 1:2
Part Number: 7 of 8	Filename: Side_Sheet.ipt
Material: Steel sheet, AISI 1006-1013	
Designer: ME450 Group 20, Fall 2007	Date: 11/13/2007

H. Process Plan

Bottom and Sides		
Tools Needed	Materials Needed	Description
Sheet Metal Cutter	AISI 1006-1018 Steel Sheet 0.762 mm	Cut sheet metal to a 853 mm x 604 mm rectangle.
Band Saw	Bottom and Sides	Cut out rectangles of 55 mm from the width and 48 mm from the length at each corner.
Metal Break	Bottom and Sides	Bend bottom and sides 90 degrees across the width 48 mm from the side.
Metal Break	Bottom and Sides	Repeat step 3 for other side.
Metal Break	Bottom and Sides	Bend bottom and sides 90 degrees across the length 55 mm from the side.
Metal Break	Bottom and Sides	Repeat step 5 for other side.

Front 1		
Tools Needed	Materials Needed	Description
Sheet Metal Cutter	AISI 1006-1018 Steel Sheet 0.762 mm	Cut sheet metal to a 757 mm x 79 mm rectangle.
Metal Break	Front 1	Bend front 1 90 degrees across the width 17 mm from the side.
Metal Break	Front 1	Repeat step 2 for other side.

Front 2		
Tools Needed	Materials Needed	Description
Sheet Metal Cutter	AISI 1006-1018 Steel Sheet 0.762 mm	Cut sheet metal to a 784 mm x 99 mm rectangle.
Metal Break	Front 2	Bend front 2 90 degrees across the length 17 mm from the side.

Back 1		
Tools Needed	Materials Needed	Description
Sheet Metal Cutter	AISI 1006-1018 Steel Sheet 0.762 mm	Cut sheet metal to a 757 mm x 79 mm rectangle.
Metal Break	Back 1	Bend back 1 90 degrees across the width 12 mm from the side.
Metal Break	Back 1	Repeat step 2 for the other side.

Back 2		
Tools Needed	Materials Needed	Description
Sheet Metal Cutter	AISI 1006-1018 Steel Sheet 0.762 mm	Cut sheet metal to a 742.70 mm x 92.42 mm rectangle.
Metal Break	Back 2	Bend back 2 90 degrees across the length 12.70 mm from the side.

Parts # 6 x 2	**Dividers**		
Step	Tools Needed	Materials Needed	Description
1	Sheet Metal Cutter	AISI 1006-1018 Steel Sheet 0.759 mm	Cut sheet metal to a 508.00 mm x __mm rectangle.
2	Metal Bender	Dividers	Bend __mm x __mm sheet 90 degrees across the length 76.20 mm from a side.
Assembly # 1	**Drawer**		
Step	Tools Needed	Materials Needed	Description
1	Spot Welder	Dividers + Bottom and Sides	Place a divider n x 28.45 mm from the right of the drawer (when looking and the front) with the inside of the bend facing the right. Make sure that the divider is parallel to the sides of the drawer. Spot weld the divider to the bottom of the assembly. Repeat this process n times, placing the divider n*28.45 mm from the right of the drawer. n = divider number
2	Spot Welder	Front 2 + Current Assembly	Place front 2 outside the front bend of the bottom and sides with the bend of front 2 underneath. Center front 2 and spot weld both the bottom and front.
3	Spot Welder	Front 1 + Current Assembly	Place front 1 inside the front bend of the bottom and sides with the inside of the bends facing the back of the drawer and flush with the top of front 2. Place the bends of front 1 outside the side bends of the bottom and sides. Spot weld the sides together then spot weld the fronts together.
4	Spot Welder	Back 2 + Current Assembly	Place back 2 outside the back bend of the bottom and sides with the bend of back 2 underneath. Center back 2 and spot weld both the bottom and front.
5	Spot Welder	Back 1 + Current Assembly	Place back 1 inside the front bend of the bottom and sides with the inside of the bends facing the front of the drawer and flush with the top of back 2. Place the bends of back 1 outside the side bends of the bottom and sides. Spot weld the sides together then spot weld the backs together.
6	Spot Welder	Bearing Sliders + Current Assembly	Place the inner slide of the bearing sliders 38.10 mm from the bottom and flush with the sides of the drawer and with front 1. Spot weld the slider to the drawer.
7	Welder	Handle + Current Assembly	Center the handle on the front of the current assembly. Weld it in place.

Part # 7 x 2	Front Corner Angle		
Step	Tools Needed	Materials Needed	Description
1	Band Saw	Low Carbon Angle Steel	Cut angle steel to a 110.00 mm length.
2	Band Saw	Front Corner Angle	Lay the front corner angle on one side and cut from the bend to the center at a 45 degree angle.
3	Band Saw	Front Corner Angle	Repeat step 2 for the opposite corner.
4 & 5	Mill	Front Corner Angle	Place front corner angle on opposite side and repeat steps 2 and 3.
6	Mill	Front Corner Angle	Place front corner angle in mill so that one side is facing upwards. Mill 0.91 mm down 6.35 mm from the bend to the end across the entire length.
7	Mill	Front Corner Angle	Place front corner angle in mill so that the milled side is facing down. Mill 12.70 mm down across the entire length.

Part # 8 x 2	Back Corner Angle		
Step	Tools Needed	Materials Needed	Description
1	Band Saw	Low Carbon Angle Steel	Cut angle steel to a 110.00 mm length.
2	Band Saw	Back Corner Angle	Lay the back corner angle on one side and cut from the bend to the center at a 45 degree angle.
3	Band Saw	Back Corner Angle	Repeat step 2 for the opposite corner.
4 & 5	Mill	Back Corner Angle	Place back corner angle on opposite side and repeat steps 2 and 3.
6	Mill	Back Corner Angle	Place back corner angle in mill so that one side is facing upwards. Mill 0.91 mm down 6.35 mm from the bend to the end across the entire length.
7	Mill	Back Corner Angle	Place back corner angle in mill so that the other side is facing upwards. Repeat step 6.

Part # 9 x 4	Side Angle		
Step	Tools Needed	Materials Needed	Description
1	Band Saw	Low Carbon Angle Steel	Cut angle steel to a 530.00 mm length.
2	Band Saw	Side Angle	Lay the side angle on one side and cut from the bend to the center at a 45 degree angle.
3	Band Saw	Side Angle	Repeat step 2 for the opposite corner.
4 & 5	Mill	Side Angle	Place side angle on opposite side and repeat steps 2 and 3.
6	Mill	Side Angle	Place side angle in mill so that one side is facing upwards. Mill 0.91 mm down 6.35 mm from the bend to the end across the entire length.
7	Mill	Side Angle	Place side angle in mill so that the other side is facing upwards. Repeat step 6.

Part # 10 x 2	Front Angle		
Step	Tools Needed	Materials Needed	Description
1	Band Saw	Low Carbon Angle Steel	Cut angle steel to a 813.00 mm length.
2	Band Saw	Front Angle	Lay the front angle on one side and cut from the bend to the center at a 45 degree angle.
3	Band Saw	Front Angle	Repeat step 2 for the opposite corner.
4 & 5	Mill	Front Angle	Place front angle on opposite side and repeat steps 2 and 3.
6	Mill	Front Angle	Place front angle in mill so that one side is facing upwards. Mill 0.91 mm down
			6.35 mm from the bend to the end across the entire length.
7	Mill	Front Angle	Place front angle in mill so that the milled side is facing down. Mill 12.70 mm down across
			the entire length.

Part # 11 x 2	Back Angle		
Step	Tools Needed	Materials Needed	Description
1	Band Saw	Low Carbon Angle Steel	Cut angle steel to a 813.00 mm length.
2	Band Saw	Back Angle	Lay the back angle on one side and cut from the bend to the center at a 45 degree angle.
3	Band Saw	Back Angle	Repeat step 2 for the opposite corner.
4 & 5	Mill	Back Angle	Place back angle on opposite side and repeat steps 2 and 3.
6	Mill	Back Angle	Place back angle in mill so that one side is facing upwards. Mill 0.91 mm down
			6.35 mm from the bend to the end across the entire length.
7	Mill	Back Angle	Place back angle in mill so that the other side is facing upwards. Repeat step 6.
8	Mill	Back Angle	Mill with a 3.18 mm bit 3.18 mm away from the bend from the end to 25.40 mm towards
			the center and all the way through the thickness of the angle steel.
9	Mill	Back Angle	Repeat step 8 for the opposite end.

Part # 12 x 6	Slider Mount		
Step	Tools Needed	Materials Needed	Description
1	Band Saw	Low Carbon Steel Bar	Cut steel bar slightly larger than 106.65 mm x 12.70 mm x 9.53 mm.
2	Mill	Slider Mount	Place bearing slider mount into the mill and mill to a thickness of 9.53 mm.
3	Mill	Slider Mount	Place bearing slider mount into the mill and mill to a width of 12.70 mm.
4	Mill	Slider Mount	Place bearing slider mount into the mill and mill to a length of 106.35 mm.
5	Mill	Slider Mount	Drill a __mm diameter hole centered on the width __mm away from one end to a depth of
			8.00 mm.
6	Tap	Slider Mount	Tap the hole to fit a __ bolt.
7	Grinder	Slider Mount	Grind off the top and bottom edges on the opposite side of the hole.

Part # 13 x 2	**Connector Tab**		
Step	Tools Needed	Materials Needed	Description
1	Band Saw	Low Carbon Steel Bar	Cut steel bar slightly larger than 76.20 mm x 25.40 mm x 3.18 mm.
2	Mill	Connector Tab	Place connector tab into the mill and mill to a thickness of 3.18 mm.
3	Mill	Connector Tab	Place connector tab into the mill and mill to a width of 25.40 mm.
4	Mill	Connector Tab	Place connector tab into the mill and mill to a length of 76.20 mm.
5	Mill	Connector Tab	Drill a __mm diameter hole through the connector tab centered on the width and 19.05 mm away from one end of the length.

Part # 14 x 2	**Top & Bottom Sheet**		
Step	Tools Needed	Materials Needed	Description
1	Sheet Metal Cutter	AISI 1006-1018 Steel Sheet 0.914 mm	Cut sheet metal to a 800.30 mm x 517.30 mm rectangle.

Part # 15 x 2	**Side Sheet**		
Step	Tools Needed	Materials Needed	Description
1	Sheet Metal Cutter	AISI 1006-1018 Steel Sheet 0.914 mm	Cut sheet metal to a 517.30 mm x 97.30 mm rectangle.

Part # 16	**Back Sheet**		
Step	Tools Needed	Materials Needed	Description
1	Sheet Metal Cutter	AISI 1006-1018 Steel Sheet 0.914 mm	Cut sheet metal to a 800.30 mm x 97.30 mm rectangle.

Part # 17 x 3	**Case Divider**		
Step	Tools Needed	Materials Needed	Description
1	Band Saw	AISI 1006-1018 Steel Sheet 0.914 mm	Cut sheet metal to a 25.40 mm x 78.20 mm rectangle.

Part # 18 x 2	**Angled Slide Stop**		
Step	Tools Needed	Materials Needed	Description
1	Band Saw	AISI 1006-1018 Steel Sheet 0.914 mm	Cut sheet metal to a 25.40 mm x 105.00 mm rectangle.
2	Metal Break	Angled Slide Stop	Bend sheet 20 degrees across the width 25.40 mm from the side.
3	Glue	Magnet + Angled Slide Stop	Place the magnet on the 25.40 mm length on the inside of the bend. Glue it in place and allow it to cure.

Assembly # 2 **Frame**			
Step	Tools Needed	Materials Needed	Description
1	TIG Welder	Back Angle + Side Angle	Place back angle with the slit facing downwards. Place the side angle perpendicular to the back angle with their ends flush. TIG weld the two pieces together.
2	TIG Welder	Side Angle + Current Assembly	Repeat step 1 on opposite end of back angle with another side angle.
3 & 4	TIG Welder	Front Angle + Current Assembly	Place front angle with short side facing upwards. Place the front angle perpendicular to the two side angles and flush with their ends. TIG weld both ends.
5, 6, 7, & 8	TIG Welder	Back, Side, and Front Angles	Repeat steps 1 through 4 with the remaining back, side, and front angles.
9	TIG Welder	Front Corner + Current Assembly	Place the front corner perpendicular and flush with a corner made by the front and side angles of one of the assemblies. Place the front corner so that the short side is touching the short side of the front angle. TIG weld the front corner to both contacts.
10	TIG Welder	Front Corner + Current Assembly	Repeat step 9 at the opposite corner made by the front and and side angles.
11	TIG Welder	Back Corner + Current Assembly	Place the back corner perpendicular and flush with a corner made by the back and side angles.
12	TIG Welder	Back Corner + Current Assembly	Repeat step 11 at the opposite corner made by the back and side angles.
13	TIG Welder	Other Assembly + Current Assembly	Place the other assembly down with the bends facing upwards. Place the current assemblyon to of it with the corner angles facing down and the top mirroring the bottom. TIG weld all contacts.
14	TIG Welder	Slider Mount + Current Assembly	Place the side of the slider mount opposite the hole flush with the side angle with the hole closer to the bottom and __mm away from the back angle. TIG weld it in place.
15 & 16	TIG Welder	Slider Mount + Current Assembly	Repeat step 14 for __mm and __mm away from the back.
17, 18, & 19	TIG Welder	Slider Mount + Current Assembly	Repeat steps 14 through 16 for the opposite side.
20	TIG Welder	Connector Tab + Current Assembly	Place the connector tab inside the slit in the bottom back angle with the hole __mm down from the bottom. TIG weld it in place.
21	TIG Welder	Connector Tab + Current Assembly	Repeat step 20 on opposite side of bottom back angle.

Assembly # 3	**Unit**		
Step	Tools Needed	Materials Needed	Description
1	Metallic Spray Paint	Drawer	Spray paint the vertical part of the dividers. Allow to dry.
2	Tape	Drawer	Tape over the bearing sliders, the handle, and the vertical parts of the dividers.
3	Black Spray Paint	Drawer	Spray paint the entire drawer. Allow to dry.
4	Metallic Spray Paint	Frame	Spray paint the entire frame. Allow to dry.
5	Black Spray Paint	Sheet	Spray paint the top, bottom, back and side sheets. Allow to dry.
6	Black Spray Paint	Angled Slide Stop + Case Divider	Spray paint the angled slide stop and case dividers. Allow to dry.
7	Wrench	Drawer + Frame	Bolt the outer slides of the bearing sliders to all of the slider mounts.
8	Glue	Top Sheet + Current Assembly	Place the top sheet so that it sits on top of the current assembly in the milled out section.
			Glue it in place and leave it to cure.
9	Glue	Bottom Sheet + Current Assembly	Place the bottom sheet so that it is in the milled out portion of the bottom of the frame.
			Glue it in place and leave it to cure.
10	Glue	Side Sheet + Current Assembly	Place the side sheet so that it is in the milled out portion of the right side of the frame.
			Glue it in place and leave it to cure.
11	Glue	Side Sheet + Current Assembly	Repeat step 10 with the remaining side sheet and the left side.
12	Glue	Back Sheet + Current Assembly	Place the back sheet so that it is in the milled out portion of the back of the frame. Glue it
			in place and leave it to cure.
13	Drill Press	Current Assembly	Drill a __mm diameter hole in the back of the assembly 19.05 mm away from the top and
			28.58 mm away from the right side.
14	Drill Press	Current Assembly	Repeat step 13 for the left side.
15	Hand	Plunger + Current Assembly	Screw the plungers into the two holes just drilled.
16	Hand	Slide Stop + Current Assembly	Place the angled slide stop in one of the rows with the inside of the bend
			facing the back of the drawer.
17	Hand	Slides + Current Assembly	Place slides in a row in front of the angled slide stop.
18	Hand	Case Divider + Current Assembly	Place case dividers between the different slides.