Concrete is the single most used material on urban construction sites. It is inexpensive, durable, and strong in compression. It is also fairly easy to mix, mold, and spread into smooth surfaces. Concrete is often reinforced with steel rebar and then used in building construction to form floors and walls, among other building elements. It is no surprise then that on a typical deconstruction site, as observed by the Volvo CE team on our site visits, concrete removal is one of the more common tasks undertaken. The common methods of concrete removal involve either using a skid steer or excavator to break the concrete slabs using a suitable attachment or, when heavy machinery cannot access a given space, having construction workers use jackhammers to manually break the concrete. The slabs are then lifted, typically by construction workers, and hoisted out of the work area with wheelbarrows.

While using a skid steer with the appropriate attachment is usually an effective method of concrete removal, oftentimes these interior spaces cannot fit a skid steer or other heavy machinery. Therefore construction workers need to enter these rooms and use jackhammers to break the concrete. Because concrete removal produces a great deal of dust, the room must be effectively closed off and ventilated. Dust also creates an environment in which visibility is greatly decreased. Jackhammers alone are fairly dangerous pieces of equipment, and along with the dusty environment and uneven surfaces, this concrete removal method can be quite hazardous to the workers’ health. Figure 1-1 shows one such environment.

Figure 1-1: Stanford Animal Research Facility
For a material that is so voluminous on deconstruction sites and a task that is so common, the team believes that concrete removal represents a space in which Volvo CE could establish itself as a trailblazer. Volvo CE could create a more efficient and effective method of concrete removal, as well as ensure the safety of workers on a construction site. Construction workers could then be removed from the dark, dusty environments and move onto other jobs on the construction site that require their intuition and problem solving skills.

The Volvo 310X is a prototype concrete planing machine that is designed to more effectively remove concrete and facilitate the safe and efficient transport of the concrete debris from the work area. The machine is remotely controlled and removes concrete flooring layer by layer. Key features of the Volvo 310X are its weight and size. The Volvo 310X weighs less than 1000lbs (~ 460 kg) so that it is lighter than a skid steer and as such can be supported by weaker floors and many elevators. At 29.5” (75cm), it will fit through an average interior doorjamb of 30” (76cm). This addresses the need for accessibility.

Figure 1-2 shows the team’s current prototype of the machine. It uses 2 DC motors for the drive system, and an AC motor to turn the concrete planing drum, which is raised and lowered with a spring-loaded cam-lock mechanism.

Another important aspect to the Volvo 310X is the associated business model on which our global counterparts at the Blekinge Institute of Technology (BTH) in Sweden are currently working. Our global vision is to create a business model that will seamlessly integrate the Volvo 310X into
Volvo’s present product line. This business model includes a use case scenario and life cycle analysis, which highlights the functions of the 310X and its impact throughout its lifespan.

The complete global team envisions creating not only a product that removes concrete but also a sub-system within the construction industry. We believe that this machine and overall system model can create a shift in the construction industry toward smaller, semi-autonomous machines being used to address the monotonous and dangerous tasks on a job site. This will allow the construction workers - the valuable human resource on these sites - to use their skills and prowess in more effective decision-making roles on the job site.

1.2 Glossary

- **Benchmarking**: An information gathering process conducted at the beginning of a design challenge to discover existing analogous products, services or experiences that can inform the design of your product.
- **Brokk**: A company that produces remote control robotic arms for the construction industry
- **Concrete**: Concrete is a composite material that is composed of cement, rock and water. It is one of the most widely used materials on construction sites.
- **Dark Horse**: A prototype based on concepts that seemed unlikely to succeed or difficult to implement at first pass.
- **Debris**: unrecycled material that is bound for a landfill.
- **Discoverability**: the ease with which material can be located
- **Diversion**: the process of recovering and reusing materials that would otherwise have gone to a landfill
- **Extraction**: removing the material in a manner that preserves its value and is efficient and effective
- **Funktional Prototype**: A ‘funky’ prototype or proof of concept. The purpose of the funktional prototype is to convey the critical function of the product or experience by spending minimal effort on the seamless integration of the design elements.
- **Grapple**: An attachment for excavators and loaders that can grab things in in a way similar to a claw
- **Hauler**: Large machine meant for moving materials (basically a large dump truck)
- **Leachate**: a liquid byproduct of landfills and it is created from water that has drained through the waste in the landfills and as such contains high concentrations of toxic materials
- **Mapping**: locating the potentially valuable materials in an urban environment
- **Mining**: the process or industry of extracting minerals, metals or coal from a mine (excavation in the earth)
- **NPT**: National Pipe Thread. A measurement standard for hoses and fittings.
- **PPE**: Personal Protective Equipment.
• **Prepared and Unprepared Material:** in deconstruction, a prepared section of material is one that has been cut to less than 5 feet while an unprepared section has a length greater than 5 ft. There is more value for prepared material because it is easier to pack and ship.

• **Recoverability:** the ease with which material can be accessed, efficiently removed and reused

• **Recyclability:** the capacity a material has to be reclaimed and reformed into another useful material and the value that is achievable in this process

• **Recycling:** the process of converting a material into something new

• **RFID:** Radio-frequency identification. Uses differing radio frequencies accepted via a transceiver to identify different items.

• **Selective Deconstruction:** removing parts of a building or structure in a systematic and organized way that distinguishes between the different materials being removed

• **Separation:** sorting and organizing the material that has been recovered in order to prepare them for the next step (whether it be disposal, reuse, recycle)

• **Skid Loader (Skid-steer Loader):** a small engine powered machine that has arms that lift

• **Transceiver:** An electronic device that both transmits and receives electromagnetic signals

• **Urban Mining:** recovering or extracting valuable materials from a city environment

• **Urban Mining Sectors:** the four categories our group has divided Urban Mining into in order to better understand the design space. The four sectors are Mapping, Extraction, Separation and Recycling.
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2 Context

Our corporate sponsor, Volvo Construction Equipment (Volvo CE), first presented our global team with the design challenge of innovating in the urban mining industry. Volvo CE is known for their “big yellow machines”-construction vehicles such as skid steers, excavators, and haulers that are commonly found on mining or construction sites. Volvo is beginning to feel that their machines are becoming somewhat of a commodity and so, through their Emerging Technologies Department, they wanted to investigate the possibility of tapping into a burgeoning sub-industry in mining: urban mining.

2.1 Corporate Partner: Volvo Construction Equipment

Founded in 1832, Volvo CE is a leading developer, manufacturer, and supplier of construction equipment including but not limited to: articulated haulers, graders, compact and heavy wheeled loaders, and wheeled and tracked excavators. Volvo CE mainly distributes its machines through independent dealers to customers in more than 200 countries. As a subsidiary of the Volvo Group, Volvo CE maintains the core values of quality, safety, and environmental care.

2.1.1 Corporate Liaisons

Jenny Elfsberg – Director of Emerging Technologies, Volvo CE

Andreas Nordstrand – Manager: Emerging Technologies Department, Volvo CE

2.2 Need Statement

By the end of fall quarter, both the Stanford and BTH teams had spent a considerable amount of time doing needfinding and benchmarking in urban mining. Our findings led us to settle in the area of urban deconstruction—endeavoring to create a solution that would address the needs and inefficiencies in this industry. Subsequently, more directed needfinding during winter quarter helped the team distill four key needs in the industry. We identified the following needs:

a. Remove workers from hazardous situations

b. Make efficient use of human resources on a jobsite
c. Eliminate fumes and minimize noise

d. Enable machinery to access confined spaces

The team’s initial needfinding in the deconstruction industry led to contemplating improvements that could be made to the skid steer—one of the most commonly used tools in urban deconstruction. However, digging deeper into the industry, the team realized that the real pain points in the industry are not found around the skid steer’s abilities, but around its limitations. The team felt it could make its largest impact on the deconstruction industry if it tackled the tasks that existing technology cannot complete. The team chose to look to jobs that necessitate manual labor because of the shortcomings of existing heavy machinery, such as concrete removal in tight spaces.

2.3 Problem Statement

The team considered all of our learnings from needfinding and benchmarking. The prevalence of concrete removal stood out to the team. It was commonly mentioned in interviews and seen during site visits. This made us think more about the issue of manual concrete removal in tight spaces and what could be done to mitigate this problem. We identified the following pain points with concrete removal:

a. Volume of Concrete Produced. On average, over 7 billion tons of cement are produced annually. Further research showed that global concrete production has created a multi-billion dollar industry. The vast majority of this concrete is used on construction sites across the US and Europe. In the US alone, the concrete industry is valued at approximately 30 billion dollars annually. Therefore concrete removal is a task that will always be present in the construction industry in the near future.

b. Concrete removal is a loud, messy, monotonous and dusty process.

c. Accessibility—A skid steer is often unable to fit in the necessary space and so construction workers need to use jackhammers to manually break concrete.

d. Improper tooling—At times, faster concrete removal could occur if the right tool (end attachment on a skid steer) was used.

After identifying these pain points in concrete removal, we were motivated by the following questions:

- How might we remove construction workers from the dark, dusty environments which require limited innovation or problem-making skills?
- What if we could create a machine that could do the monotonous work currently done by construction workers?
- How can we decrease the noise and fumes associated with concrete removal?
- How might we increase the accessibility of machines on a job site?
We brainstormed and sketched several ideas as shown in Figure 2-1 to create and choose our final concept solution.

Figure 2-1: Winter Storming Session
2.4 Meet the Team

Stanford University

**Jack Brody** is from Atherton, CA. He has a bachelor’s degree in Product Design from Stanford University. He is currently pursuing his Master’s in Mechanical Engineering from Stanford University with a focus in design and innovation. He enjoys surfing, photography, learning about different cultures, and meeting new people.

**Calder Hughes** is originally from Portland, OR where his passions growing up were soccer and skiing. He completed a combined liberal arts and engineering degree between Whitman College and Columbia University. After college Calder moved to Hood River, Oregon where he spent 6 years working for a start-up Unmanned Aerial Systems Company called Insitu. He was married in 2011 to a journalist and avid skier, Lilly. Calder is in the second year of his master’s degree in mechanical Engineering.

**Tim Martin** is from Casco, Maine. He completed his undergraduate degree in Mechanical Engineering at Tufts University in Massachusetts. He is in his first year of the Master’s program in Mechanical Engineering at Stanford, specializing in design and dynamics. He spends his free time snowboarding, golfing, and playing guitar.

**Kezia Alfred** is a MS mechanical engineering student who is interested in design and manufacturing who grew up in Kingston, Jamaica. She has always been interested in making things, creating solutions and project management which is why her experience in ME310 has been a gratifying learning experience. Kezia enjoys good conversations, snacking and watching movies.
Blekinge Institute of Technology

Yi Chai is from Shanghai, China. She holds bachelor degrees in both Electrical Engineering and Automation. Now she is a master student at Blekinge Institute of Technology with a focus in Sustainable Product-Service System Innovation (MSPI). She is an amiable person who is interested in creative thinking and overcoming challenges. Music and sports are necessary in her life.

Zhenqing Gao is from Shanghai, China. He holds a bachelor degree in Electrical Engineering and Automation. Now he is a masters student at Blekinge Institute of Technology focusing in Sustainable Product-Service System Innovation (MSPI). He likes innovation and new ideas. He also likes to make friends.

David Andersson is from Varberg in Sweden. He is studying a Master of Science in Industrial Management and Engineering with a focus on mechanical engineering and sustainable development. He is a creative person with a high interest in politics, culture, and strategic sustainability. In his spare time he dances lindy hop, bugg and plays the viola.

2.4.1 Coach

Michael Balsamo – Drive Train Engineer, Tesla Motors
3 Design Requirements

3.1 Introduction

The deconstruction environment is highly demanding of both personnel and equipment. Workers in this industry must regularly endure loud, dirty and hazardous work environments. The equipment these men and women operate is no different. Demolition equipment must be able to operate in the most extreme conditions on these jobsites. Additionally, workers and site managers expect the equipment they use to provide reliable and robust functionality on a daily basis. Equipment must be easy to use, and perform the tasks expected of it.

The purpose of our vehicle is to demolish and remove concrete during the selective deconstruction of buildings in the urban environment. This setting provides challenges on many levels, both in terms of the functionality of the vehicle, as well as integration with the environment. Our vehicle must be able to successfully and efficiently remove concrete of varying specifications (dimension, strength, age, etc). It must also integrate well within the constraints of the modern urban jobsite, where power and access are limited, and noise and dust emissions are tightly controlled.

With this environment, and these users in mind, the team has developed requirements for the Volvo 310X that ensure that the final product delivers the promised functionality. The figure below (Figure 3-1) shows some of the early requirements development.

This diagram clearly shows the sub-systems we have designated for the vehicle, and some of the initial requirements. The following section provides more detailed requirements. Requirements are grouped into Functional Requirements, and then Physical Requirements. Within each of these sections, requirements are grouped into tables; System Level Requirements, Sub-System Requirements, Constraints, and Assumptions.
3.2 Functional Requirements

The Functional Requirements section identifies system and sub-system requirements related to functions that the system shall be able to achieve.
3.2.1 Functional Requirements

Table 3-1: Functional System Level Requirements

<table>
<thead>
<tr>
<th>Met?</th>
<th>#</th>
<th>Requirement Description</th>
<th>Metric</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>1.1</td>
<td>The system shall be able to remove concrete from any horizontal surface.</td>
<td>Removes concrete &gt;20 cubic ft/hr (0.566 cubic m/hr)</td>
<td>This rate is greater than what is achievable by two workers with jackhammers.</td>
</tr>
<tr>
<td>Y</td>
<td>1.2</td>
<td>The system shall reduce the overall noise on the jobsite caused by concrete removal.</td>
<td>Noise emission will be &lt;100 dB</td>
<td>Quieter than one jackhammers</td>
</tr>
<tr>
<td>N</td>
<td>1.3</td>
<td>The system shall reduce the dust on the job site caused by concrete removal</td>
<td>&lt;5% of the concrete crushed can enter the environment</td>
<td>Dust management on job sites is a major pain point, and a health risk for workers</td>
</tr>
<tr>
<td>Y</td>
<td>1.4</td>
<td>The system will allow a single operator to control the device remotely</td>
<td>Up to 75 ft away</td>
<td>This enables operators to be outside the rooms where the concrete removal is occurring</td>
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Table 3-2: Sub-System Functional Requirements

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<tr>
<th>Met?</th>
<th>#</th>
<th>Requirement Description</th>
<th>Metric</th>
<th>Rational</th>
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<tbody>
<tr>
<td>Y</td>
<td>2.1</td>
<td>Shall have sufficient traction and suspension to travel across an uneven floor</td>
<td>Climb a ledge up to 4” (10cm) or up to a 13 degree incline.</td>
<td>The vehicle must be able to access interior rooms, navigate obstacles and operate on the surface it leaves behind as it removes concrete.</td>
</tr>
<tr>
<td>Y</td>
<td>2.2</td>
<td>Shall be steerable</td>
<td>Can achieve at least a 3ft (~1m) turning radius.</td>
<td>This turn rate enables the vehicle to turn corners in tight hallways, and maximize the usefulness in confined rooms.</td>
</tr>
<tr>
<td>Y</td>
<td>2.3</td>
<td>The vehicle shall have multiple speeds that enable it to move about the jobsite and drive itself forward while removing concrete.</td>
<td>Multiple speed settings (speed control)</td>
<td>The vehicle needs to be able to transport itself, as larger equipment capable of moving the vehicle is not available inside buildings.</td>
</tr>
<tr>
<td>Y</td>
<td>2.4</td>
<td>The drive system must be immune to dust and debris created by the vehicle</td>
<td>System is not damaged or stopped by debris created during normal operation.</td>
<td>Motors and gears can easily be damaged by abrasive materials such as concrete dust and debris.</td>
</tr>
</tbody>
</table>
The power for the drive system shall be able to operate for at least an hour without need for recharge. Batteries should be at least rated at 75Ah. Final product would have an AC powered drive system. Thus the batteries should be sufficient to move the 310X from its storage point to inside the building where it would connect to AC supply.

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<td>Y</td>
<td>2.5</td>
<td>The power for the drive system shall be able to operate for at least an hour without need for recharge. Batteries should be at least rated at 75Ah. Final product would have an AC powered drive system. Thus the batteries should be sufficient to move the 310X from its storage point to inside the building where it would connect to AC supply.</td>
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**Communication & User Interface**

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<td>Y</td>
<td>2.6</td>
<td>Vehicle shall communicate wirelessly with a remote user in line-of-site with the vehicle. The person operating the vehicle must be able to see the vehicle directly. Without line-of-site operation, the vehicle will not comply with OSHA regulations.</td>
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<td>Y</td>
<td>2.7</td>
<td>Vehicle shall be equipped with external emergency stop mechanism. Located within arm’s reach of a person standing at any point around the vehicle. Another stop mechanism should be located at point of power supply. This feature ensures that any worker on the jobsite can shut down the machine.</td>
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<td>Y</td>
<td>2.8</td>
<td>The user interface, communications, and safety systems shall remain active for a specified amount of time even if electrical power is lost to the vehicle. Time before system shutdown &gt; 10 minutes. Safety and communications systems with the machine must remain active even if power to the vehicle is cut in order to ensure safe operation under all conditions.</td>
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**Concrete Milling**

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<td>Y</td>
<td>2.9</td>
<td>The depth of concrete removal shall be adjustable. 0.125” to 0.25” (3mm-12mm). This range should enable optimal removal rates, given the variation in the hardness/strength of the various concretes used in slabs.</td>
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<tr>
<td>Y</td>
<td>2.10</td>
<td>The power used by the concrete removal system shall not exceed available power supply options. Can be powered by a power source &gt;8HP and &lt;27HP ( &gt;6kW and &lt;20kW). This requirement doesn’t exceed the power available on the jobsite.</td>
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<tr>
<td>Y</td>
<td>2.11</td>
<td>Fragmentation method shall break concrete into pieces small enough to be picked up by the vacuum system. Fragments ~0.25” (8mm). Fragments this size are easily picked up by a vacuum standard shop vacuum and lend themselves to easier recycling.</td>
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**Structure & Body**

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<td>Y</td>
<td>2.12</td>
<td>The chassis must support the concrete removal system. Supports and restrains concrete removal system for all normal operation. The chassis must interface with all other vehicle sub-systems and meet their support and restraint needs.</td>
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<td>---</td>
</tr>
<tr>
<td>Y</td>
<td>2.13</td>
<td>The chassis must support the dust removal sub-system</td>
<td>Supports and restrains dust removal system for all normal operation.</td>
</tr>
<tr>
<td>Y</td>
<td>2.14</td>
<td>The chassis must support the Drive sub-system</td>
<td>Maximum load is 1000 lb (~450 kg)</td>
</tr>
<tr>
<td>Y</td>
<td>2.15</td>
<td>The chassis must provide routing for power systems.</td>
<td>Necessary mounting points and pass-thrus shall be provided</td>
</tr>
<tr>
<td>Y</td>
<td>2.16</td>
<td>The vehicle shall be aesthetically appealing</td>
<td>Shall be identifiable as “Sexy” by 9/10 nerds</td>
</tr>
<tr>
<td>Y</td>
<td>2.17</td>
<td>The outer body shall be durable</td>
<td>Shall not be permanently deformed by a 1lb (.45kg) spherical object dropped from 2 ft (60cm)</td>
</tr>
<tr>
<td>Y</td>
<td>2.18</td>
<td>The body shall have a lowering mechanism to create engagement of planer with floor</td>
<td>Vehicle should be lowered in increments of 0.25” (6mm)</td>
</tr>
</tbody>
</table>

**Power**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>2.19</td>
<td>The high voltage system will provide the necessary power to Drive, and Concrete Fabrication Subsystems</td>
<td>Maximum power supply is 240V, 30A single phase</td>
<td>High voltage systems can operate high power equipment more efficiently. Therefore the high power systems on the vehicle will be powered from this source.</td>
</tr>
<tr>
<td>Y</td>
<td>2.20</td>
<td>A low voltage power system will provide power to the onboard electronics and safety equipment</td>
<td>The onboard electronics and switching mechanisms are connected to the low voltage power system (6V)</td>
<td>Most small electronics and control hardware is designed for use with low voltage systems.</td>
</tr>
</tbody>
</table>

**Dust Collection & Containment**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>2.21</td>
<td>The dust collection system shall remove the majority of debris produced on each pass of the vehicle.</td>
<td>&gt;90% of debris removed</td>
<td>At this level of removal, debris created by a previous pass of the vehicle should not hinder subsequent passes of the vehicle, or interfere with concrete fragmentation</td>
</tr>
</tbody>
</table>
The vehicle shall keep the remaining dust within the footprint of the vehicle <5% of dust escapes into operating environment This will dramatically reduce the dust created by this operation on the jobsite, reducing the amount of work necessary to confine these areas on the jobsite

The overall system will transport concrete debris to a storage receptacle within a reasonable distance of the vehicle Debris transported to a distance < 75ft This is reasonable distance to transport the debris using a vacuum collection system based on the specifications of such systems.

Moveable by four workers at full weight capacity with no power Can be transported 200ft by 4 workers The concrete removal area is often some distance from the external pick-up points for concrete debris

Notes Regarding Unmet Requirements

- Dust and Debris Removal and Containment
  
  The team was unable to get conclusive data regarding the amount of dust generated by jackhammers and so we were unable to measure by what exact percentage the Volvo 310X reduced the dust and debris generated.

3.2.2 Functional Constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>The device must be more reliable and efficient than workers currently removing concrete.</td>
<td>Current workers are late, get sick, get tired, and get injured. The machine must be more reliable than the current system to be appealing to demolition site managers. It should be more efficient in order to be cost effective for demolition companies.</td>
</tr>
<tr>
<td>The device must continue to function in dusty conditions.</td>
<td>Regardless of the dust containment of our device, it must be assumed that the jobsite will be dusty and dirty.</td>
</tr>
<tr>
<td>The device should be transportable using an elevator with 4’ x 6’ interior dimensions, and a 1000 lb maximum load.</td>
<td>The vehicle will not be designed to travel up and down stairs, therefore elevator transport must be possible.</td>
</tr>
</tbody>
</table>
3.2.3 Functional Assumptions

Table 3-4: Functional Assumptions

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>This vehicle will be useful even if it cannot demolish vertical concrete</td>
<td>To include the capability to demolish vertical walls would expand the scope of our machine beyond our capacity within the class. We see this as a future opportunity.</td>
</tr>
<tr>
<td>walls.</td>
<td></td>
</tr>
<tr>
<td>This tool will still be desirable even if steel reinforcements still</td>
<td>Workers currently switch tools when they reach steel reinforcements. They use a torch to cut the steel, and then remove the fragments by hand.</td>
</tr>
<tr>
<td>require manual removal.</td>
<td></td>
</tr>
<tr>
<td>Increased efficiency will be required for deconstruction companies to</td>
<td>Already, the amount of valuable material a deconstruction company can salvage from a project can give it a competitive advantage in the bidding stage – doing this more efficiently in the future will be necessary.</td>
</tr>
<tr>
<td>remain competitive.</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Physical Requirements

The following tables outline the requirements which pertain to physical characteristics of the vehicle and system.

3.3.1 Physical Requirements

Table 3-5: System Level Physical Requirements

<table>
<thead>
<tr>
<th>Met?</th>
<th>#</th>
<th>Requirement Description</th>
<th>Metric</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>3.1</td>
<td>The vehicle shall operate on commonly available electric power.</td>
<td>Operates on 240V single phase power</td>
<td>Use of our vehicle should not require special infrastructure requirements.</td>
</tr>
<tr>
<td>Y</td>
<td>3.2</td>
<td>The vehicle shall not consume more current than commonly available on a single circuit.</td>
<td>Shall not require more than 40 amps</td>
<td>Use of our vehicle should not require special infrastructure requirements.</td>
</tr>
<tr>
<td>N</td>
<td>3.3</td>
<td>The vacuum system shall provide sufficient flow rate to remove dust and debris created during concrete removal.</td>
<td>Shall achieve 2500 CFM</td>
<td>This flow rate is what is provided by industrial dust collection systems, or ~10 heavy duty shop vacuums.</td>
</tr>
<tr>
<td>Y</td>
<td>3.4</td>
<td>The vehicle must be heavy enough to enable concrete demolition.</td>
<td>Must weigh more than 400lbs (180kg)</td>
<td>Based on the weight of 2 workers and their equipment which we are using as our removal rate benchmark.</td>
</tr>
</tbody>
</table>
The vehicle must be transportable in elevators, or travel on surfaces not rated for large industrial equipment. Must weigh less than 1000lbs (450kg) Based on rated capacities for elevators, and upper story floors and walkways.

<table>
<thead>
<tr>
<th>Met?</th>
<th>#</th>
<th>Requirement Description</th>
<th>Metric</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>3.5</td>
<td>The vehicle must be transportable in elevators, or travel on</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>surfaces not rated for large industrial equipment.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Must weigh less than 1000lbs (450kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Based on rated capacities for elevators, and upper story floors</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>and walkways.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-6: Sub-System Physical Requirements

<table>
<thead>
<tr>
<th>Met?</th>
<th>#</th>
<th>Requirement Description</th>
<th>Metric</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>4.1</td>
<td>The drive system shall deliver sufficient power to meet</td>
<td>&lt;5 HP (~4kW)</td>
<td>The requirements to travel over rough surfaces and to drive the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>maneuverability and travel requirements</td>
<td></td>
<td>concrete removal system will require high torque, though it does not</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>need to travel fast.</td>
</tr>
<tr>
<td>Y</td>
<td>4.2</td>
<td>The vehicle shall propel itself for transport (not on active</td>
<td>~300ft/min (1.5m/s)</td>
<td>This rate supports the needs to transport the unit within buildings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>roadways)</td>
<td></td>
<td>where heavy equipment is not available.</td>
</tr>
<tr>
<td>Y</td>
<td>4.3</td>
<td>Vehicle shall propel itself while removing concrete</td>
<td>&lt;300ft/min (&lt;1.5m/s)</td>
<td>This rate supports the desired</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>concrete removal rate of the system</td>
</tr>
<tr>
<td>Y</td>
<td>4.4</td>
<td>The wheel base of the vehicle will fit within the vehicle</td>
<td>Wheel base &lt; 30&quot; (&lt;80cm)</td>
<td>The wheel base must be no wider than the outside vehicle dimensions.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>footprint</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Communication, User Interface & Safety

<table>
<thead>
<tr>
<th>Met?</th>
<th>#</th>
<th>Requirement Description</th>
<th>Metric</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>4.5</td>
<td>The vehicle shall operate on a common, robust frequency</td>
<td>2.4 Ghz</td>
<td>This is a band commonly used for remote control vehicles, so radio and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>antennas are readily available.</td>
</tr>
<tr>
<td>Y</td>
<td>4.6</td>
<td>The user shall have an interface that they can hold in</td>
<td>Approximately</td>
<td>The user control device must be easily held in 2 hands by an operator.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>their hands.</td>
<td>6&quot; x 5&quot; x 2&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(15cm x 12cm x 5cm)</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>4.7</td>
<td>The user control unit must be able to withstand a drop test</td>
<td>Shall be</td>
<td>Equipment must be durable, and the user control unit is critical to</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>unharmed when</td>
<td>vehicle operation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>dropped from</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4ft (1.2m) in any</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>orientation</td>
<td></td>
</tr>
</tbody>
</table>

Concrete Milling

<table>
<thead>
<tr>
<th>Met?</th>
<th>#</th>
<th>Requirement Description</th>
<th>Metric</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>4.8</td>
<td>The weight of the concrete breaking system shall not exceed a</td>
<td>250lbs (110kg)</td>
<td>This weight should be moveable with an external engine hoist.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>specified weight maximum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Structure & Body

<table>
<thead>
<tr>
<th>Met?</th>
<th>#</th>
<th>Requirement Description</th>
<th>Metric</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>4.9</td>
<td>The outside dimensions of the vehicle frame shall fit within the</td>
<td>&lt; 30&quot; (&lt;80cm)</td>
<td>The subsystem must comply with the system level requirements.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vehicle envelope</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>4.10</td>
<td>The weight of the chassis shall not exceed 200lbs (90kg)</td>
<td>This weight fits within the system level requirement, and will help to ensure the vehicle.</td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>------</td>
<td>-------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>4.11</td>
<td>The vehicle will have structural hard points to enable it to be easily hoisted. Minimum of 3 points, each rated to the maximum vehicle weight.</td>
<td>At times it may be convenient to lift the vehicle onto other vehicle for transport, or onto upper or lower floors of buildings using a crane, or other such large piece of equipment.</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>4.12</td>
<td>The vehicle shall have tie down points Minimum of 3, each rated to the maximum vehicle weight</td>
<td>Tie down points are useful for securing the vehicle during transport, or for storage while it is not in use.</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>4.13</td>
<td>The structure shall have mounting points for ballast Shall be able to accommodate 200lbs (90kg)</td>
<td>In the event that the vehicle is not sufficiently heavy to react the concrete fragmentation forces, more weight may be necessary.</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>4.14</td>
<td>The body shall be easy to clean Can be wiped clean with dust rags and mild detergent.</td>
<td>The vehicle will be in an extremely dusty environment. The surfacing and components of the body and subsystems should be easy to clean with common cleaning supplies.</td>
<td></td>
</tr>
</tbody>
</table>

**Power**

| Y  | 4.15 | The drive system shall not consume excessive electrical power <5 HP (<4kW) of power | Motors in this range are available, and can provide sufficient power to meet functional requirements while not exceeding the vehicle system power limits. |
| Y  | 4.16 | The low voltage drive power system will be powered off of an onboard battery. Low voltage power system connects to the onboard battery | The battery is necessary to maintain control and safety features in the event of a loss of power to the vehicle. |
| Y  | 4.17 | The onboard battery will have sufficient energy storage to power the communication and safety equipment for the required time if electrical power is lost to the vehicle. 1.5 kWh | This energy storage level will enable the vehicle to continue operating critical communications and safety systems in the event that there is a loss of power to the vehicle. |
| Y  | 4.18 | The low voltage power system will provide power to the onboard electronics and safety equipment 24 V | This low voltage power is compatible with most off the shelf electronics hardware, and will be sufficient to power these systems. |

**Dust Collection**
Notes Regarding Unmet Requirements

- Dust Collection Capacity
  The team was unable to find a portable vacuum system that would allow both the required volume and easy mobility. The decision was made to prioritize mobility over capacity for the present prototype.

3.3.2 Physical Constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambidextrous User Interface</td>
<td>The user interface must be easy to use for both left and right handed workers</td>
</tr>
<tr>
<td>Doorways</td>
<td>Standard internal doorways are 30” (80cm)</td>
</tr>
<tr>
<td>Hallways</td>
<td>Many internal hallways are only 36” (90cm) wide, and have 90 degree corners.</td>
</tr>
<tr>
<td>Reparability</td>
<td>Basic repairs must be made by technicians on the jobsite.</td>
</tr>
</tbody>
</table>
### 3.3.3 Physical Assumptions

Table 3-8: Physical Assumptions

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased urbanization</td>
<td>The future will continue to require smaller and more capable equipment to extend the life of existing structures.</td>
</tr>
<tr>
<td>Future Power Availability</td>
<td>Our design assumes that the power available on jobsites of the future is equivalent to today's standards</td>
</tr>
<tr>
<td>Future use of concrete</td>
<td>Concrete will continue to be a common construction material in the future.</td>
</tr>
</tbody>
</table>
4  Design Development

4.1  Prompt Exploration
Given such a broad prompt of urban mining, our first goal was to better understand the assigned design space. In initial meetings with Andreas Nordstrand from Volvo CE, the team learned that Volvo was open to a great range of possible definitions of urban mining. To aid in our understanding, the team decided to break down urban mining into four different sectors. These sectors are mapping, extraction, separation, and recycling (please refer to the glossary for comprehensive definitions).

4.2  Brainstorming
Breaking down urban mining into a few separate areas helped to organize and direct the team’s thoughts. The team decided to explore various existing and futuristic methods of executing mapping, extraction, separation, and recycling. Each team member spent time individually putting together 50 ideas and then the ideas were brought together and expanded upon, leading to the diagram below, which includes many of the ideas we discussed.
This brainstorming led us to the need-finding experiences which will be discussed in the following section.

4.3 Needfinding

In developing a better understanding of the possible definitions of urban mining, the team also developed a hunger for knowledge about existing technology, processes, and needs. With that mindset, we moved forward with needfinding. Based on research and brainstorming, the team identified potential sites for urban mining. Landfills, underground utility projects, consumer electronics recycling facilities, aboveground construction and demolition projects, among other sites were brought up as potentially worthwhile sites to look into. We decided to focus our initial efforts on these four areas:
The most important part, and perhaps the most difficult part, about the need-finding experience was finding contacts in relevant industries. With some determination and a bit of luck, the assembled a rich list of contacts and appointments. See the table below for a list of contacts and their fields (organized chronologically).

Table 9: Need-finding contact information

<table>
<thead>
<tr>
<th>Contact</th>
<th>Company</th>
<th>Field</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bino Garcia</td>
<td>No E-Waste</td>
<td>Electronics Recycling</td>
<td>Heyward, CA</td>
</tr>
<tr>
<td>Dan North</td>
<td>Novato Landfill (WM Facility)</td>
<td>Landfill</td>
<td>Novato, CA</td>
</tr>
<tr>
<td>Matt Finley/David Kirk</td>
<td>McGuire &amp; Hester/Stanford</td>
<td>Underground Utilities</td>
<td>Stanford, CA</td>
</tr>
<tr>
<td>Tom Sako</td>
<td>Self-Employed</td>
<td>Builder</td>
<td>Menlo Park, CA</td>
</tr>
<tr>
<td>Steve Schwanke</td>
<td>Schwanke Architecture</td>
<td>Architecture</td>
<td>Menlo Park, CA</td>
</tr>
<tr>
<td>Sean Holifield</td>
<td>Silverado Contractors</td>
<td>Demolition</td>
<td>Oakland, CA</td>
</tr>
<tr>
<td>Steve Cunningham</td>
<td>Turner Construction</td>
<td>Construction</td>
<td>San Francisco, CA</td>
</tr>
</tbody>
</table>

4.3.1 No E-Waste – Heyward, CA
At the No E-Waste facility in Heyward, CA, the team received a tour and was given a great deal of useful information about electronics recycling.
Key Findings and needs considered moving forward:

- Most boards etc. are broken down to pure components by smelters overseas, sometimes in hazardous and unsafe conditions.
- Disposal of screen glass is difficult.
- Electronics are mostly taken apart by hand. The variation in construction and contents makes it difficult and sometimes unsafe to automate.

4.3.2 Redwood Landfill – Novato, CA
At the Novato, CA landfill, the team met with the site manager from whom we learned a great deal about the inner workings of landfills, and then were given a very informative tour of the site.
Key Findings and needs considered moving forward:

- Landfills are always looking to increase diversion rates because they can only be open as long as they stay below a certain level above sea level.
- Pre-regulation landfills potentially contain a great deal of valuable material.
- Regulations in CA and the USA overall can be very strict.
- Film plastic, drywall, and leachate are large problems at landfills.

4.3.3 McGuire & Hester – Stanford Underground Utilities Project
The Stanford and McGuire & Hester project managers gave the team a tour of an underground utility project on Stanford’s campus.
Key Findings and needs considered moving forward:

- Only old wiring/conduits etc. will be removed, if dug up completely as part of the job or they only take sections that are uncovered while the rest is left in the ground.
- It is very expensive to pay labor for underground projects. Every day a trench is open costs money.
- Salvaged material can be sold for a bit of money and is generally put back into the project budget.

4.3.4 Silverado Contractors – Oakland, CA
The team met with a site manager of many deconstruction projects. He took us through the process of deconstructing a few different types of structures.
Key Findings and needs considered moving forward:

- Many people are involved in deconstruction, which is a dangerous job due to the machines and tools to which workers are exposed and also the dust and debris generated.
- Material is more valuable if separated effectively and cut into small pieces (<5’).
- As of now, huge amounts of material are ripped out of wall with machines not intended for demolition, and then that material is finely separated by people on the floor.
- Dust can be dangerous to people in the area. The level of dust is reduced by water spray, which usually involves a worker with a hose. Water spraying attachments exist but usually a person seems more effective.
- The fewer people there are involved, the more predictable and safe the jobsite is, and the less liability there is for the company.
- Especially in buildings close to others or in projects where only parts of a building are being torn down, noise, vibration, and fumes are not looked upon fondly. (Electric machines would be helpful here.)
- Ladders are used to help workers cut down pipe etc. This is dangerous with tools in hand.
4.3.5 Turner Construction – Transbay Terminal Project, San Francisco
The team was granted a tour of the currently underground Transbay Terminal Project in downtown San Francisco. The tour was given by one of the managing contractors who answered a multitude of questions.

Figure 4-7: Transbay Terminal site

Key Findings and needs considered moving forward:

- The construction process can require as much as 10 times the amount of material that the actual structure retains.
- In urban environments, minimizing fumes and noise is of paramount importance.
- Many jobs require continuous driving back and forth-- perhaps automation would be beneficial.

4.4 Converging
After the first five visits above, the team felt the most pressing needs were in the area of construction and demolition. More specifically, interviews with the architect and the builder indicated that the deconstruction industry would be a great space to explore. The team also felt that Volvo CE would be more interested in a product aimed at the deconstruction industry, rather than an industry in which they are not already well entrenched (such as recycling). More research revealed that construction and demolition waste accounts for 170 million tons of debris
per year in the US alone, three times that of paper waste.\textsuperscript{1} Because we are a global team, we looked to our Swedish partners in this decision. They had also done some extensive needfinding in the deconstruction industry, and reported that it would be a worthy industry to pursue. (Refer to Appendix for more of our Swedish partners’ work.)

Thus the team chose to design for the deconstruction industry. However, this space was still quite broad. So before pressing on with more focused needfinding, the team wanted to break down this space into more approachable elements. This would help to simplify the problem and to better identify the questions to ask in subsequent need-finding experiences. We looked back to our breakdown of the four sectors of urban mining and focused them specifically on urban construction and deconstruction:

![Figure 4-8: 4 category breakdown of deconstruction](image)

The descriptions of each urban mining sector are as follows and each carries with it some questions that fueled our needfinding in the deconstruction industry:

- **Mapping**: Before an urban mining operation, we projected that it may be useful to know where the valuable material is in hopes that the deconstruction process may be expedited.
  - How important is this step?
  - Is this already done in an analogous space or one mentioned above?
  - What technology could be redirected for this purpose (imaging etc.)?

- **Extraction**: After finding the minable material, this sector involves removing the material.
  - To what extent is this done in urban deconstruction?
  - How difficult is this?
  - Would a new tool be useful here?

- **Separation**: Many times in typical mining operations, the valuable and sought after material is extracted along with undesired material. This necessitates a separation step.
  - How is this currently done with materials recovered from buildings to be demolished?

\textsuperscript{1} www.EPA.gov
- How is this done in analogous spaces such as materials mining?
  - Recycling: Once valuable material is removed, there are potential difficulties involved with effectively and sustainably reusing the removed material.
    - To what extent is this done in urban deconstruction?
    - At that point in the needfinding process, the question was how can the existing processes be improved?

In further needfinding meetings, we kept our breakdown of urban mining in mind as we asked questions and learned more about the space of deconstruction. In the descriptions of building deconstruction given to us by Mr. Holifield of Silverado Contractors and Mr. Cunningham out of Turner Construction, it seems that mapping is not currently done beyond that of the existing building plans. Considering the way in which building deconstruction is executed currently; a piece-by-piece removal where things are removed in the reverse order that they were installed, mapping technology seems an unnecessary piece in the puzzle.

Further, we learned that material removed from deconstructed buildings is currently being recycled at a rate of 70-99%. For this reason, we felt that the recycling market is a bit saturated.

With these considerations in mind, and considering the current products of Volvo CE, we felt that extraction and possibly separation are the best parts of deconstruction on which to focus moving forward.
4.5 Initial Conclusions

Within the broad topic of “Urban Mining” we refined the problem statement to focus on extraction and separation within commercial deconstruction projects. By making this process more efficient, we can encourage the collection of more of these valuable materials, and make doing so more cost effective for contractors. Our initial thought was that the best way to have an impact on these construction sites is to improve the most commonly used tool: the skid steer. We believed that if we could improve the skid steer – a tool that is found on nearly every deconstruction site – then we would be increasing effectiveness of deconstruction companies.

In order to improve the skid steer we envisioned the Urban Mining vehicle of the future as having three general characteristics:

1. It must be designed for the user with the specific task of deconstruction in mind – and provide the necessary functionality and ease of use to displace current methods.
2. It must provide value to the customer by increasing the efficiency of building deconstruction.

3. It must align with the demands of the crowded urban environment – low noise and low emissions.

We thought that an all-electric version of the current Volvo CE skid-steer loader, with an articulated multi-degree of freedom arm in place of the current buckets and grabbers would accomplish these three goals. The articulated, multi-DOF arm would allow the operator to easily reach, cut, and remove specific materials, thus speeding the process of extraction and sorting. A quick tool change capability for the arm would mean that operators could always use the most efficient tool for the task without time consuming and frustrating tool change operations. And finally, the all-electric drive and actuation system would be much quieter than today’s diesel machines, eliminate the fumes generated by burning diesel in enclosed spaces, and reduce the operating cost of these machines for the company.

Figure 4-10: Mockup of the final vehicle we are envisioning

4.5.1 Exploring a better skid steer

In the interest of improving the skid steer, we wanted to focus our attention back toward autonomy on the jobsite.
4.5.2 Initial Prototype

Interested in creating a small-scale autonomous construction vehicle, we purchased an iRobot Create, a reprogrammable version of iRobot’s Roomba: the autonomous vacuum cleaner, and outfitted it with a bucket for picking up items.

We used two IR transceivers so that the robot could follow the tag and RFID so that the robot will know when it has reached the desired location, and then read the tag to see what task it must carry out. We fabricated two wooden boxes akin to birdhouses so the IR signal would be directional, and placed RFID tags on the floor in front of the boxes. The robot was programmed to read the first tag, and then back up and find the other tag. This was a situation representative of a pickup/dropoff task on a jobsite.

The app interface would allow our user to control how the autonomous machines could best be used on the job site. It allows the user to control which tasks the machines perform, where they should go, and monitor their activity. The key point in this interface is that in controlling how the machines work, it’s also allowing the user to decide when human input (for decision making or
sensing) is necessary. It allows Ned to act in an integral capacity on the job site as the decision maker or the conductor.

![Image](image.png)

Figure 4-13: App front page, additional screens in Appendix

### 4.5.3 Takeaways

From our user testing and prototype, we gained the following insights:

- Activity logs would be useful for site managers so they track how each machine performs.
- Site managers today already make use of 3D imaging software to map out and make plans for deconstruction.
- Having a local positioning system (LPS) would be vital to facilitate effective communication with machines on a job site. IR and RFID would not be viable outdoors or in such complex environments.
- A lot of information is needed to automate a task. It could involve organizing several simultaneous tasks or sequencing events. This helped us recognize the benefit of human input on a job site.
- There is opportunity for more integration of the information provided to site managers and construction workers (incorporating visual real time data, activity log of machines and workers, site plans and pictures).
- Incremental automation or the integration of human and machine on the job site has great potential.
Though we learned a great deal from the prototype, our main takeaway concerned incremental adoption of autonomy. Due to the huge amounts of environmental awareness necessary for proper autonomy on the ever-changing deconstruction site, the best way forward with autonomy would have to be incremental. In addition, urban deconstruction is inherently done in proximity to other people, buildings, and residential areas. Consequently, deconstruction jobs must be mindful of their surroundings to keep people safe and to minimize distractions. Armed with these insights we refocused our attention on improving the skid steer.

4.6 Refocusing

As mentioned previously, the skid steer is one of the most commonly used tools on the jobsite. With that said, the skid steer is not perfectly suited for the deconstruction environment, and we felt that this meant there is room for innovation regarding the skid steer. Currently, changing between tools and attachments of a skid steer is a cumbersome (requiring 2+ workers) and time consuming (5+ minutes) process. It involves driving the machine over to the location of the desired attachment, having someone outside the vehicle remove the pins holding the current attachment, and lining up the vehicle with the new attachment on the ground. Because of this, many machine operators choose to use tools poorly suited to the task at hand. For example, a jackhammer is often used bit to push concrete out of the way between jackhammer locations. In our prototype, we considered the case of having a jackhammer attachment and grapple attachment onboard.

We wanted to tackle this problem for the Funktional prototype. The solution involved three main components:

- Automatic tool change
  - The operator can press a button and have the tool be changed without help from another worker on the site
- Onboard tools
  - A small number of attachments would be kept onboard the skid steer
- Increased degrees of freedom for skid steer arm – dual purpose
  - Facilitates the quick change system
  - Increases the delicacy with which the skid steer may accomplish tasks (important in selective deconstruction jobs)

We believed that adding these capabilities to a skid steer would allow operators to more efficiently change attachments, and become more efficient workers.
4.6.1 Scope

Before we could begin to design this solution, we first needed to lay out the scope of our solution. First, we laid out the deconstruction environment to see where this solution fits. We felt that we could influence much of what the deconstruction worker does with this solution.

Then, we laid out system level diagram of our Funktional prototype solution. As shown in the diagram, the operator inputs a tool change command. The processor takes this in, and uses the encoded actuators to move to rough positions, and the camera to replace or attach the desired tools. There also would be a visual display for the operator, but for this prototype we decided to concern ourselves with the location of the tools, and the learning the number of degrees of freedom to accomplish our objectives.
With that, we began to design the mechanism and narrow down the possible onboard locations for the tools.
4.6.2 The prototype for a better skid steer

The prototype system consisted of the following components:

Our prototype consists of:
- A robotic arm made up of a servo that powers a small gear train and two linear actuators controlled by an Arduino
- An electromagnet that serves as our grabber attachment
- Three Lego trays that act as our tool holders
- Three tools (nuts)
- A Lego skid steer

It successfully accomplished the following tasks:
- Picks up tools from 3 different locations on body
• Drops tool in trays on 3 different locations on skid steer
• Extends arm to reach position far from body

4.6.3 Learnings

We gleaned the following from the Funktional Prototype:

• Degrees of Freedom- At least 3, 4 is sufficient and 5 would be optimal
• Servo position seems sufficient to get range of motion we would want on the real skid steer.
• Electromagnets can be difficult to work with.
• Current tool position seems effective.
• Encoders are sufficient for position data and execution. While visual is appealing, it might also bring more trouble than it’s worth.

4.6.4 Concerns

While the experience was a positive one, the teaching team raised some valid points about the value of this capability at full scale. Some of the questions that came up are as follows:

• Do operators change tools often enough to make this useful?
• Because machine weight is already a concern, will this add too much weight?
• Is there a different solution that could have a bigger impact?

These questions gave us a thirst for more knowledge about the deconstruction and so we reached out to some contacts in the interest of speaking to more experts.

4.7 Additional Needfinding

4.7.1 San Jose State Project

After inquiring about the possibility of speaking to some machine operators about their jobs, we were set up with a crew from Silverado Contractors. We spoke with them over their lunch break during a small project at San Jose State University. The superintendent of the crew was Luis Alvarez (Figure 4-17), and he gave us some valuable insights into the workplace for demolition workers that drastically changed our direction for the course of the project.
Key Learnings:

- Skid steer loaders do not generally fit in elevators.
- When machinery does not fit into a space, demolition work must be executed by hand
- There is a desire in industry for machinery controllable from outside the room in which the machine is being utilized

It was after this incredibly insightful interview with Mr. Alvarez that we realized maybe we have been asking the wrong question the entire time. Maybe the question is not “how can we improve the skid steer?” but rather “in what situations does the skid steer fall short?”

4.7.2 Stanford Animal Research Facility Project

With this new question in mind we continued on our site visits and needfinding. We were invited for a guided tour of the renovation project taking place at the Stanford Animal Research Facility at the Medical School. Stanford contracted the renovation job out to McCarthy Building Companies, who had in turn subcontracted Silverado Contractors to do the demolition work. Ephraim Bahiru of McCarthy and Jake Schell of Silverado showed us around the site.
This was the site that gave us the inspiration for our final design direction. We walked into the room pictured above and were shocked by what we saw. It was dark, dusty, and incredibly loud. Because skid steers are too large to access this particular room in the deconstruction site four jackhammer operators were forced to remove the concrete manually. They worked in this room for 8 hours a day – we could hardly be in there for 5 minutes. This led us to believe that there may be an opportunity to help construction companies remove concrete from these ever-common confined spaces on urban deconstruction sites.

4.7.3 Four distilled needs
With Luis’ interview and the animal research facility project as inspiration we distilled four final needs we believed were compelling enough to design for.

Those four main needs are:

1. **Need to remove workers from hazardous situations**
   - Situations similar to the scene of manual concrete removal in the animal research facility are dangerous, tedious, and inefficient.

2. **Need to make better use of human resources on the job site**
• Humans should be utilizing problem solving skills to perform more intellectual tasks, while machines should be left to do the heavy lifting.

3. **Need to minimize dust, fumes, and noise on the urban deconstruction site**
   • Urban deconstruction is in close proximity to business, people, and residential areas. Thus it is important to mitigate the amount of noise, dust, and fumes that may affect their surroundings

4. **Need to provide machinery greater access to confined locations**
   • Confined spaces are a reality on urban deconstruction sites. Hallways, elevators, and doorways, in renovations or selective deconstruction jobs limit the use of efficient heavy machinery on these job sites and necessitate the use of hazardous and expensive manual labor.

4.7.4 **The case for concrete**

Before going forward, however, we wanted to make sure that concrete removal was prevalent enough to warrant a solution. What we found was staggering:

• Concrete is the single most widely used material in the world
• Twice as much concrete is used in construction around the world than the total of all other building materials

4.7.4.1 **The business case**

In addition, our Swedish teammates looked into the business case associated with more efficient concrete removal.

They discovered that concrete consumption in the world is estimated at two and a half tons per capita per year (CAMBUREAU, 2008; Mehta, 2009). To make this huge volume of concrete 2.62 billion tons of cement, 13.12 billion tons of aggregate, and 1.75 billion tons of water is necessary. More often than not, this aggregate is collected from mountains or river gravels. A significant amount of natural resource can be saved if demolished concrete is recycled and reused as this aggregate. In addition to the saving of natural resources, recycling of demolished concrete will also create additional business opportunities and save the cost of disposal.

At present, the amount of global demolished concrete is estimated at 2~3 billion tons (Torring and Lauritzen, 2002). It is also estimated that in the next ten years, the amount of demolished concrete will be increased to 7.5~12.5 billion tons (Torring and Lauritzen, 2002). If technology and public acceptance of using recycled aggregate are developed and 100% of demolished concrete is recycled for new construction, there will be no further requirement for new (non-recycled) aggregate.
4.7.4.2 **Value of recycled concrete**

The Swedish team also found that “if the aggregate has higher flakiness index and used for making concrete, the developed fresh concrete will have lower workability. Meanwhile, the elongated particles also adversely affect the strength of concrete especially the durability and flexural strength because the bond between the aggregate and cement paste depends on it” (Gambhir, M. L., 2004). According to their search, the size of recycled concrete affected the compressive strength of new concrete. The results showed that 10mm and 14mm size of recycled concrete is better than the larger 20mm size.

Figure 4-19: Concrete broken up by the 310X into recyclable sizes

In addition, concrete buildings, when demolished, can serve as an excellent source of new building materials to proximal buildings. “Instead of transporting aggregate from far away, we can use local buildings as a source for aggregates” (Francesco Di Maio, 2013). Preserving and adapting older building for new uses will increase their energy efficiency and reduce their carbon footprint. Concrete buildings, when demolished, can serve as an excellent source of new building materials. More on our global team’s findings are available in the Appendix.
4.8 Addressing the needs

With such compelling needs and a very convincing case for concrete removal we decided to go forward with designing a solution for the aforementioned needs with specific attention to concrete removal. We wanted our machine to have six key features:

- Concrete breaking
  - An array of pneumatic chippers will break concrete away from the slab to be removed
- Concrete crushing
  - An array of pneumatic hammers will crush the broken concrete to a reduced size
- Debris removal
  - A vacuum system will transport the broken concrete to a receptacle in another location
- Dust mitigation
  - A skirt setup will keep the dust under the vehicle, while a water spray system will keep the dust at ground level
- Noise dampening
  - Vibrational damping throughout the machine will reduce the noise typically associated with concrete removal
- Driver control
  - Remote control will be implemented to allow a worker to control the device with minimal physical strain

4.8.1 Initial Prototype

In the interest of the first prototype, we focused on the most pivotal feature mentioned above: concrete breaking. We wanted to know if concrete breaking with an array of jackhammers on a cart-like structure was possible, and how motion would be achieved with this configuration. This necessitated design, creation, and testing of a few systems.
4.8.1.1 **Pneumatic Chipper Hammers**

We purchased one midsize Husky brand pneumatic chipping hammer (Figure 4-20), which runs on 2cfm of air at 90psi. We poured 2’x2’ square of concrete, and broke this up with the hammer to test its effectiveness, as well as experiment with the most effective way to break up concrete (angle, application force, etc.). We found that starting with the gun perpendicular to the concrete, and then angling the gun to go across the slab was the most effective (Figure 4-21).

![Husky brand handheld pneumatic chipping hammer](image1)

**Figure 4-20: Husky brand handheld pneumatic chipping hammer**

![Benchmarking with a Husky hammer](image2)

**Figure 4-21: Benchmarking with a Husky hammer**

With these learnings, we went out and purchased one more of the midsize pneumatic chipper, and two of the smaller version with similar pneumatic specifications. At this point, we had purchased two air compressors so that we could run all four guns at once.
4.8.1.2 *Cart Structure*

A 27”x40” cart was constructed from 2”x4” wood. We purchased four 10” lawnmower wheels, and mounted them with a 5/8” shaft and pillow brackets. Not concerned with turning, we fixed the pillow brackets to the frame. In the frame we mounted two boxes for holding the four pneumatic chipping hammers. One box holds the guns straight up and down. The other box holds the guns at an angle in the rear of the cart so that these guns can find the holes created by the forward guns and break strips on concrete down the slab. Both boxes were constructed with adjustability in mind for testing purposes. The first iteration of the boxes was built with Duron and aluminum. The second was built purely of aluminum, with 80/20 bracing.

4.8.1.3 *Pneumatic System*

Using assorted fittings and ¼” NPT air hose, we fashioned an air system from the compressors to the guns. The front and rear guns were activated by two different switch. The rear guns’ switch also activated two pneumatic linear actuators that lifted the front hammers out of the way, allowing the vehicle to move forward with the rear angled hammers engaged (Figure 4-23).
4.8.1.4 **Testing and Results**

Testing the device was relatively successful as well as extremely informative. The following is a list of learnings we achieved through the functional prototype.

- Feasible design
- More weight required behind chippers
- Stronger air pistons required for lifting vertical chippers
- Aluminum provides ample rigidity for holding chippers (at least for short time)
- Back and forth motion required for continuous forward breaking
- More chippers or alternate concrete removal method required
- Increased maneuverability will be necessary

We came out of the functional prototype experience with some concerns regarding the effectiveness of the array of pneumatic chipping hammers as our removal mechanism and decided to explore other methods.
4.9 Final Prototype

4.9.1 Alternate concrete removal mechanisms

When exploring different concrete removal mechanisms we knew that we wanted to look into milling methods. In our search for concrete milling equipment we came across Smith Manufacturing, a company that manufactures and sells sidewalk “scarifiers” – machines used to level uneven sidewalk edges. After watching their product videos, reading about their products, and conversations with engineers within the company we decided that this would be a valid method to experiment with further.

Smith Manufacturing offers an array of different cutting drums – all suited to different materials and tasks.

Smith Manufacturing engineers recommended the “Plane-It” drum (Figure 4-24) with Tungsten Carbide tips for higher volume concrete milling. We decided to employ this new concrete removing method in our final prototype and it drove a lot of the final design.
4.9.2 Subsystems

In order to make the final design of the 310X prototype more approachable, it is broken down into manageable subsystems. These subsystems include: the concrete planing/cutting system, the rigid chassis or vehicle body, the drive system (including tracks, drive motors, power, and control), the planer engagement system, the vacuum, and dust mitigation skirt.

4.9.2.1 Designing the planing system

As with the first prototype, we began by concentrating our efforts on the actual concrete removing mechanism as this was the most critical feature of our machine. We benchmarked Smith Manufacturing’s SPS10 electric Multi-Use Surface Preparator to aid in our design.
The SPS10 uses a single-phase 5.0 HP motor to drive its cutting drum and advertises a 1/8” planing depth. Because efficient concrete removal was one of our main requirements we decided to use a 7.5 HP motor in the hopes that we would be able to improve on the SPS10’s planing depth. Experts in the industry had said that the cutting depth of the SPS10 and machines like it are limited by power, not the drum itself. The unit’s weight of 250 lbs also gave us a minimum weight requirement that we would need to meet in order to plane concrete.
The team decided on the Leeson 132044.00 7.5 HP single-phase 240 volt AC motor to drive our planing drum. In designing the subsystem, we placed the 80 lb. motor above the drum so as to use its weight as a counter to the up-cutting drum. The team coupled the motor and drum with a belt using a 2:1 ratio so that the drum would spin at half the speed of the motor and run at the manufacturer’s rated cutting speed of 1800 RPM.

Finally, knowing that the cutting mechanism would need to raise and lower, the team implemented a welded frame of steel tubing, to which hinge arms could later attach, and give the hinge arms a rigid frame to move.

4.9.2.2 Designing the chassis

The chassis of the vehicle would act as the rigid structure on which all other subsystems were mounted. Most importantly, it needed to be able to make the moving planer assembly rigid when the cutter was engaged. As such it had to be structurally sound, with ample flexibility for design and assembly changes. In order to achieve this rigidity the chassis was designed to incorporate 1.5” square steel tubing with ⅛” wall thickness welded together at its joints.
The chassis also included ⅜" spacing plates welded to its sides to space the side plates that would provide an interface to the tracks away from the outside of the steel tubing -- allowing the planing system arms to pivot freely.
4.9.2.3 **Designing the drive system**

The drive system for the Volvo 310X is a critical feature as it would determine how the vehicle would be able to navigate the dusty and obstacle-ridden urban deconstruction environment. The team had a decision to make between wheels and tracks. After weighing the pros and cons of the two, considering factors such as aesthetics, robustness, functionality and versatility, the team decided to use tracks.

4.9.2.3.1 **Tracks**

Having decided to use tracks, the team spent a lot of time trying to locate tracks that were small enough to be used with the overall required footprint of the vehicle as well as robust enough to deal with the dusty and dirty rooms in which it would operate. It proved to be quite difficult to find the right sized tracks. For example, even smaller vehicles such as snowmobiles had tracks that were too wide. The tracks that were ultimately used were found when the team went to visit A Tool Shed Equipment Rental in Santa Clara and saw the right sized tracks on a Barreto track trencher.

The tracks used on the Volvo 310X are 7” (20cm) and have 40” (101 cm) of ground contact.
Tracks proved to be effective because they:

- are able to climb over obstacles such as rubble or low ledges
- provide good traction even when moving over uneven surfaces
- have an aesthetically pleasing look that conveys ruggedness and versatility

4.9.2.3.2 Motors & gearboxes

Having found the tracks, motors and gearboxes needed to be specified to achieve the required cutting and non-cutting speed both on a flat surface and up to a 13 degree incline. The calculations below indicated that we needed at least one 0.5 HP motor with a 20:1 gear ratio gearbox for each side of the track.
Motor Sizing Calculations

- Calculate Necessary RPM of drive motors
  \[ v_{\text{max}} = 1.5 \frac{m}{s} \quad a_{\text{max}} = 0.75 \frac{m}{s^2} \quad \mu_{\text{roll}} = 0.03 \quad m = 250 \text{ kg} \quad r_{\text{drive}} = 0.13 \text{ m} \]
  \[ F_{\text{move}} = m \cdot g \cdot \mu_{\text{roll}} = 89 \text{ N} \]
  \[ T_{\text{move}} = r_{\text{drive}} \cdot F_{\text{move}} = 12 \text{ N} \cdot \text{m} \]
  \[ C_d = 0.82 \frac{m}{\text{rev}} \quad \text{Forward motion per revolution of the drive gear to hit } v_{\text{max}} \]
  \[ \frac{v_{\text{max}}}{C_d} = 110 \text{ RPM} \quad \text{This is the necessary output RPM of the drive motors} \]

- Calculate Necessary Torque of Drive Motors to accelerate w/o engaging drum
  \[ F_{\text{accel}} = m \cdot a = 225 \text{ N} \]
  \[ F_{\text{total}} = F_{\text{move}} + F_{\text{accel}} \]
  \[ T_{\text{total}} = \frac{F_{\text{total}} \cdot r_{\text{drive}}}{2 \text{ motors}} = 21 \text{ N} \cdot \text{m} \]

- Calculate Necessary Torque of Drive Motors w/ engaged drum
  \[ r_{\text{drum}} = 0.1 \text{ m} \quad P_{\text{drum-motor}} = 6 \text{ kW} \quad \omega_{\text{drum-motor}} = 189 \frac{\text{rad}}{s} \]
  \[ T_{\text{drum-motor}} = \frac{P_{\text{drum-motor}}}{\omega_{\text{drum-motor}}} = 32 \text{ N} \cdot \text{m} \]
  \[ F_{\text{drum-radius}} = \frac{T_{\text{drum-motor}}}{r_{\text{drum}}} = 320 \text{ N} \]
  \[ F_{\text{total}} = 500 \text{ N} \quad \text{(includes Factor of Safety)} \]
  \[ F_{\text{total}} = 250 \frac{N}{\text{drive motor}} \]
  \[ T_{\text{drive}} = F_{\text{total}} \cdot r_{\text{drive}} = 33 \text{ N} \cdot \text{m} \quad \text{So this is the limiting case} \]

We need drive motors and gear boxes that will allow us to apply \textbf{33N·m} (\textbf{23.4 ft-lb}) of torque to each drive wheel at \textbf{110 RPM}.

We used \textbf{2 1HP motors} rated for \textbf{1800 RPM} (and \textbf{2.92ft-lb}), geared down with \textbf{20:1} gearboxes. This gives us \textbf{~90RPM} and \textbf{~60ft-lb} of torque per motor.
To allow room for error, one 1 HP motor with a 20:1 gear was purchased for each side of the track.

A custom drive hub had to be made so that the shaft of the gearboxes could be coupled with the track’s sprockets. The hub was made of aluminum, turned on a lathe and a ¼” keyway was broached.

Upon testing the Volvo 310X with the 20:1 gearboxes, the team saw that the vehicle was unable to turn due to the increased amount of friction between the tracks and the surface during differential steering maneuvers. The best turning motion was a slight jerk which happened when the vehicle halted to a stop after it accelerated for a bit. To increase its chances of turning, the team incorporated a caster wheel at the front of the vehicle to decrease the amount of surface area between the tracks and the floor. This helped the Volvo 310X to turn with a wide (~5ft/1.5m) turning radius. The team then purchased 40:1 gearboxes in order to increase the amount of torque, after realizing they had underestimated the effect the friction of the tracks would have on turning ability. The 40:1 gearbox in addition to the castor wheel allowed the vehicle to turn much more smoothly with an effective turning radius of zero. It also allowed for the more sensitive speed control at the lower speeds utilized when planing.

4.9.2.3.3 Batteries

The team decided that it was important to have a power supply for the track system that was DC as specified in the design requirements so that it could be non-tethered while navigating a jobsite. The batteries chosen for the prototype were two 75Ah 12V AGM batteries. The batteries are mounted at the front of the vehicle and also serve as a counterweight for the concrete planing subsystem at the vehicle’s rear. They are also mounted in an orientation that minimizes wiring complexity. With a rating of 75Ah, this ensured that the prototype could run for at least one hour without the need to recharge. This was sufficient time for the team to test the reliability and functionality of the Volvo 310X.

4.9.2.3.4 Remote control and Speed controller

More searching was done to find a remote control system that would be long range, robust enough to handle multiple possible incoming signals and would allow for fine tune control in the lower speed range. The remote control system used is the Futaba 6J.
To allow the remote controller to communicate with the motors, a motor controller was needed that would allow two channels of 24V and up to 60A, as well as direction reversal. 24V is the desired maximum voltage created by the onboard batteries, and 60A allowed for a safety buffer above the motors’ rated maximum amperage: 40A. The team settled on the Roboteq MDC 2460. Roboteq’s products interface with their own software package that allows for easy adjustment of the motor controller. The controller also incorporates an RS232 port which allowed the RC receiver to interface with the motor controller.
4.9.2.4 Designing the cam lowering system

Clearly it would not be ideal for the concrete planer to be engaged at all times. The vehicle needs to traverse over obstacles, as well as flooring desired to be left intact. Thus, a lowering system for the cam needed to be designed. The team wanted the mechanism to lock the cutter into place, so that the main chassis could bear most of the weight, and to ensure that the cutter would not bounce during engagement.

The team designed a frame to encase the cutting drum, and a steel tube frame to attach that to two 42” steel hinge arms. These arms extend into the chassis of the 310X, and hinge near the front, just behind the battery. The long arms allow the cutter to move mostly up and down. During travel, the cutter is held up by two springs with a spring constant of 250lb/in (440 N/cm). These springs rest on plates attached to the chassis and he underside of the hinge arms, and are held in place by tapped aluminum nubs, bolted to the plates. A crossbar was welded across the hinge arms, just in front of the cutter. This allows for a cam mechanism to push the cutter frame down. A cam mechanism was designed to attach to the rear of the chassis, with a radius increasing from 4” to 8” over a 90 degree rotation. This allowed the cam to move the cutter from 2” above ground, down to ¼” of engagement. After initial testing, it was discovered that the cam was engaging the cutter at just over ½”, and thus had to be ground down to its present size. The cam featured a slight over-center, followed by a 3” flat zone; this assured that the cam and cutter were locked into position. Finally, the lowering system incorporated rubber stoppers in the chassis of the 310X onto which the hinge arms are lowered. During engagement, the hinge arms are locked between the cam and rubber stoppers, assuring no bounce of the cutter.

In order to give the user more control and increase the ease of cutter engagement, a cam handle extender was made from aluminum tubing, with a plasti-dip handle. It was painted yellow to incorporate the Volvo CE look.
Figure 4-33: Cam Assembly

Figure 4-34: Single operator planer engagement
4.9.2.5 Vacuum system

Concrete removal is a highly dust inducing process. The goal of the team was to create a vacuum system that eliminated nearly all of the dust, and would allow workers to operate in the same room as the 310X, without all of the ventilation equipment and PPE required currently. When tested without a vacuum system or dust skirt, the 310X’s rotary cutting mechanism created a great deal of dust, similar to what would be expected.

The primary aim of the vacuum system was to reduce the amount of dust that was generated when the 310X was tested without a vacuum. A 14 gallon (53 liters) 6HP (4.5kW) shop vacuum purchased from Home Depot was used. One of the end attachments for the vacuum hose was fit into a custom designed aluminum plate and subsequently bolted to the front of the cutting mechanism’s frame. With the up-cut orientation of the drum, dust is propelled up into the vacuum. The hose from the vacuum is routed through a preplanned hole in the motor mount plate, and then out the back of the vehicle where the castered vacuum body can trail the vehicle during operation.

4.9.2.6 Dust skirt and enclosures

In order to maximize the effectiveness of the vacuum system, and to keep any excess dust and debris contained inside the vehicle, a skirt was employed. The rear, top, and sides of the cutter frame were covered with 0.080” thick aluminum diamond plate with approximately 3in (7.5cm) spacing to the floor. 4” (10cm) nylon bristles from RV mud flaps were attached to the bottom of the diamond plate such that when the cutter was engaged, the skirt bristles were touching the floor, and maximized dust containment. The dust skirt was highly effective at containing dust and could potentially be improved by increasing vacuum power, increasing the number of vacuums and rubber bristles instead of nylon.

4.9.3 Manufacturing

The manufacturing process of the 310X exposed our initial design flaws, most obvious of which was the team’s mishandling of design for assembly. Fortunately, quick in situ design changes along with the use of a grinder allowed for full vehicle assembly with only minor hiccups. In order to convey the extensive assembly process and to provide instructions for the manufacturing process of the vehicle the team has compiled an instructive list of manufacturing and assembly steps.

4.9.3.1 Planer System
1. Acquire stock parts for planer subsystem.
2. Waterjet cut 5 steel plates to create the planer housing and motor mount as well as 2 aluminum plates for mounting the planer drum.
3. Weld the housing assembly.
4. Attach one of the aluminum plates to the planer housing.
5. Attach one of the bearings to the attached aluminum side plate.
6. Slide the planer shaft through the aforementioned bearing.
7. Slide the planer onto the shaft.
8. Attach the remaining bearing to the remaining aluminum plate.
9. Slide the bearing over the free shaft end, and attach the aluminum plate to the planer housing.
10. Place the belt pulley over the end of the shaft; insert key, setscrews, and Loctite.
11. Turn the inside diameter of the motor pulley to 1-¼”, place over motor shaft and insert key, setscrews, and Loctite.
12. Place aluminum motor spacers over holes in top of planer housing.
13. Place the belt over the planer shaft pulley, place motor on top of planer housing, tilt to put the belt on the motor pulley, and bolt into place.

Figure 4-35: Planer explosion
4.9.3.2 **Chassis**

1. Acquire twelve 1.5” square steel tubes with ¼” wall thickness.
2. Acquire eighteen ⅜” spacing plates.
3. Water jet cut two side plates for track interfacing.
4. Water jet cut two plates for battery placement.
5. Acquire one aluminum plate and drill holes for motor and gearbox mounting.
6. Using a mill, drill the holes for plate assembly, eye hooks, and planer system pivot arm hinges.
7. Weld the twelve 1.5” square steel tubes with ¼” wall thickness at specified joints.
8. Weld on 9 spacing plates to each side of the frame.
9. Weld on the two track interfacing side plates to the 9 spacing plates.
10. Weld on front battery mounting plate.
11. Thread on top battery mounting plate with two eye hooks.
12. Thread the aluminum motor and gearbox mounting plate to the top of the chassis.

![Figure 4-36: Chassis explosion](image-url)
4.9.3.3  **Drive System**

1. Acquire two 1 HP Leeson DC motors.
2. Acquire two 40:1 Grove Ironman gearboxes.
3. Acquire a $\frac{3}{8}$” to 1-¼” shaft coupler.
4. Turn aluminum drive hub on lathe and broach ¼” keyway.
5. Mill a ¼” key for drive hub-shaft coupler interface.
6. Mill a $\frac{3}{8}$” key for gearbox output shaft-shaft coupler interface.
7. Weld track interface plates onto chassis side plates.
8. Install tracks onto welded interface plates.
9. Mount drive motors and gearboxes to aluminum chassis plate using washers as spacers beneath the drive motors.
10. Slide shaft coupler on to gearbox output shaft with $\frac{3}{8}$” key in place.
11. Slide custom aluminum drive hub onto output of shaft coupler with ¼” key in place.
12. Mount drive sprocket to drive hub with ½” hardware.
13. Pull rubber track over the top of the newly installed drive sprockets.
14. Repeat for other side of drive system.

![Figure 4-37: Drive system explosion](image-url)
4.9.3.4  **Cam Lowering System**

1. Weld two 42” hinge arms to the planer assembly.
2. Weld two hinge plates to each of the hinge arms.
3. Weld crossbar between planer system pivot arms for cam engagement.
4. Weld two spring plates to the underside of the hinge arms.
5. Weld two spring plates to the chassis.
6. Insert hinge arms into chassis, pin into place.
7. Insert the two springs.
8. Insert the locational nubs and bolt into place.
10. Waterjet cut mounting plates out of ¼” A36 Steel.
11. Acquire necessary pins and bearings.
12. Weld cam mounting plates with ⅝” spacers.
13. Weld cam assembly to rear of chassis such the cam will engage the crossbar of the planer frame, use spacers as necessary.
14. Insert the bearings, cam, and pin.

![Figure 4-38: Cam lowering system explosion](image)
4.9.3.5 *Electronics*

4.9.3.5.1 DC Drive Motors

1. Acquire Roboteq MDC 2460 and requisite electronic parts.
2. Fasten batteries to battery mount plates.
3. Wire the system up in the following fashion.

![Figure 4-39: MDC 2460 Circuit Diagram](image)

4. Manufacture diamond electronics housing.
5. Ensure all electrical leads are tension free with wire ties.

4.9.3.5.2 AC Cutter Motor

1. Connect the motor’s junction box to one side of the electrical leads in a switch box.
2. Insert fuses into switch box.
3. Connect the other side of the switch box leads to a 208V-30A plug.
4.9.3.6 **Dust Mitigation**

1. Manufacture aluminum diamond plate skirt pieces to specifications.
2. Attach bristles to the bottom of the diamond plate skirt side plates.
3. Fasten to planer frame.
5. Attach to cutter housing.
6. Insert vacuum hose and attach.
5 Design Specifications

5.1 Introduction to Subsystems

The Volvo 310X can logically be broken down into seven subsystems.

1. Drive System
2. Chassis
3. Power
4. Communication
5. Planer System
6. Vacuum System
7. Planer Lowering System

The 310X is a largely mechanical device, powered by an assortment of electronic devices.

Figure 5-1: Subsystem CAD Explosion
5.2 Drive System

The drive system encompasses the following:

- 2 track assemblies (Figure 5-2)
- 2 1 HP DC Leeson brand motors (Figure 5-3)
- 2 right angle 40:1 gear boxes (Figure 5-3)
- 2 Custom Aluminum hubs (Figure 5-4)
- 2 shaft adapters (Figure 5-4)
- Caster Wheel (Figure 5-5)

Beginning with the purchase of the tracks, calculations were performed to size the motors and gearboxes. In order to interface the gear motor output shafts with the track’s existing sprockets, two custom aluminum hubs were turned on a lathe, the shaft adapters were used to interface the hubs with the output shafts of the gear boxes. A caster was incorporated into the front of the vehicle to reduce friction created by the tracks in turning. Figure 5-6 offers an explosion view of the drive system.
Figure 5-2: Track Assembly

Interfacing plate to weld to side plate of chassis

Figure 5-3: Motors and Gearboxes

Figure 5-4: Custom turned hub and shaft adapter
Figure 5-5: Caster under the front of the vehicle

Figure 5-6: Drive System Explosion Diagram
5.3 Chassis

The chassis (Figure 5-7) is assembled from welded 1-½” A36 steel tubing, and various water jet cut A36 steel and 6061-T6 aluminum plates. The chassis was designed to carry the loads of all the other subsystems, to interface with the tracks, and to allow the planer frame to move up and down effectively. In order to effectively interface with the tracks, side plates needed to be welded onto the side the chassis, to which the tracks could be welded (Figure 5-8). Figure 5-9 is an explosion diagram of the chassis.

Figure 5-7: Chassis Tube Frame

Figure 5-8: Chassis with side plates

Figure 5-9: Chassis Explosion Diagram
5.4 Power

The Power System for the 310X has two main objectives. The first is to power the drive system, and the second is to power the planer system. These power sources are completely separate from one another for safety, and ease of operation.

The drive system is powered with two deep draw 12V car batteries connected in series. This DC source was connected through fuses to a motor controller. The motor controller used here was a Roboteq MDC 2460. This controller allows for two channels of up to 24V and 60A each. The following circuit diagram (Figure 5-10) indicates the way the circuit operates. The lower left part of the circuit includes the car batteries that provide the power used by the motors, on the right hand side of the diagram. The upper left part of the diagram indicates the circuit used to integrate an on/off switch for the controller. Roboteq’s systems are equipped to be adjusted via their own Roborun+ software. This allowed for the specification of differential steering (tank steer) operation, as well as the maximum voltage and ampere outputs of the controller to the motors.

The planer system includes by a 7.5 HP AC Leeson brand motor. This motor is powered by 208V commercial wall power, or a 208V/220V generator. The cord from the power source is run into a switchbox with a 30A fuse.
5.5 Communication System

The communication system provides a way for the remote controller to command the motor controller. The Roboteq controller mentioned above has an RS232 port, which was split off into three 3-pin connectors that plug into the RC receiver used for the 310X. The remote controller used is the Futaba 6J (Figure 5-11), which operates at 2.4GHz and allows for up to a mile of receiver range. An explosion diagram of the communication system onboard the 310X is available in Figure 5-12.
5.6 Planer System

The planer system includes the following:

- Smith Manufacturing Plane-It Concrete scarifier drum w/ replaceable Tungsten Carbide teeth (Figure 5-13)
- 2 high load bearings
- Hex shaft
- Custom A36 steel and 6061-T6 aluminum drum housing (Figure 5-14)

The planing drum, bearings, and shaft were purchased from Smith Manufacturing, along with the requisite hardware. The custom housing was welded and bolted together to provide a sturdy and adjustable structure for the drum which spins at 1800RPM. The planer is spun by the motor via a 4-groove V-belt, and a 2:1 ratio, which takes the output shaft speed of the motor (3600 RPM) down to the manufacturer’s specified 1800RPM in an up-cut orientation. Figure 5-15 provides an explosion diagram of the planer system.
Figure 5-13: Planing Drum

Figure 5-14: Planer and housing
5.7 Planer Lowering System

The planer lowering system consists of the following:

- 1-½” A36 steel tubing legs welded to the planer housing (Figure 5-16)
- 4 Hinge plates (Figure 5-17)
- 2 5.5” springs with a spring constant of 250lb/in (Figure 5-18)
- 4 spring plates with locational nubs (Figure 5-19)
- 2 rubber stoppers (Figure 5-19)
- Cam Assembly (Figure 5-20)
  - Two A36 steel side plates
  - A36 Steel cam mechanism
  - 3 bearings
  - 1 clevis pin
Two 42” A36 steel tubes were welded to the planer drum housing, with a crossbar for stabilization. Two spring plates were welded to this larger assembly, and two were welded to the chassis to provide adequate footing for the springs. The springs were held in place by locational aluminum nubs. This larger assembly was then pinned to the chassis with clevis pins, creating a hinge point. To ensure that the planer would not bounce during engagement, rubber stoppers were employed to bridge the gap between the chassis and the plane lowering system. An explosion diagram of the cam assembly is shown in Figure 5-21.
Figure 5-17: Springs and spring plates

Figure 5-18: Hinge Plates
Figure 5-19: Springs, spring plates, and rubber stoppers

Figure 5-20: Cam Assembly
The dust mitigation system consists of two main components:

- Aluminum diamond plate skirt with brush (Figure 5-22)
- Vacuum with adapter plate (Figure 5-23)

A diamond plate skirt with brush that touches the ground when the cutter is engaged was applied to the top, back, and both sides of the planer frame. An aluminum vacuum adapter plate was fashioned for the front of the planer frame and attached to the front of the planer frame.
Figure 5-22: Dust skirt and vacuum hose

Figure 5-23: Vacuum with concrete dust
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<td>Vacuum Shroud Plate</td>
<td>Custom Plate</td>
<td></td>
<td>1</td>
<td>$25.00</td>
<td>$25</td>
</tr>
<tr>
<td>Vacuum Nozzle</td>
<td></td>
<td>1 Home Depot</td>
<td>1</td>
<td>$12.00</td>
<td>$12</td>
</tr>
<tr>
<td>Vacuum Hose</td>
<td>2.5” Diameter</td>
<td>1 Home Depot</td>
<td>1</td>
<td>$32.00</td>
<td>$32</td>
</tr>
<tr>
<td>Vacuum</td>
<td>6.5 HP</td>
<td>1 Home Depot</td>
<td>1</td>
<td>$99.00</td>
<td>$99</td>
</tr>
</tbody>
</table>

**Total System Cost** $12,886
6 Project Management

With any project, planning and organization is critical to successful competition. This especially true for projects with rigid timelines and a high degree of complexity such as ours. To tackle this challenge, our team took planning very seriously; we created careful schedules and kept track of our progress against these schedules, we maintained a detailed budget to ensure that we had sufficient funds to execute on our product visions, and we maintained frequent and open communication to ensure that tasks were being picked up and completed.

6.1 Schedule Planning

Our team used an online project management tool called Smartsheet as our primary scheduling tool. This tool enabled us to create a well-organized list of tasks, and assess the dependencies of the many activities using the Gant Chart feature. This was critical in determining priorities for the team, and in establishing deadlines.

The team worked together to create the schedule, then shared access to the schedule document via the online capabilities of the Smartsheet tool (rather than having a single person in charge of the schedule). This enabled the schedule status to be easily maintained, changes to be quickly communicated, and created a sense of ownership and buy-in for everyone on the team.

Figure 6-1 shows the original schedule that the team created the week of April 1st.
<table>
<thead>
<tr>
<th>Task Name</th>
<th>Mar 2</th>
<th>Mar 9</th>
<th>Mar 16</th>
<th>Mar 23</th>
<th>Mar 30</th>
<th>Apr 6</th>
<th>Apr 13</th>
<th>Apr 20</th>
<th>Apr 27</th>
<th>May 4</th>
<th>May 11</th>
<th>May 18</th>
<th>May 25</th>
<th>Jun 1</th>
<th>Jun 8</th>
<th>Jun 15</th>
<th>Jun 22</th>
</tr>
</thead>
</table>
| Figure 6-1: Original Spring Quarter Schedule | created the week of April 1st.”

**System Planning**

- **Olive System Development**
  - CAD Models and Final Design
  - Design Phase (materials, filter, drawing)
  - Motor & Motor Arm
  - Track Arms
  - Motor Assembly & Testing

- **Concrete Fracture System Development**
  - Design
  - Test

- **Communication System Development**
  - Design
  - Test

- **Chassis/Structural Design**
  - Design

- **Vacuum and Dust Collection**
  - Design

- **System Integration**
  - Olive System Integration
  - Concrete Fracturing System Integration

- **Full System Testing**
  - Full System Testing
  - System Refinement
Following Penultimate Review, the team re-planned for the final 3 weeks. This final schedule is shown in Figure 6.2.

<table>
<thead>
<tr>
<th>Task Name</th>
<th>May 11</th>
<th>May 18</th>
<th>May 25</th>
<th>Jun 1</th>
<th>Jun 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penultimate Review + Concrete Cutting Demonstrated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EXPE Shear</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acquire/Install Vacuum System Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install Vacuum System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body Accents</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic Dip Handle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Add Diamond Plate around Batteries</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean up/Install &amp; Box Electrical Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install Push Button Emergency Disconnect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install Mounting for CAM Handle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drive System Development</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Research and Install Alternate Drive Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install and Test Front Cover</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Order Motors and Gearboxes (1/24)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fabricate additional battery</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install upgraded Motors &amp; Gearboxes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EXPE Booth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Booth Layout</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Order Booth Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Create Demo Video</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assemble EXPE Booth &amp; Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.2: Final 3-week project schedule.
6.2 Cost Planning
We knew from early conversations with our partners at Volvo CE that they were very interested in a full-scale prototype. Early in Winter Quarter, the team recognized that the scope of our potential project was going to exceed the standard $8k budget for the class. We prepared a brief presentation on some of our early Skid Steer Prototype Concepts to show what we thought we could do with the existing budget, and how much additional budget would be required to do a project at full scale. The figure below shows some key excerpts from the document that was sent.

Figure 6-3: Presentation to Volvo to request additional project budget.

In response to our proposal, Volvo CE granted us a budget extension of $15k to work with for the final project. With this expanded budget, and the project scope that it allowed, managing the budget became an even more critical activity. Even with the additional budget, the team had to consider cost on several critical system components that were central to the design of the vehicle. To do this effectively, it was necessary to map out our anticipated expenses for the vehicle, and for the final quarter of the class.
Using conservatively high values, we created estimated costs for each subsystem on the vehicle, including a contingency allocation of $2500. The main goal of this activity was to determine if we had sufficient budget to purchase some of the high cost, long lead items that we were planning for vehicle; such as tracks and concrete milling components. These components had to be purchased well in advance of having completed the design of the rest of the vehicle which created project risk since the remaining costs could not be fixed at the time of the long lead item purchases. The budget, shown in Table 6-1 below was the tool we used to manage this risk.

<table>
<thead>
<tr>
<th>Budgeted Items</th>
<th>Vendor</th>
<th>Budgeted Cost</th>
<th>Remaining Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concrete Planar</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leeson 132044.00 Motor</td>
<td>Ebay</td>
<td>$410.00</td>
<td>$18,663.00</td>
</tr>
<tr>
<td>Milling Drum &amp; Hardware</td>
<td>Smith MFG</td>
<td>$2,591.60</td>
<td>$15,893.40</td>
</tr>
<tr>
<td>Steel housing for Part x</td>
<td>Platinum Water Jet Cutting</td>
<td>$382.25</td>
<td>$15,511.15</td>
</tr>
<tr>
<td>AC Motor Parts</td>
<td>Royal Electrical</td>
<td>$140.00</td>
<td>$15,371.15</td>
</tr>
<tr>
<td>Miscellaneous Hardware + tools</td>
<td>McMaster-Carr</td>
<td>$208.00</td>
<td>$15,163.15</td>
</tr>
<tr>
<td>Belts</td>
<td>V Belts For Less</td>
<td>$44.00</td>
<td>$15,119.15</td>
</tr>
<tr>
<td>20’ Steel Tubing</td>
<td>Alan Steel</td>
<td>$47.99</td>
<td>$15,071.16</td>
</tr>
<tr>
<td><strong>Drive</strong></td>
<td></td>
<td>$15,071.16</td>
<td></td>
</tr>
<tr>
<td>Barreto Tracks</td>
<td></td>
<td>$4,435.47</td>
<td>$10,635.69</td>
</tr>
<tr>
<td>Motors + gear boxes</td>
<td></td>
<td>$1,453.00</td>
<td>$9,182.69</td>
</tr>
<tr>
<td>Speed Controllers</td>
<td></td>
<td>$428.67</td>
<td>$8,754.02</td>
</tr>
<tr>
<td>Batteries</td>
<td></td>
<td>$410.64</td>
<td>$8,343.38</td>
</tr>
<tr>
<td><strong>Chassis</strong></td>
<td></td>
<td>$8,343.38</td>
<td></td>
</tr>
<tr>
<td>Mounting plate for tracks</td>
<td></td>
<td>$500.00</td>
<td>$7,843.38</td>
</tr>
<tr>
<td>waterjet plates</td>
<td></td>
<td>$800.00</td>
<td>$7,043.38</td>
</tr>
<tr>
<td>steel tubing</td>
<td></td>
<td>$300.00</td>
<td>$6,743.38</td>
</tr>
<tr>
<td>hardware</td>
<td></td>
<td>$250.00</td>
<td>$6,493.38</td>
</tr>
<tr>
<td><strong>Lowering Mechanism</strong></td>
<td></td>
<td>$6,493.38</td>
<td></td>
</tr>
<tr>
<td>Water jet cams</td>
<td></td>
<td>$300.00</td>
<td>$6,193.38</td>
</tr>
<tr>
<td>Shaft + bearings</td>
<td></td>
<td>$170.00</td>
<td>$6,023.38</td>
</tr>
<tr>
<td>Springs</td>
<td></td>
<td>$50.00</td>
<td>$5,973.38</td>
</tr>
<tr>
<td><strong>Body kit</strong></td>
<td></td>
<td>$5,973.38</td>
<td></td>
</tr>
<tr>
<td>Foam and bondo</td>
<td></td>
<td>$100.00</td>
<td>$5,873.38</td>
</tr>
<tr>
<td>paint</td>
<td></td>
<td>$50.00</td>
<td>$5,823.38</td>
</tr>
<tr>
<td>hood actuators (dampers)</td>
<td></td>
<td>$200.00</td>
<td>$5,623.38</td>
</tr>
<tr>
<td><strong>RC electronics</strong></td>
<td></td>
<td>$5,623.38</td>
<td></td>
</tr>
<tr>
<td>Radio Transceiver</td>
<td></td>
<td>$185.96</td>
<td>$5,437.42</td>
</tr>
<tr>
<td>Servos + wiring</td>
<td></td>
<td>$200.00</td>
<td>$5,237.42</td>
</tr>
</tbody>
</table>
Vacuum system

<table>
<thead>
<tr>
<th>Budgeted Items</th>
<th>Vendor</th>
<th>Budgeted cost</th>
<th>Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Cleaner and extensions</td>
<td></td>
<td>$300.00</td>
<td>$4,937.42</td>
</tr>
<tr>
<td>Planer Adapter (SLS part)</td>
<td></td>
<td>$200.00</td>
<td>$4,737.42</td>
</tr>
<tr>
<td>Autonomy</td>
<td></td>
<td></td>
<td>$4,737.42</td>
</tr>
<tr>
<td>fence + sensors</td>
<td></td>
<td>$150.00</td>
<td>$4,587.42</td>
</tr>
<tr>
<td>Arduino + electronics</td>
<td></td>
<td>$100.00</td>
<td>$4,487.42</td>
</tr>
</tbody>
</table>

Budget Continued…

<table>
<thead>
<tr>
<th>Budgeted Items</th>
<th>Vendor</th>
<th>Budgeted cost</th>
<th>Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXPE</td>
<td></td>
<td></td>
<td>$4,487.42</td>
</tr>
<tr>
<td>Poster</td>
<td></td>
<td>$200.00</td>
<td>$4,287.42</td>
</tr>
<tr>
<td>T-shirts</td>
<td></td>
<td>$200.00</td>
<td>$4,087.42</td>
</tr>
<tr>
<td>Marketing materials</td>
<td></td>
<td>$500.00</td>
<td>$3,587.42</td>
</tr>
<tr>
<td>Concrete + housing</td>
<td></td>
<td>$100.00</td>
<td>$3,487.42</td>
</tr>
<tr>
<td>Generator</td>
<td></td>
<td>$250.00</td>
<td>$3,237.42</td>
</tr>
<tr>
<td>SUDS</td>
<td></td>
<td>$100.00</td>
<td>$3,137.42</td>
</tr>
<tr>
<td>Contingency Fund</td>
<td></td>
<td>$2,500.00</td>
<td>$637.42</td>
</tr>
</tbody>
</table>

After thorough research we determined that the concrete milling drum was a critical component for the vehicle, and central to meeting our design objectives. This was the first major purchase we made, and the first system that we designed and built for the vehicle. The rest of the vehicle, and budget, then took shape around this system.

The Barreto tracks were the other major purchase decision for our team. We wanted tracks for the mobility they offered (as it enabled us to meet several requirements), as well as the aesthetics of the product. However, at over $4000 it was a significant part of our budget. Using the planning tool in Table 6-1 above we were able to show that we had sufficient budget to enable purchase of the tracks, and moved ahead with the tracks in our design.

As the quarter proceeded, our team kept an up to date Expense Tracking sheet using Google Documents. Anytime a P-Card purchase was made, it was entered into our tracking sheet by the person making the purchase. Our CFO tallied and submitted expense reimbursement reports monthly for all out of pocket expenses, and bi-monthly in May as the rate of expenses increased. Budget status reports were shared with the team on a weekly basis.

Ultimately, the team’s expenses for the quarter tracked very well with our initial estimates. Our remaining account balance at the end of the quarter was just over $2000. Table 6-2 below shows a summary of the expenses for the quarter. It includes costs for the major vehicle systems, transportation costs, and major class deliverables.
### Table 6-2: Summary of Spring Quarter Costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive System</td>
<td>$1,589</td>
</tr>
<tr>
<td>Vehicle Chassis</td>
<td>$5,677</td>
</tr>
<tr>
<td>Planar System</td>
<td>$4,172</td>
</tr>
<tr>
<td>Planar Lowering Assembly</td>
<td>$249</td>
</tr>
<tr>
<td>Onboard Power System</td>
<td>$397</td>
</tr>
<tr>
<td>Communication &amp; Control System</td>
<td>$635</td>
</tr>
<tr>
<td>Vacuum System</td>
<td>$270</td>
</tr>
<tr>
<td>Concrete Testing Materials</td>
<td>$615</td>
</tr>
<tr>
<td>EXPE Materials, Final Report</td>
<td>$1,400</td>
</tr>
<tr>
<td>Expendable Materials &amp; Tools</td>
<td>$600</td>
</tr>
<tr>
<td>Replacement Gear Boxes</td>
<td>$650</td>
</tr>
<tr>
<td>Shipping, Freight &amp; Mileage</td>
<td>$805</td>
</tr>
<tr>
<td><strong>Total System Cost</strong></td>
<td><strong>$17,058</strong></td>
</tr>
</tbody>
</table>

| Budget Allocation                        | $19,073|
|**Total Costs**                           | **$17,058**|
| **Remaining Budget**                     | **$2,015**|

The complete summary of our expenses can be found in the Appendix and a breakdown of the components in each subsystem can be found in the Bill of Materials contained within the System Specification section.

### 6.3 Task and Resource Management

Our Team used an informal task management system. We met on a regular basis to work jointly on design tasks, and would then divide up work to do between meetings. Tasks that were typically done between meetings were getting quotes, placing orders, machining parts, designing sub-systems in CAD, or delivering drawing sets for quotes. This tasking was generally based on availability, and sometimes access to tools or facilities (such as Solidworks, or the Stanford Product Realization Lab). We often worked on these tasks individually, and occasionally in pairs.

We generally worked on large design, analysis, or assembly tasks together as a group. We never had set meeting times, but would typically plan work times on a week to week basis depending on the team’s availability.

This approach worked for our team because we had excellent communication, and each individual member of the team was committed to the project and personally responsible. We
were lucky in this respect, and the flexibility that this approach allowed was part of our overall success on the project.

Our Global Team from BTH was a substantially different composition from our team, and had a different focus. They were mostly focused on the high level system analysis, lifecycle analysis, and the ways in which large companies such as Volvo CE integrate technology and concepts produced by academic partners into their technology roadmaps. This paired nicely with the product focus of our team, and enabled us to incorporate a much larger view into our final product vision. We had weekly Skype calls with our Global Teammate to stay connected and sent information to each other via email. The Global Team did not participate directly in the design or fabrication of our final prototype, which made task management a non-issue. We did gain valuable insights from them during our weekly reviews that ultimately influenced some of our design decisions.

6.4 Future Work

The team’s vision is that the Volvo 310X will define a new way to do urban mining and specifically urban deconstruction. With increased urbanization, it is expected that approximately 60% of the world’s population will live in a city by 2030. This means there will be an increased demand for construction vehicles that are suited to work in urban environments because of the renovation that will take place to accommodate more people. Machines like the Volvo 310X that are specialized, robust, compact, minimally intrusive in terms of noise, dust and fume emission meet the needs of the urban deconstruction site. As shown in Figure __, there will be a great increase in the amount of concrete demolished and so there will still be a recycled concrete market from which to derive value.
In order to be ready for the future we envision, the following are areas for future work with the 310X. For more details and additional future work, please refer to the BTH thesis draft in the Appendix.

6.4.1 Autonomous Capability
The jobsites of the future will have the framework and regulations to utilize autonomous vehicles. This way the Volvo 310X can be programmed to remove a specific area and volume of concrete at a specified removal rate. Autonomy would also mean that no worker would have to spend time doing a monotonous job. They can be doing more meaningful and effective work on the jobsite.

6.4.2 Larger Motor Capacity
The prototype uses electrically driven motors. In future iterations, more powerful hydraulic motors would be used. This would enable the 310X to function completely untethered.

6.4.3 Removal of steel reinforcements
Most concrete structures contain steel rebar embedded within the concrete. Today, as men with jackhammers reach these elements within the slab, they bring in blow torches to cut the steel rods. Removing steel rebar automatically would be a valuable feature to have. This feature could either be included in the Volvo 310X’s capabilities or there could be another machine that works in tandem with the 310X.

6.4.4 Network Enabled
Connecting the machine to a network on the jobsite could enable site managers to track progress across multiple sites. This would be a useful feature that again speaks to the future of the urban
deconstruction site. With a network of machines working, there could be communication across geographical distances for example when a complete job has multiple site renovations occurring.

6.4.5 Debris Segmentation
This feature would be useful for recycling purposes. Filtering the concrete debris by size would allow easier collection and transportation for future recycling. Investigation has shown that the average size of a suitable recyclable concrete fragment is 10mm. With debris segmentation, workers on a job site could remove one step in the recycling process if the machine can do the separation on its own.

6.4.6 Removal of Vertical Concrete Walls
Vertical concrete walls often require demolition as well. If the Volvo 310X could achieve this functionality as well, it would become more useful, especially in an urban room renovation project.

6.4.7 Multi-Lingual
A digital user interface could facilitate users in many different languages without customized equipment. This would be particularly useful to Volvo CE given their worldwide presence.

6.4.8 Sensor Detection
To have the machine be able to detect objects in its path is an added safety feature. It could then avoid humans, other equipment or foreign materials in floor. This could be incorporated by either having a camera installed or it could detect foreign objects via sonar technology.

6.4.9 Mapping and Sensing
Sensors that enabled mapping of the environment around the robot could be used for future design, or fit checks.

6.4.10 Towing
A small tow hitch could allow other equipment to be towed by the 310X. Or this towing feature could mean that the 310X can be hitched onto other machines to increase its versatility and mobility.

6.4.11 Modular Design
This could add allow the machine to be outfitted differently depending on the task (adding a wider planer milling drum) or this could enable its towing capabilities by having it attached to existing vehicles.

6.4.12 Connection via personal mobile devices
Enabling the vehicle to be controlled via a smart phone or tablet could reduce the learning curve, and improve communication on the jobsite.
6.4.13 Anti-Theft System
The vehicle could have a GPS tracker so that its movement and location can be monitored.

6.4.14 Physical Motion Recognition
An infrared (IR) emitter and an IR depth sensor could enable the vehicle to sense certain gestures that the operators allowing some features to be enabled without a physical interface.

6.5 Reflections

Jack Brody
Making the Volvo 310X a reality in spring quarter has been an incredible experience. It made all the hard work from fall quarter on well worth it. It has been enlightening to take on such a long-term project from beginning to end – and experience you do not get very often in academic settings. I am very happy with the way we approached design problems this quarter. We always had a clear focus and took on problems one step at a time. It was this process that allowed us to experiment with a wide breadth of prototypes while still staying focused on the needs that we had discovered along the way. We also brought a lot of focus to the final design of our vehicle. We checked and double-checked everything – increasing our chances of things working first try (a phenomenon that was actually more common than I could have ever hoped for). However, spending long days and nights in VAIL working on the 310X taught all of us an important lesson on design for manufacture as grinding parts down to fit became a common occurrence.

Our group dynamics this year was exceptional. I’m really happy with how we worked as a team. Everyone played a different, but crucial role. I couldn’t have asked for a better group to take on and overcome the challenges we faced this quarter. I’ve learned a lot about the design process, and being an engineer from the way my group members’ approach and tackle different problems and I can’t wait to see where they all end up in the future.

Calder Hughes
I embarked on this project with no idea what to expect from our design challenge; to address Urban Mining. Urban Mining has turned to be a fascinating design space which many interesting opportunities. Fall Quarter was largely devoted to exploring and defining the space of Urban Mining. Entering Winter Quarter we had begun to focus on tools for deconstruction in the urban environment, but took the time to explore a variety of ideas within the space. Concepts around vehicle autonomy on sites with close human interaction, and the need for incremental adoption emerged as a particularly interesting idea out of this early exploration. By the end of Winter Quarter we had discovered the needs around concrete removal, and gained traction on
this idea with the teaching team, our corporate partner, and our industry contacts. Tackling this need led to the design of the 310X which is undoubtedly one of the most interesting and enjoyable projects I’ve ever worked on. We had a great experience as a team, and exceeded our own expectations for our product. The 310X was a great project because it addressed a real and compelling need, had a solid business case, and worked the way we had envisioned. The work itself was challenging and interesting. I personally got a lot better at welding this quarter, and much more familiar with AC power. And to see the 310X rip through concrete on demo day was truly a pleasure.

Kezia Alfred

This year has passed by quickly; it really does seem as if we had just received our design prompt from Volvo CE. This has been an incredible learning experience for me. I did the ME coterm so that I would be able to take this course and my experience has not disappointed. I have learnt what it means to go through the design process from start to finish. I also gained valuable project management. My team and I were able to identify a need in a previously unknown space and then go all the way to finding a solution for the need. While in past quarters I learnt about prototyping and planning, this quarter I learnt about execution. I learnt about what is needed to get a project completed well. I have learnt about how I function in group dynamics. I have learnt what it means to step up to a task so that it can be completed. I have (somewhat) learnt about managing time. If nothing else, this quarter has shown me the importance of a common vision, concerted effort and enjoying either the company or project or both along the way. I also have more confidence in my engineering skills which is good to have moving forward into the working world.

Tim Martin

Creating the 310X was such a gratifying and exciting experience. I learned a great deal through designing and building our various prototypes, especially the 310X. We got to try everything from welding to marketing. Our group worked exceptionally well together, which made the project, trip to Sweden, and long hours working, quite enjoyable. I learned so much from my teammates and our many contacts in industry. A great deal of the people we asked for help from went above and beyond the call of duty, for which we were so grateful. Volvo CE was an unbelievably supportive corporate partner, and our partners at BTH were fantastic hosts and collaborators. I hope that we have somehow made an impact for construction workers we worked so hard to understand.
7 Resources

Industry Contacts

Ephraim Bahiru, Project Manager, McCarthy Building Companies, Inc.
Jake Schell, Project Manager, Silverado Contractors
Sean Holifield, Silverado Contractors
Matt Finley, Project Manager, McGuire Hester
David Kirk, Project Engineer, Department of Project Management, Stanford University
Luis Alvarez, Foreman, Silverado Contractors
Fares Beainy, Research Engineer, Volvo CE
Andreas Nordstrand – Volvo CE
Jenny Elfsberg – Volvo CE
Steve Cunningham – Turner Construction
Bino Garcia – No E-Waste
Dan North – Redwood Landfill
Tom Sako – Builder
Steve Schwanke – Architect
Michael Balsamo – Tesla Motors
Peter Alfred – St. Catherine Metal Recyclers

Websites


**Articles**


## Appendix

### 8.1 Final Budget

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<tr>
<th>Team Name:</th>
<th>Reference</th>
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**Total:** $51,000.00

**Available Balance:** $23.30
# ME310 Expenses Spreadsheet - Winter Quarter AY14

**Team Name:** Volvo CE  
**Budget Monitor:** Adi

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**Rollover balance from Fall AY13**  
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**Winter Allocation**  
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8.2 Custom Part Drawings

List of Drawings

1. 01-001-A, Top Housing
2. 01-002-A, Front Housing
3. 01-003, Side Housing
4. Upper Battery Plate
5. Spring Base Plate
6. Side Plate V4
7. Planar Pivot Plate
8. Cam Plate V2
9. Blast Shield Plate
10. Front Grill
11. Electronics Enclosure Side Plate
12. Electronics Enclosure Face Plate
13. Electronics Enclosure Front Plate
14. Planar Dust Skirt
15. Planar Dust Enclosure Top Plate – Belt Side
16. Planar Dust Enclosure Top Plate
17. Custom Sprocket Adapter
18. Drive Chassis Assembly
19. Motor Block
20. Motor Mount Plate
21. Upper Battery Plate
side_housing

01-003

1318 STEEL

SHAW
**Background**

**Urban Mining = Recovering Valuable Materials Out of a City Environment**

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<td>E-Waste</td>
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<td>Recycling</td>
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<tr>
<td>Landfill</td>
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<tr>
<td>Construction &amp; Demolition</td>
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131
Respirators

Full body suits

Steel-toe boots

Water spray for dust management
1. TO REMOVE WORKERS FROM HAZARDOUS SITUATIONS

2. TO MAKE EFFICIENT USE OF HUMAN RESOURCES ON THE JOB SITE

3. TO ELIMINATE FUMES AND MINIMIZE NOISE

4. TO ENABLE MACHINERY TO ACCESS CONFINED SPACES
THE VOLVO 310X
COMPACT CONCRETE PLANER

REMOTE CONTROL
SINGLE WORKER OPERATION

ELECTRICALLY DRIVEN

DUST AND NOISE MITIGATION
- 1000 ft indoor remote control range
- 1 foot/sec max planing speed
- 62 ft³/hour removal rate
- 90 dB from 15 ft
- 29.5” x 60” footprint
- 950 lbs
550 LBS OF STEEL
15 WATERJET CUT PLATES
22 CUSTOM PARTS
40 FT OF WELD
THANK YOU
8.4 Dark Horse App

App Pages allowing the user to program a tag

App Pages allowing the user to program a tag and track vehicle usage
App Pages allowing the user to track vehicle productivity
Debris must be moved by hand due to lack of machine accessibility
Debris must be moved by hand due to lack of machine accessibility
Utilities tagged not to be removed in selective deconstruction

Jackhammering a concrete slab and removing pieces via cart
8.6 Brainstorming

Constituent technologies leading to Funktional prototype vision
Scoring Process used to check the 4 ideas’ relevance before the functional prototype
Brainstorming around Brokk Attachment concept

Brainstorming around concrete Roomba concept
Brainstorming around combo tool concept
Concrete benchmarking
Hammer bits contacting concrete

Front view, on the on-ramp
8.8 Winter Quarter Final Presentation

Volvo CE

Kezia Alfred
Tim Martin
Calder Hughes
Jack Brody

Volvo CE
Team

Team Sweden

David Andersson
Yi Chai
Zhenqing Gao

Team Mascot
Urban mining = recovering valuable materials out of the city environment

Sources

- E-Waste
- Recycling
- Landfill
- Construction & Demolition

Four General Needs
Relieve workers from dirty and dangerous tasks

Eliminate repetitive tasks
Eliminate unsafe and inefficient work-arounds associated with improper tooling.

Increase accessibility of heavy machinery on job sites.
Four General Needs

- Relieve workers from dirty and dangerous tasks
- Eliminate repetitive tasks
- Eliminate unsafe and inefficient work-arounds associated with improper tooling
- Increase accessibility of heavy machinery on job sites
“Practical, well thought out, and fills a need in the industry.” ~ Matt Finley, McGuire & Hester Construction

“Sexy.” ~ George Toye, Teaching Team

“Novel.” ~ Andreas Nordstrand, Emerging Technologies Group, Volvo CE

“Would solve lots of problems.” ~ David Kirk, Stanford Construction Manager

The Volvo 310x
The 6 Critical Functions

1. Concrete breaking
2. Concrete crushing
3. Debris removal
4. Dust mitigation
5. Noise dampening
6. Driver control

Volvo CE Specifications

Weight ..................... ~600 lbs
Power ..................... ~10 HP
Air Usage .................. ~20 ft³/min
Removal Rate ............. ~2 m³/hour
Dimensions ............... 60” x 30” x 25”
Core Benefits:

Remove material more economically
Relieve workers from dangerous, repetitive tasks
Decrease time to complete task

Allow construction workers to remove more material, in a safer way, in less time.
Fracture Mechanisms
8.9 Prototype Summaries

The Pipe Cutter

Background: Currently only bigger machines are employed in the realm of construction and demolition. “Selective deconstruction” with a machine is not very conducive to actually being selective (the size of the machines limits its dexterity). Ladders and sawsalls are a standard method for removing piping and ductwork yet it is inefficient and dangerous. In addition, construction companies receive more money for “prepared” material (<5 ft sections of material) than unprepared material (over 5 ft in length). Our team wanted to experiment with smaller robots & devices taking the place of manual work, as we think this could be an effective future direction since it leads to increased efficiency and safety.

Solution: The Pipe Cutting robot-a robot that could autonomously crawl through piping of different diameters, cutting them from the inside-out. This would eliminate the need for ladders and sawsalls as well as increase the efficiency and safety of the job.

Takeaways:

- Cutting from the inside is a viable option that would help satisfy a need in demolition.
- Centering the cutting mechanism in the pipe is important.
- 3 blades would be more stable and effective.
- For this concept to be useful, it would need to be able to cut large variation of diameters.
- More powerful motors would be needed for cutting pipes of different materials.
- Experimentation with different cutting blades would be necessary going forward.
Redesign the building

Background: Based on learnings from our needfinding and benchmarking, we deduced that:

- Construction rarely considers deconstruction.
- The deconstruction process is forced to consider construction.
- We could improve deconstruction by improving the industry’s tools.

We learned that deconstruction is a messy and inexact process. Our end-of-quarter plan involved reimagining the tools used in modern deconstruction. But what if we can increase the ease of deconstruction, not by changing the tools, but by changing the buildings?

Solution: We are not planning to focus on modular walls, or new large scale building techniques, but rather details of the building construction that might make the deconstruction process easier. Our chief idea is to design a set of mounting hardware for pipe and conduit that could be remotely triggered to release (think exploding bolts without the explosion). This would enable deconstruction teams to 'drop' all of a certain type of material at once in a building allowing for easier collection and recycling.

For our prototype, we have created a model of a house, with four different materials in the ceiling, and four different release strings, to prototype the experience of immediate material collection.

For the fasteners, we created a prototype of how an electromagnet-held connector might work. The idea behind the prototype was that two parts of a fastener are held together magnetically and when a current is applied on part of the fastener, the polarity is reversed and so the connection is broken. Our second prototype experiments with the possibility of burning through a bolt to sever the connection. We inserted an electronically powered heating element in the plastic bolt to see if it’s possible to burn through the bolt to create a failure point that would easily break.

Takeaways:

Though extremely difficult to implement and scale (it would take a huge infrastructure overhaul), these ideas would vastly benefit the deconstruction and recycling issues facing demolition companies.
Technology to Enable Human Interaction within an Autonomous Job Site of the Future

Background: When we first received our design challenge, Volvo outlined to us their vision of future vehicles that are largely autonomous. We also observed the need and potential value of this in our fieldwork last quarter for issues of safety and efficiency on the job site. With this prototype, we are thinking along the lines of innovative technological components that would work in tandem with autonomous vehicles in the construction or deconstruction environment. How might construction workers of the future interact with autonomous vehicles and technology on a job site?

Solution: One part of our solutions was to create a user interface. This interface would allow our user to control how the autonomous machines could best be used on the job site-controlling which tasks they perform, where they should go and monitoring their activity. The key point in this interface is that in controlling how the machines work, it’s also allowing the user to decide when human input is necessary. It allows the user to act in an integral capacity on the job site as the decision maker or the conductor.

The other part to our solution is a concept vehicle- a Roomba that has been programmed to respond to two IR beacons in ways analogous to an autonomous machine on job site. The responses with which we prototyped are to move towards a beacon, reverse and retreat and also to stop. We believe that if these IR beacons could be made into programmable tags for example, then this would allow the user to control how and where the vehicle can move on the job site.

Takeaways:

- Activity logs would be useful for site managers so they track how each machine performs.
- Site managers want to be on the job as opposed to sitting in an isolated command room controlling what happens. They feel that they are limited if they act remotely.
- Site managers today already make use of 3D imaging software to map out and make plans for deconstruction.
- Having a some sort of local positioning system (LPS) would be vital to facilitate effective communication with machines on a job site.
- A lot of information is needed automate a task. It could involve organizing several simultaneous tasks or sequencing events. This helped us recognize the benefit of human input on a job site.
Skid steer with quick-change attachments

Background: Currently, changing tools and attachments on a skid steer is a cumbersome (requiring 2+ workers) and time consuming (5+ minutes) process. It involves driving the machine over to the location of the desired attachment, having someone outside the vehicle removing the pins holding the current attachment, and lining up the vehicle to the new attachment on the ground. This means that for temporary tasks, many machine operators use tools poorly suited to the task at hand. For example, using a jackhammer bit to push concrete out of the way between jackhammer locations.

Solution: Our solution combines keeping attachments onboard the skid steer, having additional degrees of freedom in the skid steer’s arm and automated tool change. This would allow operators to more efficiently change attachments, and become more effective workers. The quick-change attachments would allow operators to switch tools simply by pressing a button, similar to how a CNC mill works.

Our prototype consists of:
   a. A robotic arm made up of a servo that powers a small gear train and two linear actuators
   b. An electromagnet that serves as our grabber attachment
   c. Three Lego trays that act as our tool holders
   d. A Lego skid steer

Takeaways:
   a. Degrees of Freedom- At least 3, 4 is sufficient and 5 would be optimal
   b. Servo position seems sufficient to get range of motion we would want on the real skid steer.
   c. Electromagnets can be difficult to work with.
   d. Current tool position seems effective.
   e. Encoders are sufficient for position data and execution. While visual sensing is appealing, it might also bring more trouble than it’s worth.
   f. Users generally liked the idea of having machines doing more of the work (such as switching tools) for them.