MSU Bean Seed Dryer

Final Report

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Abstract

Beans are integral to humans as a means of protein procurement and nourishment. During bean growth, harvesting, and storage, bean moisture content must be strictly regulated in order to prevent early germination, spoilage, and other issues related to bean quality. Design Team 18 was tasked with creating a dryer for black and red beans that lowered the moisture content of the beans from an initial value of 20-30% to 12%. The device is to be used by Central American farmers, and must be readily creatable by a farmer on his farm.

A modular “solar chimney design concept” was chosen as the building block for the bean seed dryer design solution. The shed of dryer was created primarily out of members of angle iron to ensure structural stability, and variously sized wood pieces. The shed was outfitted with a solar collector, which stores solar energy in sand placed in the body of the collector, to heat the drying air. A motor-less centrifugal fan was used to force air through the duct of the solar collector and into the bean seed dryer shed, where the beans lay in three shelves. The exposed drive shaft of the fan interfaced with the device powertrain, which contained a bicycle, rubber belt, and pulley.

The concept of the bean seed dryer was proved during testing at Michigan State University (MSU) Plant Science Greenhouses, and mathematical grain drying models presented in this report were validated. Values for the drying constant $K$ were obtained for both black and red beans, which can be used to predict drying times for beans of given initial moisture contents.

It is suggested that more testing of the bean dryer be completed in order to fully understand how the drying constant of the system depends on relative humidity, temperature, and velocity of the drying air. Also suggested in the report are mechanical refinements for the bean seed dryer, such shed seals and a more robust bicycle support system.
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I. Introduction

Beans are integral to humans as a means of protein procurement and nourishment. Although perhaps presumed straightforward, the process of obtaining healthy beans is a complex science. During bean growth, harvesting, and storage, bean moisture content must be strictly regulated in order to prevent early germination, spoilage, and other issues related to bean quality.

Unlike in China and the United States, Central American farmers do not have access to sophisticated equipment designed to hasten and control the process of bean drying; current drying practices are not technologically developed and are time- and labor-intensive. The goal of Design Team 18 was to engineer a mechanically-powered bean seed dryer, for use by farmers in Central America, to quickly dry black and red beans for both seed and grain use.

During collaboration with project consultants, such as project sponsor Dr. Luis Flores, current Michigan State University (MSU) faculty Dr. James Kelly and Dr. Irwin Widders, and MSU emeritus faculty Dr. Lawrence Copeland and Dr. Dale Harpstead, the definition of the problem was refined. It was learned that bean moisture content of beans entering the bean seed dryer will be variable, but will likely reside between 20-30%. It was also learned that beans exiting the bean seed dryer should be of 12% moisture content. If the exiting beans are significantly higher than 12% moisture content, they have an increased probability of spoiling during storage. If the beans are lower than 12% moisture content, the bean seed coat is relatively susceptible to fracture.

More information about the customer of the bean dryer, farmers of rural Central America, was also obtained; Dr. Flores encouraged Design Team 18 to utilize the fitness of the farmers and to devise a human-powered bean seed dryer. Finally, the bean seed dryer was not to be of
such complex construction that Central American farmers were unable to fabricate the device on his or her farm; the bean seed dryer should be modular and of simple construction.

II. Background

Security of food is something that seems to be taken for granted in the United States. On the other hand, in Central and South America there is no assurance of a guaranteed next meal; the security of bean farmers in rural farming communities in Central and South America is becoming more and more uncertain. This is primarily due to erratic weather conditions that make harvesting beans no longer a dependable activity on which farmers may rely.

For the past several hundred years, after beans were harvested and threshed, they were simply laid out in the sun until the elements sufficiently dried the beans. This process is still employed in the vast majority of rural farmers in Central and South America. Nowadays, it is becoming increasingly inefficient to dry beans in this manner as weather conditions become increasingly unreliable. If, at any time during this rudimentary drying process, there is rain or a significant relative humidity ratio, then the crop is ruined. A ruined crop is disastrous for the majority of these farmers for several reasons. First and foremost, beans are a large part of farming families’ income as the seed from the beans are sold in the common market following the drying process. In addition, each family typically leaves a hundredweight sack of beans in their home to eat throughout the next growing season. Thus, a premature rainfall is devastating for these families because they lose their primary source of income and a key staple of their diet.

The nutrimental value of beans cannot be overstated in developing countries such as Honduras, Guatemala, and Nicaragua. Beans are frequently referred to as “nutrient dense” due to their nutritional properties. During conversations with Dr. Luis Flores, it was described to Design
Team 18 that a diet consisting of approximately 60% beans and 40% corn provides sufficient nutrients for humans. Therefore, it is very critical for these farmers to dry their beans before storage. However, Central and South American farmers are not the only farmers that would benefit from shorter drying times of beans. Beans are a food staple for billions of people throughout the world, from the jungles of Central America, to the plains of Africa, and the steppes of Eastern Asia. Therefore, although Central America will be the target region of Design Team 18’s bean seed dryer, the team retains hopes of spreading the principles and technology of the bean dryer throughout the world.

It is noteworthy that there is a difference between being food secure and seed secure in the eyes of Central American farmers. Generally, there is enough food from other non-bean sources to keep families fed. However, these other food sources do not contribute to the farmers’ business of selling beans for income. Therefore, it is imperative that farmers obtain a more aggressive and reliable way to dry beans instead of being constrained by climate.

While there are several progressive farmers in Central America that have constructed tents to house the beans to protect against adverse weather conditions, these ad hoc structures are few and inefficient. Thus, the purpose of Design Team 18’s engineering efforts was to create a reliable bean-drying device to accelerate the drying process of black and red beans.
III. General Design Solution

To start the process of bean seed dryer design analysis, each member of Design Team 18 compiled myriad design ideas and presented them to a panel of agriculture gurus, Dr. Lawrence Copeland, Dr. Dale Harpstead, and Dr. Jim Kelly. Each of these MSU faculty members is an expert in a different aspect of agronomy. Furthermore, Dr. Harpstead and Dr. Kelly have a wealth of international experience having worked with developing nations’ agriculture. Upon presentation of the design concepts to the agricultural panel, the “good” and “bad” ideas were seen after absorbing the commentary of the panel. Furthermore, the panel informed the team about unforeseen constraints. For example, it was recommended that design concepts utilizing a “beast of burden” be discarded due to the cost and unreliability of horses and mules.

Following this meeting, Design Team 18 took feedback from the panel and formulated a design believed to have great potential to quickly dry beans. At this point in the design process, both quantitative and qualitative analysis was conducted simultaneously to determine the bean dryer with the greatest potential to quickly dry beans and meet the other criteria of the design specification. A ranking-weighting scheme was created in which four design proposals were scored objectively according to variously weighted parameters identified as relevant to the design specification of the bean seed dryer.

Although this was a telling exercise, Design Team 18 realized that the best design to pursue was not necessarily the one that scored highest on this decision matrix. One major downfall inherent to the decision matrix was the selection of parameters each design concept was scored against. Indeed, there seemed to be many relatively unimportant parameters present in the decision matrix. By sheer volume of these relatively unimportant parameters, the most important
parameters, such as product performance, had a reduced contribution to the score given to each design proposal.

To buttress the design selection process, Design Team 18 chose to conduct an international survey, soliciting the feedback of Dr. Flores’ associates in Central America. Dr. Flores distributed the designs to his associates and received responses commenting on the feasibility of each design. The feedback was in favor of the solar chimney design concept. As a result, the design solution Design Team 18 chose to pursue was a solar chimney design. The solar chimney design features an enclosed shed, a solar collector, a centrifugal fan, and a powertrain comprised of a bicycle and belt-pulley system to drive the centrifugal fan.

The enclosed shed is constructed of durable and stiff angle iron chosen for its structural stability, 2” x 4” wood members for further support, and plywood walls for an economic enclosing solution. Furthermore, the shed cap, also skeletally supported via angle iron, possesses sheet metal implemented in an aesthetically pleasing manner, with the hope that Central American farmers will be drawn to the device’s appearance. The shed contains a hinged door such that three baskets, to be used to hold beans during drying within the shed, can be inserted and withdrawn from the device. The baskets are constructed of 1” x 4” wood members and aluminum mesh commonly used on screen doors of residential homes. The bean shed was sealed using materials assumed to be obtainable by a Central American farmer, such as duct tape and bike tire liner.

The next major component of the bean seed dryer is the solar collector. The purpose of the solar collector is to absorb solar irradiation to heat the air that will dry the beans. The solar collector is rectangular and comprised in principle of wood members. Inside of the rectangular
wooden structure of the solar collector, however, is sand. The sand is used to store thermal energy provided to the collector by solar irradiation. The sheet metal surface below the protective layer of Plexiglas is painted black to maximize the absorptivity of the collector.

A centrifugal fan is used to force convection within the bean seed dryer system. A centrifugal fan is chosen rather than an axial fan to force convection because of the fan’s characteristic ability to move high volumes of air and overcome significant pressure losses within a system. Also, the rectangular output duct geometry of the centrifugal fan interfaces more naturally with the thin, rectangular duct geometry of the solar collector. Finally, a centrifugal fan was obtained that interfaces naturally with the proposed powertrain of the bean seed dryer, the bicycle drive system.

The bicycle drive system is comprised of a used bicycle, a belt, a pulley, and a structure to support the bicycle during operation. A large belt is stretched over the rear tire of the bicycle and is connected to a pulley, which is fixed to the exposed drive shaft of the centrifugal fan. Since the belt is attached to the rear tire of the bicycle to a much smaller pulley, a high gear ratio is obtained allowing for efficient bean seed dryer operation. The bicycle drive system presents a comfortable method of spinning the centrifugal fan at a significant angular speed. Even though a used, not-fully operational bicycle is included in the bean seed dryer prototype, the flexibility to implement a bicycle with a fully operational gear set is present, allowing for even higher gear ratios to be obtained.

The bean seed dryer is modular; the baskets, cap, and legs of the shed may be removed from the shed, and the solar collector, centrifugal fan, collector-fan duct, and bicycle may be removed from the shed.
IV. Detailed Design Solution

A. Grain Drying Modeling

During bean dryer design conceptualization, research was conducted with the goal of obtaining an appropriate mathematical model for drying of black and red beans. Discovered were multiple *grain drying models*. A grain drying model is an abstract model that expresses the average moisture content of grain as a function of drying time (Pabis et al).

There are many grain models that have been used by agronomists to model grain drying. Table 1 shows various mathematical models that have been developed and applied to drying of various grains.

<table>
<thead>
<tr>
<th>Model no.</th>
<th>Model name</th>
<th>Model</th>
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<tbody>
<tr>
<td>1</td>
<td>Newton</td>
<td>$MR = \exp(-kt)$</td>
</tr>
<tr>
<td>2</td>
<td>Page</td>
<td>$MR = \exp(-kt^a)$</td>
</tr>
<tr>
<td>3</td>
<td>Modified page</td>
<td>$MR = \exp[-(kt)^a]$</td>
</tr>
<tr>
<td>4</td>
<td>Henderson and Pabis</td>
<td>$MR = a \exp(-kt)$</td>
</tr>
<tr>
<td>5</td>
<td>Logarithmic</td>
<td>$MR = a \exp(-kt) + c$</td>
</tr>
<tr>
<td>6</td>
<td>Two term</td>
<td>$MR = a \exp(-kt) + b \exp(-kt)$</td>
</tr>
<tr>
<td>7</td>
<td>Two term exponential</td>
<td>$MR = a \exp(-kt) + (1 - a)\exp(-kt)$</td>
</tr>
<tr>
<td>8</td>
<td>Wang and Singh</td>
<td>$MR = M_0 + at + bt^2$</td>
</tr>
<tr>
<td>9</td>
<td>Approximation of diffusion</td>
<td>$MR = a \exp(-kt) + (1 - a)\exp(-kt)$</td>
</tr>
<tr>
<td>10</td>
<td>Verma et al.</td>
<td>$MR = a \exp(-kt) + (1 - a)\exp(-gt)$</td>
</tr>
<tr>
<td>11</td>
<td>Modified Henderson and Pabis</td>
<td>$MR = a \exp(kt) + b \exp(gt) + c \exp(ht)$</td>
</tr>
<tr>
<td>12</td>
<td>Aghabashlo model</td>
<td>$MR = \exp\left(-\frac{k_1 t}{1 + k_2 t}\right)$</td>
</tr>
<tr>
<td>13</td>
<td>Weibull</td>
<td>$MR = \exp\left(-\frac{t}{a^b}\right)$</td>
</tr>
<tr>
<td>14</td>
<td>Midilli et al.</td>
<td>$MR = a \exp(-kt^a) + bt$</td>
</tr>
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</table>
Pabis et al. introduce a few of the models present in Table 1 and explain their origins and restrictions. Perhaps the two most commonly used grain drying models are the Newton model and the Page model, Equation (1) and (2), respectively.

\[ MR = \exp(-Kt) \]  

\[ MR = \exp(-Kt^n) \]

In Equations (1) and (2), \( MR \) is the ratio of moisture of the grain, \( t \) is the time the grains are dried for, and \( K \) and \( n \) are experimentally determined constants. Indeed, \( K \) is referred to as the drying coefficient (or drying constant) as it dictates the decay rate of the exponential functions.

Despite research efforts and consultation with project resources, reliable and published numerical values of the drying coefficient and \( n \) for black and red beans were not found in literature. However, Design Team 18 obtained values for \( K \) during device testing, outlined in the Bean Dryer Experimentation section of this report. In addition, published studies by various academic and professional organizations have been conducted upon other produce, such as apples or grapes, and have found the values of \( K \) and \( n \) empirically. More importantly, relationships showing how these values correlate to process variables, e.g. air drying temperature and velocity, and initial moisture content of the grain, were determined.

Upon inspection of the Page model, Equation (2), it can be mathematically seen that the moisture ratio of the grain decreases as \( K \) and \( n \) increase. During an investigation of drying grapes, Azzouz et al. determined that the constants \( K \) and \( n \) correlated with the temperature and velocity of the air moving over the grape, and the moisture content of the grape: “We observed that for the constant \( K \), the temperature of the air has the most important effect. Consequently, the air velocity and initial water content of product have a considerable effect on the constant
Azzouz et al. present the empirical correlation for the constants for drying of a Chasselas grape.

\[
K = \exp(K_1' + K_2'T_a + K_3'X_i) \quad (3)
\]

\[
n = N_1' + N_2'
\sqrt{V_a} + N_3' \ln X_i \quad (4)
\]

In Equations (3) and (4), \(K_1', K_2', K_3', N_1', N_2',\) and \(N_3'\) are experimentally determined constants, and range from -0.1338 to 4.554 for the Chasselas grape. Upon inspection of Equations (3) and (4), one can conclude that increasing the air temperature, air velocity, and local moisture content, \(T_a, V_a,\) and \(X_i\), respectively, increases values of \(K\) and \(n\). This in turn decreases the moisture ratio of the product, a desirable outcome.

A relatively new model for single-layer drying was created by Midilli et al. The model, model number 14 of Table 1, has four drying constants, \(a, b, k,\) and \(n\). For pollen and mushroom samples, \(a, k,\) and \(n\) are proportional to the natural logarithm of the temperature of the air moving over the product, and \(b\) is proportional to the negative natural logarithm of the temperature of the air. As a result, in order to minimize the moisture ratio of the product using the Midilli model of grain drying, one should maximize the temperature of the air drying the product.

Lastly, Meisami-asl and Rafiee conducted a statistical analysis on the validity of all 14 models of Table 1 during the drying of apples. They ultimately concluded that the Midilli model provided the best picture of the drying curves of apples. During their study, they also concluded that “drying time [of apples] decreased with increasing drying air temperature.” Figure 1 shows results that led Meisami-asl and Rafiee to this conclusion. Table A2 of the appendix is a collection of the drying coefficients for the Midilli modeling of apple drying, in addition to calculated statistical parameters used during validation of the grain drying model.
One common restriction present on grain drying models is that they are valid for thin layers of grain. For simplicity of analysis, it will be assumed that the designed bean dryer conforms to the restrictions of the thin layer approximation.

B. Solar Collector Heat Transfer Analysis

The previous section of this report introduces two grain drying models, and explains that the drying rate of grains is increased with increased drying air temperature. In order to determine how long the bean seed dryer needs to operate to dry a quintal (100 pounds) of beans, it is essential to determine the temperature of the air going into the shed.

First, the temperature of the solar collector must be calculated. During this analysis, it is assumed that, while the solar collector is increasing in temperature, the air between the layers of Plexiglas of the collector remains stagnant. Also, it is important to assume that the solar heat flux incident on the solar collector remains constant, as well as the surrounding temperature. The one-
The solar irradiation incident upon the solar collector heats the sheet of metal covering the layer of sand, and the heat then conducts throughout the sand. The corresponding resistor model is a combination of resistors in series with another five resistors which each have two resistors that are in parallel. Figure 3 shows the thermal resistance model.

Each of these resistor series has a radiation component. From one object to the next, the radiation heat transfer is reduced. In order to calculate the amount of radiation heat transfer present at each step of the thermal resistance model, the radiation value is multiple by the emissivity of the object.
After the thermal resistance model was defined, the pertinent variables of the system are obtained. Table 2 displays these values.

Table 2. Thermal resistance system parameters

<table>
<thead>
<tr>
<th></th>
<th>Plexiglass</th>
<th>Air (300K)</th>
<th>Steel (Galvanized)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissivity (ε)</td>
<td>0.86</td>
<td>1</td>
<td>0.86</td>
</tr>
<tr>
<td>k (W/(m•K))</td>
<td>0.17</td>
<td>0.0262</td>
<td>18</td>
</tr>
<tr>
<td>Length (m)</td>
<td>0.003175</td>
<td>0.0127, 0.08</td>
<td>0.0015875</td>
</tr>
<tr>
<td>h_r (W/(m^2•K))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{Surr} (°C)</td>
<td></td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>Area (m^2)</td>
<td></td>
<td></td>
<td>0.557</td>
</tr>
<tr>
<td>q (W)</td>
<td></td>
<td></td>
<td>256</td>
</tr>
</tbody>
</table>

Then, the total resistance of heat transfer is calculated according to Equations (5) and (6).

\[ R_{total\ series} = \sum R_i \]  \hspace{1cm} (5)

\[ R_{total\ parallel} = [\sum (R_i)^{-1}]^{-1} \]  \hspace{1cm} (6)

One can then find temperature differentials within the thermal resistance network according to Equation (7).

\[ q = \frac{\Delta T}{R_{total}} \]  \hspace{1cm} (7)
After solving for the total system resistance, $R_{total} \approx 0.162$, the change in temperature from the surrounding air and the steel-metal plate inside the collector is $\Delta T \approx 41.59^\circ C$. This value is calculated assuming that there is no airflow during the heating process.

Now that the solar collector is heated to the assumed operating temperature, the temperature of the air entering the bean seed dryer shed can then be calculated. First, since air is forced through the solar collector by the centrifugal fan, the Nusselt number must be calculated. First, the Reynolds number is calculated according to Equation (8).

$$Re = \frac{U_m D}{v} \quad (8)$$

$$D = \frac{4A_c}{P} \quad (9)$$

The value of the Reynolds number indicates whether the flow through the duct of the solar collector is laminar, turbulent, or mixed. In this case of the bean seed dryer, $Re \approx 25,355$, which places the flow in the turbulent regime. The Nusselt number for turbulent flow is then calculated using Equation (10).

$$Nu_D = 0.0243 \frac{Re_D^{4/5}}{Pr^{0.4}} \quad (10)$$

Here, $Nu \approx 70.57$. With Equation (11), one can calculate the convective heat transfer coefficient describing heat transfer in the duct of the solar collector.

$$h_{air} = \frac{Nu k_{air}}{L} \quad (11)$$

Equation (11) leads to the following value: $h_{air} \approx 13.09 \frac{W}{m^2 \cdot K}$. Finally, one can calculate the heat transferred from the solar collector to the air from conduction with Equation (12).
The final temperature of the air exiting the solar collector and entering the bean dryer shed is $T_m(L) \approx T_{steel}$.

C. Forcing Convection

In order to increase the drying rate of the beans, forced convection is included in the solar-chimney design. Ultimately, a centrifugal fan is chosen to force convection in part because of the fan’s characteristic ability to move high volumes of air and overcome significant pressure losses within a system.

The solar-chimney design features three shelves containing layers of beans that are each stacked at a given thickness. The shelves are placed within a shed which is assumed to be sealed below the top shelf of beans. The loading curve of the flow system for various total bean layer thicknesses is obtained from Equation (13), the airflow resistance equation (Pabis et al).

$$T_m(L) = (T_{m,t} - T_{steel}) e^{-\frac{p_{air} L}{m c_p}} + T_{steel}$$

(12)
Figure 4 shows the system loading curve for airflow rates up to 600 CFM. Figure A2 of the appendix shows the system loading curve for airflow rates up to 2000 CFM. The airflow resistance equation contains the grain-specifics constants \(a\) and \(b\), which are obtained via table lookup (Pabis et al). Values for black and red beans are not present on the referenced grain table, so constant values for soybeans are used.

The project design specification, detailed in Progress Report I, called for the bean dryer to be passively operated or, if the dryer required an external input, for this input to be given to
the system by human or animal power. Because of the presumed prevalence of bicycles in Central American countries, Design Team 18 chose to use a bicycle to convert a human rotary input to centrifugal fan rotation. To assist in fan selection, it was estimated that a human could comfortably sustain a pedaling speed of $1 \text{ revolution/s} = 60 \text{ rpm}$. As a result, an attempt was made to obtain a centrifugal fan model that required a low operating speed, since the projected bicycle-fan belt-pulley system would have a finite gear ratio of approximately 1:10.

Multiple fan manufacturers were consulted in search for a motor-less centrifugal fan able to meet the flow and pressure values required by the system and requiring an optimal operating speed of approximately $60 \text{ rpm} \times 10 = 600 \text{ rpm}$. Fan distributors Grainger, Greenheck, and McMaster-Carr were contacted via telephone, briefed on the problem the bean seed dryer addresses, and interviewed about potential airflow solutions they have.

During this product search, it was seen that most centrifugal fans operate optimally at fan speeds greater than 1000 $\text{rpm}$, so fan performance curves for these fans at speeds less than 1000 $\text{rpm}$ were obtained directly from the fan manufacturers, if available. Ultimately, Grainger offered a motor-less single inlet forward curve direct drive blower by Dayton that met airflow system requirements and required a one day supply chain lead time. The fan, manufactured by Peerless Blowers, contains a 9” diameter centrifugal fan wheel. It was ordered on April 2, 2013 and obtained one day later.
The fan selection tool from the website of Peerless Blowers was used to determine the performance of the ordered fan, *Dayton* blower 2C938, at centrifugal fan wheel speeds lower than recommended operating speeds. The following figure shows the performance of the 2C938 at 600 rpm.

![Figure 5. Schematic of *Dayton* blower 2C938 – dimensions in inches](image)

Figure 6. Fan performance curve for 600 rpm fan rotation
By superimposing the airflow system loading curve onto the fan performance curve, one obtains the point at which the fan-airflow system operates. At 600 \( \text{rpm} \), it is estimated that the airflow system will create an airflow of 400 \( \text{CFM} \) and a static pressure of 0.2” \( H_2O \) for a total bean layer thickness of approximately 1”; 0.33” per shelf. For the \( \textit{Dayton} \) blower 2C938, a thicker layer of beans may be dried if the fan is rotating at speeds higher than 600 \( \text{rpm} \). For instance, at the original equipment manufacturer (OEM) recommended fan operating speed, 1140 \( \text{rpm} \), beans at a 6” total layer thickness can be placed in the dryer. For this system configuration, the fan will operate at 500 \( \text{CFM} \) and will create a static pressure of 0.9” \( H_2O \). More fan performance curves for the \( \textit{Dayton} \) blower 2C938 can be obtained from the website of Peerless Blowers, provided in the References section of this report.

Finally, since the cross sectional area of the fan housing of \( \textit{Dayton} \) blower 2C938 is 10.75” x 6.5”, a duct comprised of sheet steel was fabricated in order to direct the airflow of the fan into the inlet of the solar collector, which is 3” x 22.5”. Figure A3. of the appendix shows a schematic of the duct.

Due to the severe height and width differences in the outlet duct of the fan and the inlet of the solar collector, a duct that simultaneously diffuses and nozzles was created. Upon consultation with MSU Ph.D. student Mark Gaustad, it was determined that the duct design should focus upon the diffuser component of the duct. Indeed, the diffuser angle was designed to be 10°, approximately the diffuser angle of maximum efficiency. Previously studies in the MSU laboratory course ME 332 provided Design Team 18 with data regarding diffuser performance as a function of diffusing angle.
D. Powertrain Design

Design Team 18’s decision to select the solar chimney concept as a starting point enabled the combination two very different technologies that have been developed to achieve the same goal. This design enabled the team to incorporate proven large-scale bean production techniques, with traditional drying methods that have essentially not changed for centuries. However, implementing the drying technologies seen at the Michigan Crop Improvement Association (MCIA), for example, into a creatable prototype with limited resources proved to be a significant challenge.

i. Mechanical Advantage; Gear Ratios

In order to replicate the efficiency and capabilities of the large scale dryers at the MCIA, a method was devised to force airflow through the layers of beans present in the shed. Bicycle pedal power was seen as an attractive solution to this problem, given its great potential for adaptability and modification to suit the needs of our bean dryer design. Another great advantage in favor of bicycle power was the ability to implement various factors of mechanical advantage from well designed and pre-determined gearing ratios. Gears that work together (or sprockets in this case) are often referred to as gear pairs. The power output of a gear can be defined as

\[
Power = \tau \times \omega
\]

where \( \tau \) is the torque applied to the gear (units: N-m) and \( \omega \) is the angular velocity (units: rad/s). By definition, the torque applied to a gear wheel (or sprocket) is a function of its radius. Thus a gear wheel with a larger radius will produce more power than another gear of lesser radius that is rotated at the same angular velocity.

With this in mind, two gears that work as a pair will have the same level of power;
\[
Power_{in} = Power_{out} \\
\therefore \tau_{in}\omega_{in} = \tau_{out}\omega_{out}
\]

Therefore if \(\tau_{out}\) is reduced, then \(\omega_{out}\) must increase if the equation is to be up-held, and in the same token, if \(\tau_{in}\) is increased then \(\omega_{in}\) can be reduced. As a result of this relationship, we knew that implementing a large input gear with moderate angular input velocity would cause a small output gear to have a significantly higher angular output velocity. This relationship is the phenomenon known as mechanical advantage, and we could use this truth to rotate a fan, or some other airflow inducing device at very high angular speed with relatively low, and sustainable input. This principle can be applied with the same effects on contact gears, chain and sprocket drives, as well as belt and pulley applications, thus determining the optimum gear ratio would be a powertrain design solution for the bean seed dryer. The gear ratio is generally defined as the input speed relative to the output speed.

\[
Gear\ Ratio = \frac{\omega_{in}}{\omega_{out}}
\]

ii. Initial Design Proposal

The initial design idea consisted of a traditional solar chimney dryer with dual fans extracting air from the drying compartment. This design would require the fans to be located high above the ground at the exit vent of the solar chimney, and to enhance its strength and manufacturability, these fans would run on the same shaft. The image in Figure 7 below shows a theoretical model of what this design concept would look like.
Figure 7. Initial fan-powertrain interface proposal

**Advantages:**

1. This design was compatible with a bicycle driven power input system, thus making it possible to integrate it with the advantages of mechanical advantage.

2. The fans would face opposite directions to enable them to run on the same co-axial shaft, and simultaneously draw air from the drying compartment. This relationship would allow the use of a single power input and thus enhance the manufacturability of the design.

3. Drawing air from the top would enhance the natural convective currents of the solar collector, and would likely induce laminar flow through the layers of beans.

**Disadvantages:**

1. The location of the exit vent would require the fans and their shaft to be at least six feet off the ground. All in all, this would be a very difficult design to integrate.

2. Purchasing long lengths of chain or timing belt drives would add to the overall cost of the design.
3. Alignment of driving and following gears would be very difficult, as well as retaining sufficient tension and support for these components.

For this design, the disadvantages greatly outweighed the advantages, thus forcing a design modification.

iii. Second Design Proposal

The second design proposal addressed the main problems that were presented by the initial design, as well as showed an improved selection. Research concluded that a centrifugal fan would have the potential to create large volumes of airflow at attainable angular speeds, with some models attaining their optimal performance at a speed of around 1100 RPM. Using the knowledge of gear ratios, it was determined that a 1:10 ratio would attain optimal fan operating speed when subjected to an input speed of approximately 100 RPM. An input speed of 100 RPM is obtainable and can be sustained for appreciable periods of time. However, purchasing gear wheels or pulleys of excessively large diameter would be very expensive. Therefore, a proposal was made to integrate two gear pairs and create a ‘step’ system. Such a system would consist of 2 gear pairs, each of ratio 1:5, that came connected in ‘series’ to achieve a combined ratio of 1:10 via direct chain/pulley drive. Using this gearing system, the fan would be located on the ground and would feed directly in to the solar collector and into the drying compartment. The image in Figure 8 below shows the second design proposal for the powertrain of the bean dryer.
iv. Third Design Proposal

The third and final design idea is an evolution of the second proposal. The main idea was to utilize the sturdy and self-aligning properties of a bicycle frame, as well as to take advantage of the large diameter of a rear bicycle wheel. This idea allowed us to essentially have a 22” diameter drive gear and a small follower gear, thus allowing us to easily attain our desired gear ratio. Although this design change would restrict us to only be able to use a timing belt, it was realized that using the belt would allow advantage from the gear ratio of the chain drive of the bike itself to be used. With this in mind, we were able to order a follower pulley which was compatible with the fan shaft with a pitch diameter of 2.25”, thus providing a gear ratio of 1:9.77 for the belt-drive system alone. This design presented its own set of challenges, the most critical being the retention of tension in the belt to reduce slippage, especially during high torque phases of the drive process.
The bicycle wheel driven system was a natural idea to implement into the powertrain of the bean seed dryer because of its high attainable gear ratio and because of the presumed prevalence of bicycles in Central America. Although the bike wheel did not have any ‘teeth’ with which to grip the timing belt, the ‘spoke nipples’ on the inside of the rim provided sufficient friction with which to hold the timing belt to the bike wheel. Furthermore, the frame of the bicycle was easily aligned to the driver and follower wheels, as well the rigid chassis used retain tension in the belt and create a sturdy platform.

E. Manufacture of the Design

One of the most challenging problems Design Team 18 faced with respect to the bean seed dryer shed was manufacturability. Foremost, materials used to construct the bean dryer were to be readily available to the common Central American farmer. Once the bean seed dryer was completely designed, a list of building materials was created. Several of the desired building materials had to be replaced by more rudimentary materials to ensure manufacturability on rural farms in Central America. Table A1 of the appendix shows the finalized list.
The process of manufacturing the bean seed dryer began with the construction of an angle iron base. The team determined the best way to size other components of the shed was to construct the legs and base and later fabricate other components above the legs and base. Thus, lengths of angle iron were cut and welded together to form a square base. Before the tungsten inert gas (TIG) welding took place, a sizing square was used to ensure orthogonality of certain members of the shed. This ultimately guaranteed the structure would be perpendicular to the ground.

Following the welding of the base, four legs were welded onto the corners of the angle iron square at 15° angles facing away from the base. The initial design called for legs stemming from the shed base at 90°, however, this design was not used because of its lack of stability. In
addition, thick sheet metal was welded to the base of the legs to create “pads” for the structure to sit upon to further increase stability. The ends of the legs were cut and sanded to a smooth surface finish to ensure a flush fitting between the legs and the pads and to allow for a weld connecting the legs and pads to be made along a level edge. Holes were also drilled into the legs of the angle iron and the base structure to allow for adjustability of height of the shed.

Following the base construction, the frame of the dryer was built out of angle iron and attached to the rest of base by bolted fasteners. In order to make the bean dryer modular in construction and deconstruction, the frame was attached via removable ¼ - 2” bolts. Due to the excess of welding metal at the base of the frame, the vertical supports were held by a link with a 45° angle with respect to the ground. These links provided support to the structure of the bean dryer. The same style of supports was used at the top of the frame to provide additional stability. The upper frame was then used to support the roof of the bean seed dryer.

Figure 11. Skeletal structure of the roof of the bean dryer
To add additional stability, pieces of angle iron were bolted into the vertical supports in a horizontal fashion. This also allowed for 2” x 4” beams of wood to be inserted as “runners” to hold the bean trays. These runners were bolted into the newly added pieces of angle iron to further insure structural stability.

The roofing panels of the bean dryer were built out of sheet metal and painted black to absorb solar irradiation and to improve aesthetics. The sheet metal panels were cut into trapezoids. A structure made of 0.75” angle iron was constructed to support the sheet metal. Since conventional metal inert gas (MIG) welding of sheet metal melts the sheet metal, the sheet metal was fastened to the angel iron skeleton by punching holes along the sides of the panels and tack welding the panels to the structure through these holes. Additional square segments of sheet metal were welded to the structure in this same fashion to finalize construction of the roofing structure.

Figure 12. Completed bean seed dryer roof
Following the construction of the roofing structure, the team constructed the bean trays and walls for the bean seed dryer. This task was relatively straightforward. The trays consisted of 1” x 4” boards attached to each other via wood screws. Additionally, metal screening was attached to the base of the trays to support the beans and allow for free flow of air through the trays. The walls and the door were constructed of plywood cut with a band saw, and were screwed into the tray runners. The solar collector-side of the bean seed dryer had a rectangular notch removed to fit the solar collector, allowing the heated air forced through the solar collector by the centrifugal fan to be blown into the shed.

![Bean trays present in the skeletal structure of the bean seed dryer shed](image)

**Figure 13. Bean trays present in the skeletal structure of the bean seed dryer shed**

The solar collector allows air forced into the bean drying system by the centrifugal fan to be heated by solar power, reducing the time required to dry beans. The solar collector was created by cutting 0.5” thick wooden boards to dimensions appropriate to fit the bean seed dryer
shed. Steel L-shaped brackets of 0.25” thickness were then screwed into the bottom and the sides of the solar collector for static stability after sand was poured into the solar collector frame.

Figure 14. Wooden solar collector structure

Following the construction of the base of the wooden solar collector structure, three wooden planks were nailed into the structure perpendicular to the base, creating four different compartments inside the solar collector. The team then poured sand into each of the compartments, which acts as a heat storage medium. A stainless steel piece of black sheet metal was then nailed atop the compartmentalized collector. Twin Plexiglas sheets were then adhered to one another with a wooden boarder around the edge to create a 0.5” gap between the sheets. This twin-Plexiglas sheet was then attached to the solar collector via wood screws. The solar collector was then fit inside the open section of the solar collector-side wall of the bean shed, where it was primed for connection to the aforementioned sheet metal duct which connected the centrifugal fan outlet to the solar collector inlet.
Finally, bicycle tire tubing was used to ensure the bean dryer door remained relatively sealed and did not leak pressurized air. The remaining openings in the bean seed dryer shed were filled using silicon sealant and expandable foam.

F. Prototype Experimentation

i. Purpose

The purpose of experimentation was to validate the bean seed dryer design and to provide a proof of concept. The primary focuses were to (1) determine the drying rate of *Phaseolus vulgaris* seed based on initial conditions and (2) establish a relationship between drying time and the moisture content of the bean seed. Other areas of interest were to observe the effectiveness of the solar collector and the moisture distribution in relation to shelf positions: top, middle, and bottom.
ii. Methods

Testing of the bean seed dryer was conducted in the Plant Science Greenhouses of MSU on April 18, 2013. The greenhouse buildings are equipped with quantum sensors, which provide information about the ambient solar radiation, relative humidity, and temperature. The ambient condition results were logged hourly, and used in analysis.

The bean seed dryer testing utilized all three shelves, which were divided into two equal compartments for separating grain. The right portion contained the red bean seed, and the left contained the black bean seed. Measuring the grain by volume, approximately 0.003 cubic meters, or 3 liters, of seed was placed in each compartment. The three shelves had an approximate uniform thickness 1.5 centimeters. The shelves were then loaded into the BSD.

To measure the effectiveness of the solar collector, the BSD was outfitted with a thermocouple located near the exhaust outlet of the solar collector. The temperature was monitored periodically, and compared to the recorded solar radiation and ambient temperature.

Testing began by simultaneously starting a stop watch to record time and pedaling the bicycle. The bicycle was pedaled such that the fan operated at approximately 600 rpm. Attempts were made to pedal at 60 rpm by using stopwatches to monitor pedaling cadence.

Six Mason jars were then prepared, given designation labels listing the following information: shelf number, bean type, and time of test. At hour increments, the bean seed dryer was opened and 250 grams of seed was removed from the right compartment of the first shelf (“Bottom, Red”), and sealed in the corresponding Mason jar. This process was then repeated for the other shelves and compartments. The bean dryer was then closed, and the drying process was
resumed. The seeds were then simultaneously delivered to the Agronomy Farm, where the moisture content for each sample was measured and recorded.

To measure the moisture, the GAC 2100 moisture meter was used. The meter was turned on by using the power switch on the backside located near the electrical chord. The machine was then allowed to warm up and perform preliminary operations. The “Select Grain” option was then chosen by pressing the corresponding command number. Scrolling forward or backward until the desired grain was listed, the corresponding command number for the grain type to be measured was then selected. The hopper located at the top of the device was then filled, ensuring that the grain covered the inner ring “fill-line.” The load button was then pressed. The machine then performed a reading of the moisture, temperature, and average density. The moisture and density were then recorded. The unload command was then pressed, which dumped the tested seed into a reservoir at the bottom of the device. The seed was then retrieved from the reservoir, and placed into its Mason jar. Testing was concluded once moisture content results began to show insignificant change – a “leveling” of the governing exponential decay function.

The experimental methodology outlined above was highly influenced by Glen E. Page’s thesis entitled “Factors influencing the maximum rates of air drying shelled corn in thin layers.”

**iii. Materials**

The following materials were used during experimentation:

- Thermocouples
- Light Bar Quantum Sensor
- Stop Watch
- Scoop Cup (12 fl. oz.)
- Mason Jars
- Dry Erase Markers
- Vehicle (to transport beans to and from the agronomy farm)

iv. Results and Discussion

The following table is data from the greenhouse’s quantum sensors that was logged hourly.

<table>
<thead>
<tr>
<th>Time</th>
<th>Dry Temp (Celsius)</th>
<th>Dry Temp (Celsius)</th>
<th>Vapor Pressure Deficit (kPa)</th>
<th>Lightbar Readings (micromoles)</th>
<th>Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry 8F</td>
<td>F_Asp_tube</td>
<td>8A</td>
<td>8B</td>
<td></td>
</tr>
<tr>
<td>10:00</td>
<td>24.04</td>
<td>24.74</td>
<td>1.158</td>
<td>214.4</td>
<td>225.6</td>
</tr>
<tr>
<td>11:00</td>
<td>24.7</td>
<td>25.74</td>
<td>1.308</td>
<td>240.2</td>
<td>250.4</td>
</tr>
<tr>
<td>12:00</td>
<td>26.29</td>
<td>26.96</td>
<td>1.402</td>
<td>327.9</td>
<td>319.6</td>
</tr>
<tr>
<td>13:00</td>
<td>26.74</td>
<td>26.82</td>
<td>1.541</td>
<td>312.1</td>
<td>299.3</td>
</tr>
<tr>
<td>14:00</td>
<td>25.35</td>
<td>25.37</td>
<td>1.275</td>
<td>268.6</td>
<td>267.5</td>
</tr>
<tr>
<td>15:00</td>
<td>25.98</td>
<td>26.22</td>
<td>1.493</td>
<td>253</td>
<td>242.3</td>
</tr>
<tr>
<td>16:00</td>
<td>25.73</td>
<td>25.88</td>
<td>1.462</td>
<td>207.2</td>
<td>201.6</td>
</tr>
</tbody>
</table>

The relative humidity was calculated from the Vapor Pressure Deficit, station pressure, and ambient temperature. The following relations were used to compute the relative humidity:

\[
VP_{sat} = e^{\left(19.0177 - \frac{5.327}{273.15 + T_{amb}} \times \frac{P_{sta}}{101325}\right)}
\]  \hspace{1cm} (18)

\[
VP_{actual} = VP_{sat} - VPD
\]  \hspace{1cm} (19)

\[
RH = \frac{VP_{actual}}{VP_{sat}}
\]  \hspace{1cm} (20)
The relative humidity within the greenhouses was between 54% and 60% during experimentation. The hourly moisture contents are recorded and displayed in the following table. The corresponding graph plots the results and illustrates the trends observed.

Table 4. Black and red bean moisture content as a function of shelf position and time

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Moisture</th>
<th>Moisture</th>
<th>Moisture</th>
<th>Moisture</th>
<th>Moisture</th>
<th>Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Red</td>
<td>Black</td>
<td>Red</td>
<td>Black</td>
<td>Red</td>
<td>Black</td>
</tr>
<tr>
<td>0</td>
<td>18.90%</td>
<td>21.70%</td>
<td>18.90%</td>
<td>21.70%</td>
<td>18.90%</td>
<td>21.70%</td>
</tr>
<tr>
<td>1</td>
<td>17%</td>
<td>19.90%</td>
<td>17.20%</td>
<td>20.30%</td>
<td>17.30%</td>
<td>20.40%</td>
</tr>
<tr>
<td>2</td>
<td>16.20%</td>
<td>18.20%</td>
<td>16.20%</td>
<td>19.10%</td>
<td>16.70%</td>
<td>19.30%</td>
</tr>
<tr>
<td>3</td>
<td>15.60%</td>
<td>17.30%</td>
<td>16%</td>
<td>18.20%</td>
<td>16.10%</td>
<td>18.00%</td>
</tr>
<tr>
<td>4</td>
<td>15.30%</td>
<td>16.50%</td>
<td>15.50%</td>
<td>17.30%</td>
<td>15.60%</td>
<td>17.10%</td>
</tr>
<tr>
<td>5</td>
<td>14.90%</td>
<td>16%</td>
<td>15.20%</td>
<td>16.50%</td>
<td>15.40%</td>
<td>16.50%</td>
</tr>
<tr>
<td>6</td>
<td>14.80%</td>
<td>15.60%</td>
<td>14.90%</td>
<td>16.00%</td>
<td>15%</td>
<td>16.20%</td>
</tr>
</tbody>
</table>

Figure 16. Bean moisture content v. time
From the moisture content results, it is seen that black bean seed more readily relinquished its moisture. This is likely due to the physiology of the seed, as the red bean seed has a waxy shell coat and the black bean seed does not. This waxy shell, or cuticle, exists to regulate the moisture uptake and release.

A further trend is observed based on the location of the shelves. Intuitively, the bottom shelf had the fastest drying rate, while the middle shelf experienced the next fastest drying rate and the top shelf of beans dried the slowest. This is likely due to the humidity of the drying air increasing when passing through the first shelf, and with each subsequent shelf; the bottom shelf is subjected to the driest air, and the top shelf is subjected to the least dry air.

In Figure 16, exponentially fitted curves were applied to each set of data. Modifying the Newton model of grain drying, Equation (1), to account for a non-unity initial grain moisture content, the mathematical model becomes

\[ MR = A \exp(-Kt) \]  

(21)

where \( A \) is the initial moisture content of the beans. Common values of the value \( K \) are observed based on bean type. Indeed, the red bean seed relations were generally \( MR = 0.18 \exp(-0.036 \ t) \), and the black seed relations were generally \( MR = 0.21 \exp(-0.05 \ t) \). Therefore the drying constant \( K \), which was not found during grain drying research, was found for black and red beans:

\[ K_{\text{black}} \approx 0.05 \]

\[ K_{\text{red}} \approx 0.036 \]
The obtained values of $K$ for black and red beans can be used in conjunction with Equation (21) to predict the drying time for a layer of beans, given the static pressure drop of the bean layer does not exceed the operating static pressure of the centrifugal fan operating at a given angular speed. Equation (21) is rewritten to explicitly solve for drying time to aid in future operation of the bean seed dryer.

$$t = -\ln \left(\frac{MR}{A} \right) \frac{1}{K}$$  \hspace{1cm} (22)

It is noteworthy that the parameter $K$ depends on drying air temperature, humidity ratio, and velocity per the Grain Drying Modeling section of this report. It is unknown, however, how $K$ depends explicitly on these parameters. Since bean seed dryer testing on April 18, 2013 only obtains one point of these parameters, it is recommended that further testing of the bean seed dryer be completed at various temperatures, humidity ratios, and velocities of the drying air. A separate study into the effect of the drying air humidity ratio on drying would be especially useful for the bean seed dryer, as it may indicate a modification to the system that may expedite bean drying.

Finally, it must be noted that the testing conditions on April 18, 2013 were stormy. Little sunlight was incident on the solar collector, so the drying air of the greenhouse was not heated. It is expected that, during operation of the bean dryer on a sunny day, the values of $K_{black}$ and $K_{red}$ will increase, and the rate of bean drying will increase.
V. Conclusions and Recommendations

Upon the conclusion of the testing session at the MSU Greenhouses, the test data showed a unanimous trend in the orientation of the results. All three series from each of the three drying shelves shows consistent declines in the percentage moisture content of both the red and black bean varieties. The moisture ratio was reduced to near the moisture ratio target which is a satisfactory result considering that testing was conducted on a day with little sunlight. These conditions were not ideal operating conditions for which this concept was designed. When operated under conditions with more sunlight, the bean seed dryer will dry beans at a faster rate.

It is also important to note that for these tests, a thin layer of beans (approximately 1.5” total bean layer thickness) was dried in the bean seed dryer. It is not abundantly clear how the performance of the dryer would be affected in the case of drying a thicker layer of beans, but it is known that the Dayton 2C938 blower can create a static pressure of approximately 1” $H_2O$ at 1140 rpm. Per Equation (13), this corresponds to an allowable total bean layer thickness of 6”, which corresponds to roughly 100 pounds of beans distributed amongst the three shelves of the bean seed dryer.

Although the test session at the MSU Greenhouses served as a proof of concept for our bean dryer, there are still several steps of product refinement that should be undertaken. First, further testing is required to fully determine the performance of the dryer and its short and long-term effects on the batches of beans which it dries. Generally, in industry, the testing of devices that may have an effect on food processing and food security is an extended process, in which countless scenarios are replicated to ensure quality and to ensure that there are no side effects on the produce and the consumers which it is set to benefit. Currently it is unknown how the beans will react to the accelerated drying process within the dryer in terms of their plant-ability in
future seasons, and their ease of storage and cooking properties. An understanding of these characteristics is critical before such a device is fully validated for use by farmers and communities that may need it.

Design improvements can also be made to the bean seed dryer. For the powertrain, increasing the stability of the stationary bicycle and reducing the slippage between the timing belt and the steel driving wheel would be beneficial. Ways of reducing this slippage may include adding tensioners or spring loaded tension wheels to the system to increase the force of the belt on the steel wheel, and thus increase the coefficient of friction between the belt and the wheel. Increasing this coefficient of friction will improve the traction between the wheel and the belt, and will also help to keep the belt tight, thus reducing “jumping” on the follower pulley in the rear.

Finally, the drying compartment can be more effectively sealed to ensure that the maximum amount of airflow is passed through the beans and not lost to the surroundings. Multiple layers of beans across an entire cross-section of the drying compartment effectively create plugs that require a significant amount of static pressure to penetrate. Air leaks below the exit vent will result in losses and will negate the plenum pressure generated by the centrifugal fan, thus reducing the performance of the dryer.
VI. References


VII. Appendix

A. Early Design Concepts

The following designs represent a few of the concepts considered as design solutions by Design Team 18.

i. In-Storage Drying

The drying-in-storage concept was inspired by the fact that many of the beans in developing countries are stored for an extended period of time after they are dried. Having the beans in a breathable sack allows for moisture to escape the beans. In order to achieve airflow there is a basic solar collector that would facilitate natural convection through the collector, the housing, and the beans until it exits through a group of holes before the roof.

Figure A1. In-storage drying concept rendering
ii. Solar-Heated Rock Stove

The solar-heated rock stove is a multi-step dryer. First, one places a specified number of stones to be heated up to a desired temperature in the solar oven. Once these rocks reach a specified temperature they are transferred to the drying apparatus, where they are placed in the bottom drawer to heat the entire housing. This would facilitate natural convection of the air throughout the housing causing the beans on the perforated trays to dry.

![Solar-heated rock stove concept rendering](image)

Figure A2. Solar-heated rock stove concept rendering

iii. Waterfall Belt Feeder

The waterfall belt feeder is similar to how grain is fed into a silo for storage. However, it is different in that it is continuously operated. By having the beans continuously being fed through this belt feeder the falling action of the beans is comparable to having air forced through the beans on a drying rack. In order to ensure the process is continuous, the beans land on a slanted runner that feeds them back towards the start of the belt. A downside to this concept is
that it requires a continuous power input to function and will only function below a specific amount of beans.

![Waterfall belt feeder concept rendering](image)

**Figure A3. Waterfall belt feeder concept rendering**

**iv. Winding Tubing**

The winding tubing is a concept that introduces an alternative way for collecting heat from the sun to facilitate natural convection. Long tubes are used to collect solar irradiation. The tubes allow for the solar dryer to be collapsible and transportable. Also with these tubes, it provides an opportunity to gather sun in different orientations, allowing for a more diverse collection area compared to the traditional method. However, this concept lacks a reliable method by which retain absorbed heat within the tubes.
v. Solar-Chimney Fan Dryer

The solar-chimney fan dryer is an archetypical solar dryer. However, to increase system airflow, a fan is added to either push or pull the air through the system. Since this chimney will likely be tall, it is imperative to design ergonomic considerations into the device. This is accomplished by creating a pivot point for the perforated trays to allow for a large amount of beans to be poured out rather than removing the entire tray.

It is important to note that this system is dependent on the direction in which it is placed; the solar collector should face south for optimal collection in the northern hemisphere. Another downside to this design is the requirement of power for it to be effective. A unique benefit of the chimney is that it can be used to dry a variety of produce.
B. Feedback from Dr. Luis Flores’s Associates

The following image was provided to Design Team 18 by Dr. Luis Flores. Dr. Flores and his associates suggested modifications to the solar chimney design concept.
C. Airflow System

The body of the report presented an airflow system loading curve up to 600 CFM. The following Figure shows the loading curve up to 2000 CFM.

![Airflow resistance of soybeans - System Resistance Curve](image)

**Figure A7.** Bean dryer airflow system loading curve
The following fan performance curve was obtained from *Grainger* technical support.

Figure A8. *Dayton 2C938* fan performance curve for 1140 rpm operating speed
The sheet metal duct connecting the outlet of the centrifugal fan and the solar collector inlet was designed such that the angle of air diffusion was approximately 10°. The following schematic shows relations used to dimension the duct.

Figure A9. Fan-to-solar collector ducting drawing
D. Manufacturing

A list of building materials for the bean seed dryer shed:

Table A1. Building materials for the bean seed dryer shed

<table>
<thead>
<tr>
<th>2&quot;x4&quot; boards</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&quot; angle iron</td>
</tr>
<tr>
<td>.75&quot; angle iron</td>
</tr>
<tr>
<td>Metal screening</td>
</tr>
<tr>
<td>Nuts and bolts</td>
</tr>
<tr>
<td>Wood screws</td>
</tr>
<tr>
<td>Caulking agent</td>
</tr>
<tr>
<td>Plywood</td>
</tr>
<tr>
<td>Sheet metal</td>
</tr>
<tr>
<td>1” nails</td>
</tr>
</tbody>
</table>
Figures A10 – A16 show photos of various components of the bean seed dryer during the process of device manufacturing.

Figure A10. Square base of the bean seed dryer shed

Figure A11. Utilization of the 3-axis milling machine
Figure A12. Attaching the aluminum mesh to the bean tray frame via staple gun

Figure A13. Bean seed dryer shed without steel floor and wooden walls
Figure A14. L-shaped brackets fastening the solar collector

Figure A15. Top view of the solar collector before closure

Figure A16. Bean seed dryer shed and solar collector