Smallholder Farm Coffee Roaster
D-Lab Pro ABT 289A 002

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Design Brief

Smallholder Kenyan coffee farmers lack the access to an educational opportunity that will explain how to improve the quality of their coffee beans. Consequently, they have been having trouble to make a considerable profit from selling the beans. Proper sorting after harvest is the most effective way to improve their method because it can be immediately implemented. By providing an affordable, easy-to-use, and reliable coffee roaster, the farmers will be able to taste their own coffee to understand the difference in quality between beans that are properly and improperly sorted. Working with Kyle Freeman and Tonny Gitonga, we redesigned a popcorn popper to make a coffee roaster that will evenly roast coffee beans within 5 - 12 minutes.

There are many options of coffee roasters to choose from, but none of them were viable because the farmers agreed that they would only purchase roasters that are within the price range of $40 - $70 which are none of the current roasters. On the other hand, popcorn poppers are used as a coffee roasters in common households and only cost around $20 - $25. The popcorn popper of choice is the Nostalgia Electric Popcorn Popper because it chooses to have the airflow from the sides of the container instead of the bottom as shown in Figure 1. However, the heating element did not get to the desired roasting temperature, so some adjustments were made.

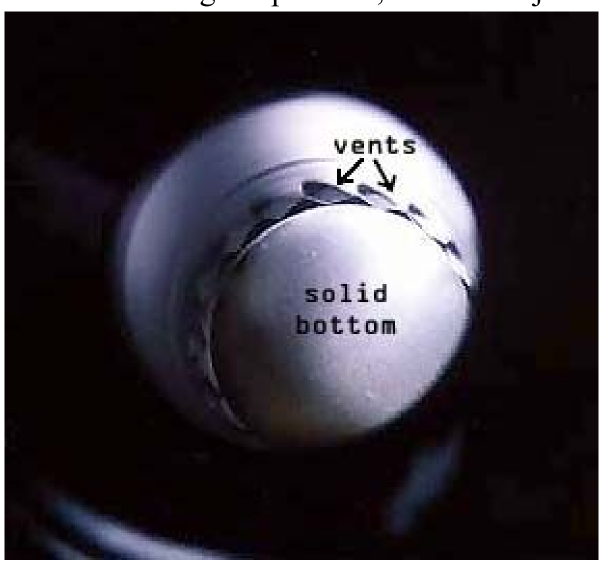

Figure 1: The inside of a Nostalgia Electric Popcorn Popper illustrating that the air comes in from the sides.

Improvements to the farming process should be made to improve the quality of the bean, but the cost of the methods need to be considered as well. For example, purchasing fertilizers or pesticides out of the price range for a majority of the farmers to maintain [1]. Also, these types of improvements that take a long time to notice considerable improvements in the quality. On the other hand, improving practices in the post harvest processing can instantly improve the bean quality marginally which can allow for higher prices [2]. The color of the bean can determine whether or not it is up to standard as shown in Figure 2. The International Coffee Organization set the standards of the bean off the discoloration which is measured within 300 g of beans.

Figure 2: Possible discolorations of coffee beans [2].

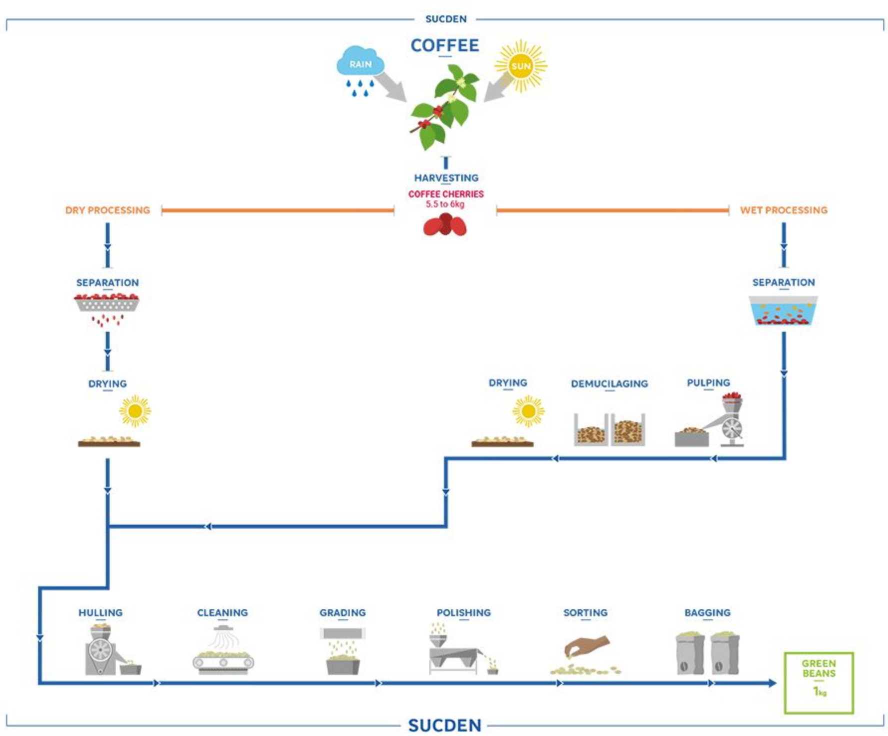

Figure 3: Post harvest coffee flowchart [4].

The coffee flowchart in Figure 3 shows the detailed steps that farmers go through to get to selling their beans. Depending on the farm, the beans are sold after certain steps. Some farms sell them after they are freshly harvested while others sell them after they are dried it depends on the equipment that is available to the farm. Even though there is a step involved that is specifically meant for sorting out the discolored beans, there are steps before that where sorting can happen as well. For starters, while harvesting the beans the farmers can be trained to learn which beans are soiled immediately by looking at it and sorting them out. Farmers are often paid for the pound, so they should keep the imperfect beans and still get paid for picking them. Some farms provide a red bracelet that represents the color of ripe coffee cherries and if the colors do not match then the pickers leave the cherries on the tree. Another test that can be implemented after picking the beans is to put them in water. The ones that float need to be removed because the bean in the middle is small and underdeveloped. During the drying process, the beans need to be regularly stirred to ensure they are evenly dried. The farmers can refer to Figure 2 during the intermediate stages between stirring to find some discolored beans.

Design Process

To design a coffee roaster that meets our clients needs, 3 main categories of design are to be considered: (in order of importance) economics, performance, and ergonomics. The design criteria for what was thought to yield the most effective product were brainstormed, then sent to the client for approval. From his feedback, the first-draft design criteria for the coffee roaster were verified and are shown in Table 1.

Criteria	Testing Procedure	Target Value	Metric	Source	Category
Selling Price	2*(Production cost)	≤70	$ (USD)	Client	Economic
Throughput	Mass of coffee per batch	1	kg/batch	Client	Performance
Roast Quality	Check for homogeneity of bean color throughout the roast	99	% same bean color	Dr. Kuhl	Performance
Chaff Removal	Mass batch before & after roasting to find mass difference	100*(1–avg. mass of chaff / avg. mass of whole bean) (TBD)	% mass difference	Experimental measurements	Performance
Consistent Roast Temperature	Measure the temperature of the beans during the roast	See figure 4	°C/second	Dr. Kuhl	Performance

Transparency of Use	Time for farmers to learn and operate the roaster	15-30	Minutes	Farmer Interview	Ergonomic
Easy to Maintain	Focus group replace heating element	15-30	Minutes	Farmer Interview	Ergonomic
Safety	Run 5 consecutive roasts	0	Combustion	Farmer Interview	Ergonomic
Portability	Able to easily hold the roaster across a room and put in high cabinets	2 - 3.5	lbs	Farmer Interview	Ergonomic

Economics:

Smallholder Kenyan coffee farmers do not have the resources to purchase basic coffee roasters, as they can cost upwards of $70 (on the low end). Research done in previous quarters revealed that $70 was the upper limit for marginal cost that the farmers themselves are willing to pay. This means that the cost of the popcorn popper and modifications must not exceed $70, or else the farmers would not buy it in the first place. The cheaper and simpler the construction materials are, the more it benefits the farmers. Economics is considered most important because this is what will initially persuade the farmers to invest in the product.

Performance:

Secondly, the performance of the roaster must be satisfactory for the farmers' needs. It must be able to yield batches large enough for the farmers to brew and sample. The roaster must also be able to follow a roast profile as close as possible to ensure a high-quality roast that brings out the most representative bean flavor. The target roast profile was specified by Dr. Tonya Khul, the local expert on all things coffee, and is shown in Figure 4 where the bean temperature

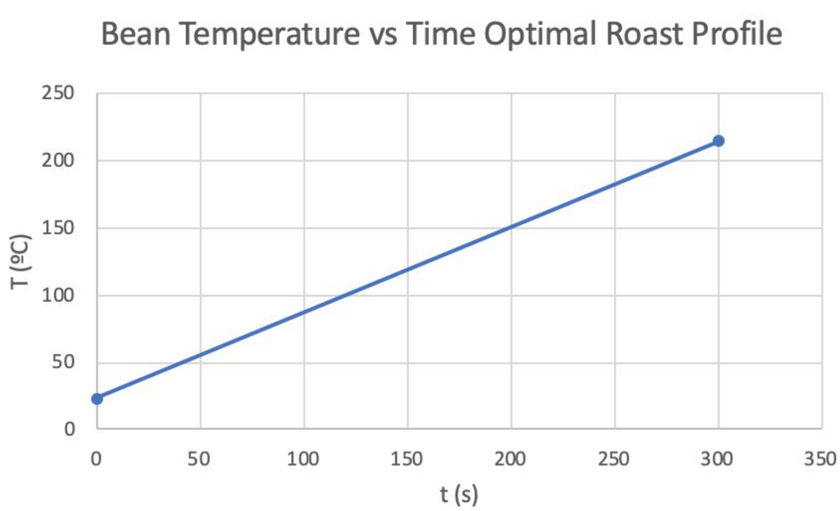

Figure 4: Target Roast profile specified by Dr. Kuhl

linearly increases for 5-12 minutes until it reaches 210-218ºC, then is quickly cooled. Mixing of the beans is important for each bean to be roasted uniformly and to prevent burning. The skin of the coffee beans, or chaff, must also be removed during roasting to minimize the chaff content in the finished batch because it cannot be ground up and brewed. These criteria are important to yield ideal roasts that best represent the coffee bean flavor and quality.

Ergonomics:

The finished roaster must also be ergonomic for the farmer's use. Simplicity, portability, and maintenance are all parallels, where added complexity would make the roaster harder to operate, add weight, and add more parts that are prone to breaking, which would require unwanted maintenance. The roaster must also be safe to handle and operate so it is not a fire hazard and to prevent burning the user.

An evaluative matrix, shown in table 2, narrowed down the most important considerations, outlined above, to be addressed during the quarter. Table 3 shows the pros and cons of each design idea. Throughout the quarter, the mesh filter, time/temperature dial, and sloped pot bottom were not implemented exactly, but their functions were accommodated by alternative and easier methods (to be discussed later).

Table 2: Evaluative matrix for best design ideas

Design Concept	Cost efficiency	Wt	Time/ Difficulty to Build	Wt.	Functionality Importance	Wt.	Simplicity	Wt.	Durability	Wt.	**Total**
Chaff filter mesh grid	4	5	4	4	5	3	5	1	5	2	**66**
Time dial	2	5	2	4	5	3	1	1	2	2	**38**
Temperature dial	2	5	2	4	2	3	2	1	2	2	**30**
Reference graph of bean roast gradient	5	5	5	4	1	3	5	1	3	2	**59**
Sloped pot bottom for better circulation	1	5	1	4	3	3	2	1	4	2	**28**

Table 3: Pros and cons for top three design ideas

<table>
<tr><th>Design Concept</th><th>Pros</th><th>Cons</th></tr>
<tr><td>Chaff filter mesh grid</td><td>-Elongates the roasters life cycle
-Makes cleaning the remaining mesh easier because there's less chaff to remove</td><td>-Have to find optimal mesh-grid size for chaff to escape but not beans
-Adds another part to keep clean and maintain
-Adds cost</td></tr>
<tr><td>Time dial</td><td>-Reduces roast supervision
-Customer does not need to find his/her own timer</td><td rowspan="2">-Difficult to implement into circuitry
-Adds complexity to modifications
-Adds significant cost
-May burn the roast if set incorrectly
-Makes operation less transparent</td></tr>
<tr><td>Temperature dial</td><td>-Reduces roast supervision
-Enables different types of roast settings (light, medium, dark)</td></tr>
<tr><td>Reference graph of bean roast gradient</td><td>-Allows the farmer to know what phase of the roast they are in</td><td>-Color may fade, creating a false reference color</td></tr>
<tr><td>Sloped pot bottom for better circulation</td><td>-Allows better mixing
-More uniform airflow that heats the beans evenly</td><td>-May require fewer beans to operate</td></tr>
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Methods & Modifications

The following steps and modifications were made to the popcorn popper to create the final coffee roaster. These next five pages will function as the final deliverable/manual for the farmers to modify and operate the final roaster.

Figure 5: Nostalgia Air-Pop Hot Air Popcorn Popper[5]

Materials:

- Nostalgia Air-Pop Hot Air Popcorn Popper[5]
- Wire cutters
- Phillips head screwdriver
- Wire strippers
- Razor
- Large twist-on wire connector
- Pliers
- Timer
- Temperature sensor
- Type-A to type-G outlet adapter

Modifications:

Step 1: Purchase the "Nostalgia Air-Pop Hot Air Popcorn Popper" ($14.99 + shipping) from Target's website, shown in Figure 5. This popcorn popper uses a fan to blow air over a heating element into the main canister.

Step 2: Use a screwdriver to disassemble the popcorn popper to separate the fan/heating/canister component from the plastic case and base.

Figure 6: Step 2

Step 3: Remove the base, then use pliers to separate the main switch from the plastic case and its wire terminals.

Figure 7: Step 3

Step 4: Remove the fan/heating/cannister component from the shell and use pliers to remove the wires from the thermal switch terminals. The thermal switch can either be removed completely or left attached to the cannister because it will not be used in operation.

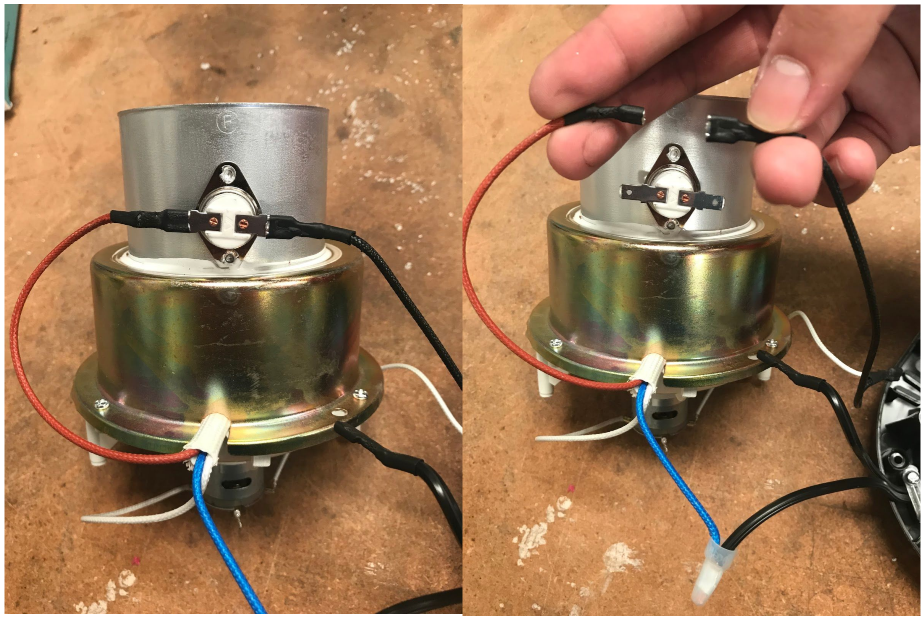

Figure 8: Step 4

Step 5: Locate the three leads that originally connected to the main switch (one white and one black stitching-insulated, and one rubber-insulated). Use wire cutters and strippers to remove the push-on terminals and expose an inch of wire. Then use the twist-on wire connector to connect all 3 wires (as if the original switch were turned on permanently).

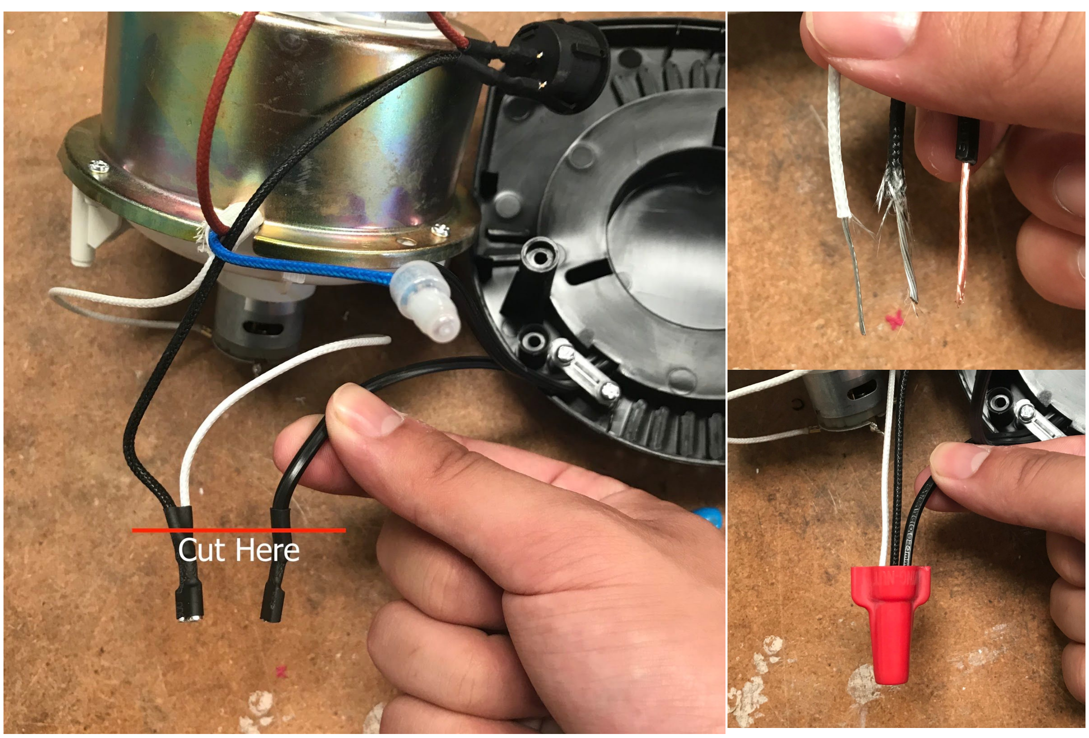

Figure 9: Step 5

Step 6: Reattach the fan/heating/cannister to the base, then the plastic case onto the base. Thread the two uncut, thermal switch push-on connectors through the main switch hole. Attach the main switch to the push-on connectors and secure it into its original spot.

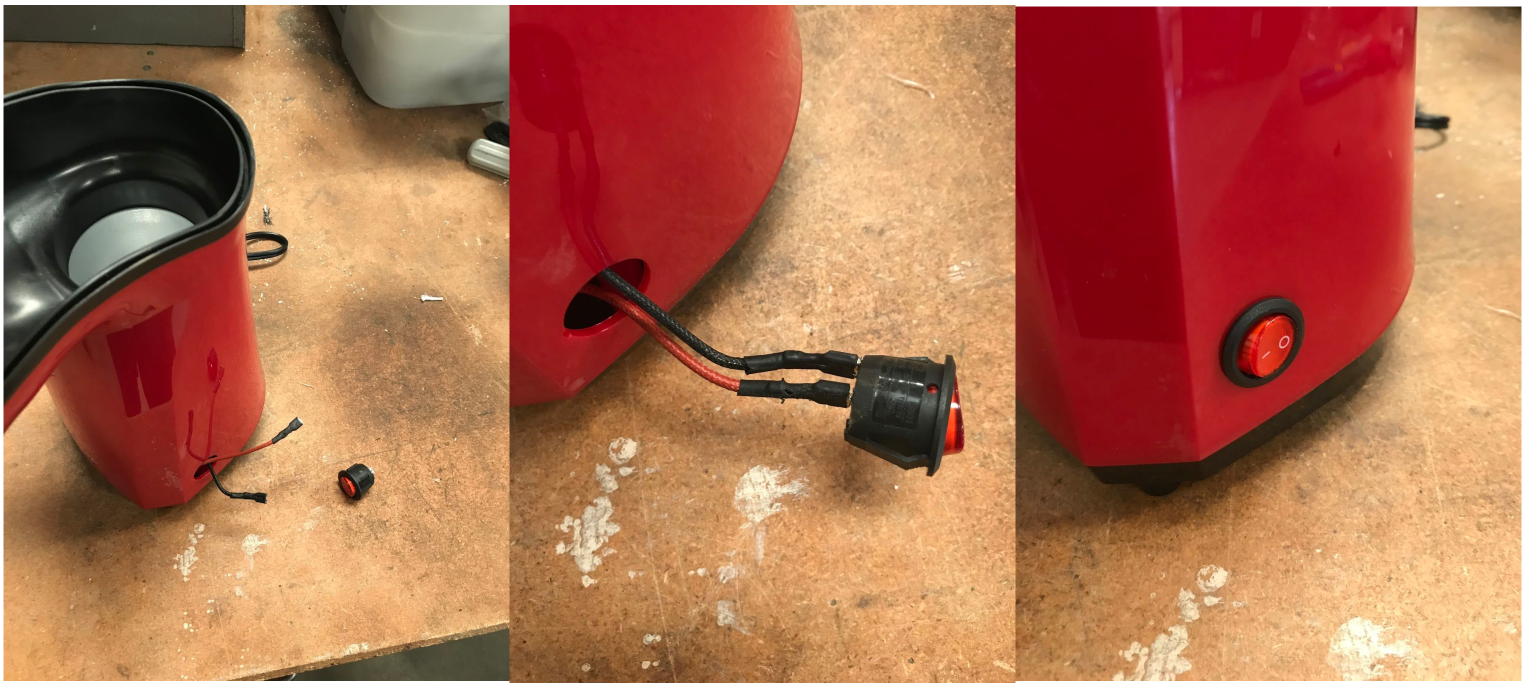

Figure 10: Step 6

Modifications are now complete! Ultimately, the main switch has been moved to control the heating element directly, bypassing the thermal switch since the fan and heating element are on independent circuits. The change in circuitry is illustrated below.

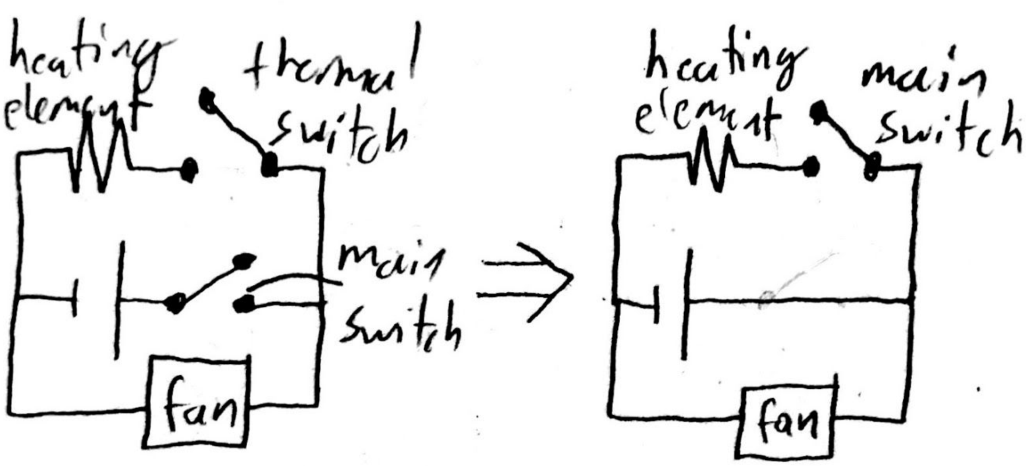

Figure 11: Original (left) and modified (right) circuitry

Operation:
Step 1: Place the roaster on a stable surface and make sure the main switch is off to prevent prematurely turning on the heating element. Plug the roaster into the type A converter, then into a type G outlet (the fan should turn on immediately). Place a bowl directly in front of the roaster to catch the removed chaff throughout the roast process.

Step 2: Measure out about 1.5 - 2 oz of raw coffee beans (the bean mass is important to allow sufficient mixing). Slowly pour the coffee beans into the roaster cannister until they mix steadily and slowly.

Step 3: Place a thermocouple or thermometer in the cannister so the sensing element is in contact with the beans. This is only required in the first few batches so that the roaster can be calibrated to the ambient temperatures, bean type, and roast conditions. Place the transparent plastic lid on the roaster.

Step 4: Once the beans can be seen mixing evenly, start a timer and switch on the heating element at the same time.

Step 5: Once 50 seconds have passed, turn off the main switch for 10 seconds, then turn back on. Repeat this on-off cycle three more times. This causes the heating element to heat up slower, making it more closely follow the target roast profile in Figure 4. If the temperature does not reach 210-218ºC within 12 minutes using four on-off cycles, then the next roast should have only three on-off cycles. Similarly, if the temperature reaches 210-218ºC **before** 5 minutes, then the next roast should have five on-off cycles. Continue to control the number of on-off cycles until the desired roast temperatures are achieved.

Step 6: During 5-12 minutes roast time, the coffee beans should be continuously compared to Figure 12. The ideal bean color should range from City Roast to Full City, which should be reached anywhere between 5 and 12 minutes. If a City Roast or Full City roast is achieved before 5 minutes, the roast may be stopped.

Step 7: Once the heating element is switched off, the beans must be quickly cooled. Use gloves or oven mitts to pick up the roaster and pour the finished beans into a large bowl. Stir or shake the bowl to remove any excess chaff that was not removed during the roast and to cool the beans faster.

Step 8: Grind, brew, and enjoy the freshly-roasted coffee!

Figure 12: Bean-color roast guide[6]

Results

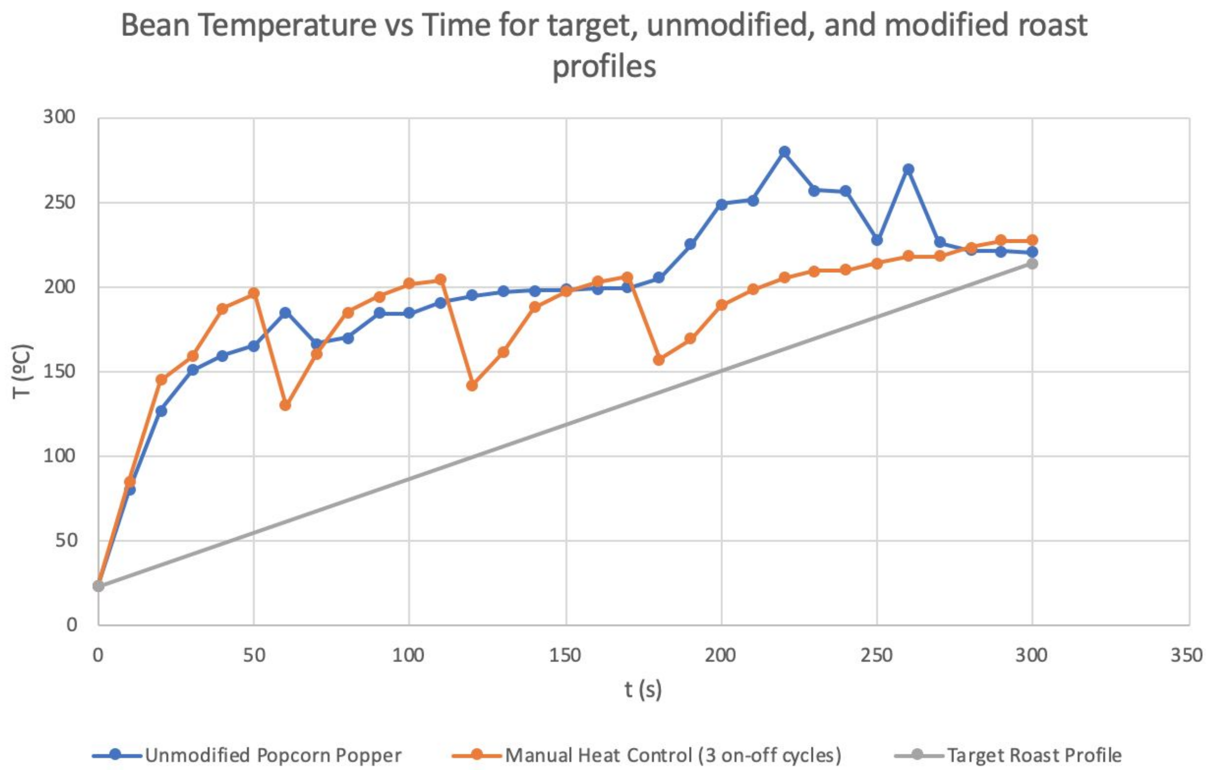

Figure 13: Resulting roast profiles compared to one another

Figure 13 shows that the unmodified popcorn popper yielded roasts that got too hot too fast when compared to the target profile. All three profiles were started from room temperature and stopped at 5 minutes, or 300 seconds. 1.5 oz of coffee beans were used for the unmodified and manual control runs. With the implemented manual heat control, the roast temperature was effectively lowered by the on-off cycles and is comparably closer to the target profile than the unmodified popper. The effects of the thermal switch, which was bypassed in the modified roaster, can be seen in the latter end of the unmodified curve where the temperature dropped after the heating element reached over 275ºC. The manual heat control curve is still not ideal, since the heating element heats up too fast after it is turned back on. The roast may be further improved by implementing more on-off cycles, which would allow for a longer roast and a slower climb to the target temperature.

Discussion

This coffee roaster still has much room for improvement, and many things cannot be tested until it is sent to the farmers. For example, transparency of use cannot be determined until the Kenyan farmers use the roaster firsthand. In terms of the first-draft of design criteria, many things proved to be unrealistic and unnecessary. Previously, we expected a throughput of 1kg/batch, but 1.5 oz/batch is sufficient to brew enough coffee for farmers to sample. We also expected complete removal of chaff, but this was impossible to measure with the given tools because the mass lost would be on the scale of milligrams.

At the beginning of the quarter, we tried to follow our design criteria closely, but after testing multiple designs in different conditions, we had to deviate from our initial plans. The first change came after testing the Nostalgia popper. It uses angled vents to blow the hot air down and around the bottom of the canister, shown in Figures 1 and 14. This air flow kept the coffee beans

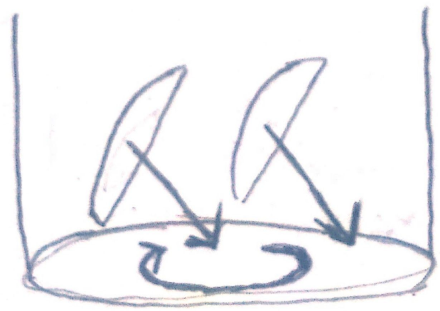

Figure 14: Nostalgia cannister with angled air vents

on the bottom of the cannister and simultaneously blew chaff out of the popper as desired. This configuration solved the need for the chaff filter mesh grid as discussed in Tables 2 and 3. The circulating airflow also provided better mixing, solving the need for a sloped cannister bottom. The fan, however, was underpowered and often could not generate enough air pressure to move the beans, burning them before they were able to move and ruining the batch. During tests with less bean mass and adequate circulation, chaff removal was less effective because the fan was underpowered. Increasing fan-power or airflow to the cannister would have fixed circulation issues and improve chaff removal.

The mixing was found to be heavily dependent on the strain of beans being roasted. At the beginning of the quarter, a lighter dry bean was used; the airflow generated was enough to sufficiently mix up to 3 oz. When we ran out of beans halfway through the quarter, we obtained denser beans that could not circulate if we used more than 1.5 oz. The modified roaster solved this problem by ensuring the beans can circulate before the heating element is turned on to prevent burning them.

During initial testing, the popcorn popper was found to be sensitive to ambient temperatures and conditions. When used outside on a 65ºF day, the temperature of the beans was 20º colder than on an 85ºF day. Wind also lowered the roast temperature by 10-15º. The temperature differences observed are enough to change the type of roast in the same amount of time (a full city requires 427ºF while a 1st crack requires only 405ºF)[6]. For this reason, in addition to the inherent differences in the bean strains, the number of on-off cycles must be calibrated to each condition set for which is it operated.

The implementation of the manual heating element control requires extra supervision during the roast process. Although this was initially undesired, it is actually a slight benefit in terms of safety and roast quality. If the user were to set a time and temperature dial then walk away from the roaster, any issues with mixing or burning beans would go unnoticed and the batch would be ruined. A time and temperature dial would work in this context, but manual on-off control over the heating element has the same purpose. It is also important to note that the heating element was prone to degrading over time; if held unregulated for over 8 minutes, its maximum temperature diminished by 20ºC.

Holding the temperature close to the target value of 210-218ºC would be detrimental to the resulting coffee flavor because this is similar to baking instead of roasting the coffee. Baking the beans can be visualized by the unmodified roast profile in Figure 13, where 200ºC is held for 100 seconds until it increases further. This “stalling” of temperature is known to yield flat coffee with little sweetness, often described as bread-like or papery[7]. The manual control curve does show an improvement, but it still bakes the beans in 20 second intervals. This can be further improved by either shorter on-off cycles or implementing a completely different method to control the voltage across the heating element.

The main success of this roaster design is the cost. All input cost is for the Nostalgia popcorn popper ($14.99 + shipping) and a G-to-A type power adapter ($3.99) making total manufacturing cost = $19 + shipping. The only modification is simple and involves moving a pre-existing switch from one location to another. No complex electronics or modifications are required.

Finally the provided manual, located in the methods & modifications section, should be referenced when first using the roaster. Figure 12 provides the bean-color reference gradient for which all batches be compared to.

Conclusion

Even though the roaster is presentable, there are elements that can be improved like the air pressure needs to be increased for adequate airflow and more control over the heating element. The current airflow allows for about 1.5 oz. of beans to roast, however, there are occasions when the beans have trouble with evenly roasted that could be solved with a higher air pressure to ensure better stirring. Also, the heating element increases the temperature too quickly which also does not allow for even stirring. Our method for compensating that is by turning the heating element off for 10s every 50s three to five times depending on the ambient conditions. This allows for a more even roast, but it also requires more supervision than we had originally intended. Our original goal is that the user turns on the roaster and it roasts the beans on its own.

In terms of the progress made for improving the roaster, we spent too much time familiarizing ourselves with the roaster and getting a good batch as opposed to redesigning the roaster and experimenting more with different parameters. We would also change too many variables at the same time which made it difficult to determine what worked and what did not work. For example, we started out roasting outside, but as stated before ambient conditions would change the quality of the roast. So, some days were windy and cold while other days were hot and dry which would change the temperature of the roast. When we decided to use the roaster inside the shed is when we decided to remove the thermal switch which lead to the heater reaching very high temperature, but we were not sure what the underlying casue was until a few more roasts. For future development we would recommend that tests on the roaster would remain indoors for consistent ambient conditions.

Recommendations

The roasters are able to get to the desired temperature and are fairly well mixed, however, they require too much supervision in order to achieve a proper batch. Our recommendation is to look into methods that will control the power to the heating element’s temperature so that it increases at a controlled rate. A potential option is to attach an arduino with a mini breadboard to the roaster that has a series of resistors and over time the arduino will turn off the resistors to gradually increase the voltage intake. This is beneficial because arduinos with mini breadboards cost about $20.

If additional method proves to be effective or if another one is found, then the popcorn popper should be sent to Kenya for the farmers to learn how the roasters look and provide feedback on what they liked and what they think can be improved. They will be providing this feedback through a survey that we wrote up and can be viewed in the appendix. Also, while all the farmers are testing the roaster, a complimentary workshop will be provided about affordable methods to implement that will improve bean quality.

After the workshops have been conducted and the farmers give their approval that they would purchase the roaster, research will need to be done on methods to ship the roaster parts out to Kenya. As far as we have researched, we have not been able to find popcorn poppers that are sold in Kenya, but outsourcing from other countries can be an option.

Bibliography

[1] Karanja, Andrew M., and James K. Nyoro. "Coffee prices and regulation and their impact on livelihoods of rural community in Kenya." Tegemeo institute of agricultural policy and development, Egerton University (2002).

[2] Molina, Angie. "How to Improve Your Coffee Quality in Harvesting and Sorting." Perfect Daily Grind 2018. Web.

[3] International Coffee Organization. "Improving Quality." 2018. Web.

[4] Sucden, S&D. "Process Flowchart: From Seed to Bean." 2019. Web.

[5] "Nostalgia APH200RED Air-Pop Popcorn Maker - 1040W - Red." *Target*, express.google.com/u/0/product/11728798889010631646_4568117027970241451_10046?utm_source=google_shopping&utm_medium=tu_cu&utm_content=eid-lsjeuxoeqt>im=CILjq9vXnIuYIhCYuY3Fg9bO1xoYsPWSByIDVVNEKJDkxegFML5O&utm_campaign=10046&gclid=Cj0KCQjwxYLoBRCxARIsAEf16-v6Vn1NfN_LeF4aAFtyDP9nF0SzSPsVIJlzfRSpy82fE5iwvW7bD-EaAoCtEALw_wcB.

[6] "Using Sight to Determine Degree of Roast." *Sweet Maria's*, 2018, legacy.sweetmarias.com/library/using-sight-to-determine-degree-of-roast.

[7] Ospina, Angie Molina. "6 Common Roast Defects & How to Recognise Them." *Perfect Daily Grind*, 19 July 2018, www.perfectdailygrind.com/2017/03/6-common-roast-defects-recognise/.

Appendix

Questionnaire for after the coffee roasting/sorting workshop:

1. On a scale of 1 - 5 how comfortable do you feel using this coffee roaster?
2. What did you have the most difficulty with while using the roaster?
3. On a scale of 1 - 5 how even was your roast?
4. Were there any technical problems with the roaster?
5. Have you roasted your own coffee beans prior to this workshop?
6. On a scale of 1 - 5 how useful was the sorting workshop for you?
7. Did you implement any of the sorting methods mentioned in the workshop?
8. Do you plan on implementing any of the methods? If not, why? If yes, which ones?
9. Would you use the roaster again?
10. Would you suggest this roaster to other smallholder coffee farmers?