Designing an Ergonomic Geothermally Heated Pinecone Seed Extractor

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Abstract

Reforestation is one key element to counteract the global climate catastrophe. The Icelandic Forest Service (IFS) provides pine tree seeds in Iceland, using a labor-intensive, time-consuming, and unergonomic process with two various machines for drying and separating the seeds from the cones. To optimize this procedure, the two machines were combined into one machine (SeedEx) following Axiomatic Design and Product Design principles. Aligning Customer Needs (CNs) to desired functionality allowed the team to realize the project in twelve weeks by minimizing design iterations through careful modularity. Changing the main rotation axis of the extractor enables operators to load cones and receive seeds ergonomically. The SeedEx prototype processes 260 % of the former daily capacity while reducing labor by 92 % and eliminating time delays between processes.

Keywords: Seed Extraction, Pinus Contorta, Convective drying, Axiomatic Design

1 Introduction

Deforestation is a major concern that is highly prevalent throughout the world, not only accelerating global warming but also declining biodiversity [1]. The country of Iceland has been hit particularly hard by this human-made catastrophe. A nation that once had 40 percent of its countryside covered by forests began to lose its tree cover in the 9th century. Today, only 2 % of Iceland is forested [2]. The IFS is reforesting Iceland, doubling the total amount of woodland and forests since 1950 by planting tree species such as Russian Larch, Alaskan poplar, Sitka spruce, and especially the Lodgepole pine tree.

Pine tree seeds are located in the pinecone, protected from environmental impacts and predators during winter, by remaining closed and sealed with resin. In nature, Lodgepole pinecones open up during summer due to the increase in temperature and evaporation of water with resin [3]. However, not all pinecones open up during summer. Studies show that a significant amount remains closed until the resin bond is melted by high temperatures above 52 °C [4][5]. In fact, these serotinous cones enable the seeds to survive wildfires and spread after the wildfire is over. Overall, the characteristic of the opening process varies from species to species.

From October to March, the IFS collects Lodgepole pinecones to plant new trees (Pinus Contorta) and sell seeds to other companies for reforestation purposes. The process the IFS is currently using to extract the seeds takes over 24 hours. The IFS starts by soaking the cones to dissolve the resin. Afterward, the cones are dried in one machine (Figure 1a) and then shaken by a different machine (Figure 1b) to bring out the seeds. Both machines require manual loading and unloading, which takes up to 60 minutes for a total capacity of 90 liters. On average, the IFS states that 30 percent of the pinecones do not open up during the first process cycle due to serotinous cones. This process of extracting the seeds is labor-intensive, time-consuming, and unergonomic. To fix these issues, the Seed Extractor (SeedEx) was designed with the goal of both drying soaked pinecones and extracting the seeds in one process, by enabling less time-consuming and ergonomic loading and unloading capabilities. Following the concepts of Axiomatic Design theory in a product design context [6], a top-level need was phrased: "$\mathbf{CN}_0$: Dry pinecones and separate the seeds in one convenient process by the worker." Based on this, the decomposed CNs can be identified as follows:

- $\mathbf{CN}_1$ Dry the pinecones to open up at least 70 % of the loaded pinecones while serotinous cones can remain closed.
- $\mathbf{CN}_2$ Separate the seeds from the pinecones.
- $\mathbf{CN}_3$ Enable one person to load and unload the machine.
- $\mathbf{CN}_4$ Cheaper than the project's budget of 500 000 ISK.
- $\mathbf{CN}_5$ Fit through standard doors (width less than 85 cm).
- $\mathbf{CN}_6$ Reliable in unheated greenhouse conditions, since it will be stored in an unheated greenhouse, all year round.
- $\mathbf{CN}_7$ Minimum loading capacity of 50 L.
- $\mathbf{CN}_8$ Pinecone temperature not exceeding 52 °C.

(a) Dryer (b) Shaker

Figure 1: IFS's current seed extraction machines.

The name SeedEx was chosen because the machine extracts seeds from pinecones. The target customer is the IFS as well as other planting companies and the companies buying seeds from the IFS. Future projects like the Reforest'Action will increase the need for seeds, which emphasizes the potential need for an additional machine for the IFS. Besides the IFS in Iceland, other governments or companies around the globe are considered to be interested in the prevalent design. The IFS was involved in the design process and provided financial resources. Therefore, the final machine design will not be turned into a business but due to the rising global demand, the potential is estimated to be 100 machines a year.

2 Prior Art

As stated in Section 1, the IFS separates seeds from Lodgepole pinecones. Considering a total variety of 115 different pine species with different physical characteristics, the prior art on pine seed extraction varies substantially. In the following chapter, recent concepts are analyzed and evaluated.

2.1 Machines for Pinecones

Two current available designs on the market are the dehuller Extractor 1300 and the smaller dehuller Extractor 800 from BCC AB. These machines are designed to extract seeds from the same species of pine trees and are therefore comparable to SeedEx.

The BCC AB Seed Extractor 1300 and 800 are large capacity and multipurpose units performing pre-cleaning and drying of pinecones and seed

(a) Dehuller Extractor 800

(b) Dehuller Extractor 1300

Figure 2: Pinecone extraction options from BCC AB. Images retrieved from company website at [7]

extraction. Pre-cleaning removes small impurities, e.g. needles, scales, and twigs before drying. This takes place due to the friction of the loaded pinecone mass inside the machine and is therefore a feature that SeedEx would also perform when applying motion to the cones.

Both machines use convectional drying and rotational moving of the cones. During the drying process, the cone gradually opens for the seed to be extracted [7]. Applying this process for SeedEx appears promising, since the current machines of the IFS work with the same principle. Figures 2a and 2b show the inside of Extractor 1300 and the front of Extractor 800, which are similar to the first design ideas of SeedEx.

However, the BCC AB units do not fulfill all the CNs of the IFS, for example, reliability (CN_6). BCC AB machines are not built from stainless steel. In an unheated greenhouse environment, it is possible for a small scratch in the paint to cause severe consequences over time.

Additionally, the units consume 1.5 kW of electricity for the heating element [8]. Electric heating elements burn up over time and require an advanced controller. SeedEx aims to outperform the BCC AB units by using hot water for heating, considering the fact that geothermal hot water eliminates fire hazards and is comparatively cheap in Iceland. Next, the two units do not fit through doors. Even though the capacity of the Extractor 1300 with 200 L fulfills the CN of the IFS, the design was not chosen to fit through doors. Hence, Seedex must rely on two bearings and a long-shaped drum.

Finally, the machines of BCC AB are not ergonomically beneficial for the IFS. Like the current machine, it is essential for one person to be able to manually load and unload the pinecones with small bags. SeedEx can outperform this process by utilizing gravity for unloading and allowing heavy machinery to load the machine. In conclusion, the overall drying and separating process of the Extractors 1300 and 800 applies to SeedEx, but has to be modified to accomplish the CNs of the IFS.

Another available design on the market comes from Jiaozuo Zhoufeng Machinery Co. Ltd. The pinecone and seeds separating sheller processing machine differs from other designs. It is built on a trailer and is powered by a 20 hp diesel engine, enabling a flexible field of operation. The machine consists of a feeding hopper and a conveyor belt, allowing constant feeding of the machine. The capacity of the machine is 500 kg. The main shaft speed is 800 RPM, the fan speed is 800 RPM, and its dimensions are 3250 mm by 750 mm by 1280 mm [9].

The high flexibility of the machine comes with both high operating and fixed costs, as well as a notable environmental impact due to the greenhouse gas emission of the diesel engine. The IFS does not require a self-sufficient design. consequently, this design is solving distinct CNs.

However, designing SeedEx on wheels enables one person to handle the machine and is therefore an important takeaway from this design.

2.2 Machines for Pine Nuts

The variety of different pine species resolves in a range of various pine seeds. Pine nuts are larger than Lodgepole pine seeds and are edible. The seed extraction process is therefore different but still worth considering since both have the same goal of extracting the seed undamaged.

The pine nut shelling machine from Zhengzhou Tonde Machinery Co. Ltd cracks pine nuts without causing any damage to the kernels. The electrical power of this machine is 9.68 kW with a capacity is 300 L. The machine is 3 m tall and the gross weight is 4000 kg. The machine consists of a feeding hopper and a laminated spring plate conveyor belt allowing constant feeding. The machine processes the maximum capacity in one hour. After the pinecone is cracked open the pine nuts are shaken by sizing decks and the kernels flow to gravity tables [10].

Applying this process to Lodgepole pinecones comes with the risk of not succeeding in the given project time of twelve weeks, considering breaking these species open without damaging the seed was not proven to work before. Moreover, filtering out the seeds from impurities would resolve in a higher complex machine which is not suitable for the budget of 500.000 ISK and project time of twelve weeks.

2.3 Functional Requirements and Constrains

The CNs in Section 1 result in a list of Functional Requirements (FRs) and Constraints (Cs) by using Axiomatic Design Theory. FR satisfies a CN by adding a required function, whereas Cs are boundaries on acceptable solutions [6].

The following list shows the Functional Requirements regarding the CN for the SeedEx machine, starting with the overall: "$\mathbf{FR}_0$ Dry and separate the seeds from the pinecones by requiring one operator. Add mechanical advantage for unloading." which is then decomposed into further FRs.

FR$_1$ Dry the soaked pinecones to open up at least 70 % of the loaded cones.
FR$_2$ Add kinetic energy to pinecones to separate the seeds.
FR$_{2.1}$ Add kinetic energy to the pinecone to get the seeds released.
FR$_{2.2}$ Strain seeds from pinecones.
FR$_3$ Allow one person to load and unload.
FR$_{3.1}$ Allow one person loading.
FR$_{3.2}$ Allow one person unloading.

The following list shows the Constraints regarding the CNs for the SeedEx machine:

C1 The project cost must not exceed 500.000 ISK.
C2 The machine has to fit through doors with a maximum width of less than 85 cm.
C3 Corrosion resistance, particularly against moisture.
C4 Minimum loading capacity of 50 L.
C5 Maximum pinecone temperature of 52 °C.

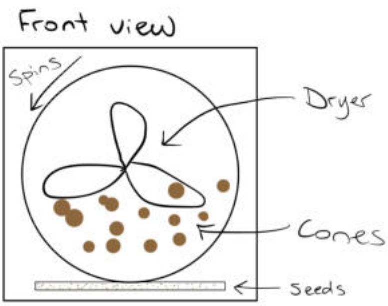
3 Design

In this chapter, the development of the design is explained. The design process was conducted with Axiomatic Design to determine the most simple and independent solution [6]. Brainstorming ideas, drawing sketches, and crafting prototypes assisted in the process to identify design issues and to be creative in decomposing the FRs into Design Parameters (DPs) while satisfying the Cs.

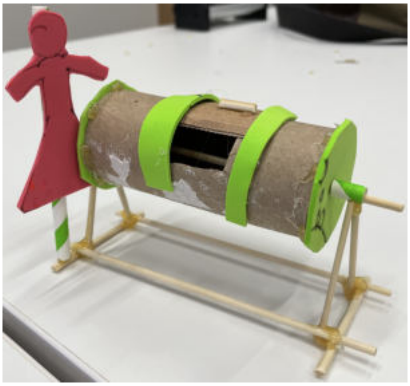
3.1 Design Process

The design process starts with analyzing the CNs and examining the prior art as described in section sec:prior-art. Figure 3 shows the first idea of SeedEx being influenced by the current designs from BCC AB. As the brainstorming and analysis continued, more changes were developed. As shown in 3 the idea consists of one bearing holding the drum. To satisfy the minimum capacity and maximum width, the design was developed in a longer drum. To then support the increased stress, two bearings are necessary, and therefore the loading and unloading needed to be reconsidered. This prototype was then produced in cardboard and is shown in Figure 3b.

Autodesk Inventor Professional 2021 was used for the CAD drawings shown in Figure 4b and 4a. At this point, the loading height was designed to be at 1.125 m, so the loading is comfortable and ergonomic [11]. The length was set to 1.5 m which was calculated for a maximum loading capacity of 200 L. For loading and unloading, the top half of the hexagon is opened and one-third of the drum slides open. The bottom part of the hexagon was designed to be open, so the seeds can fall out during the process and the empty pinecones can be dumped after the process is over.



(a) Front loading concept with single bearing



(b) Sketch prototype with two bearings enables relative sizing and ergonomics

Figure 3: Initial concepts

During the design process, the movement of the pinecones was estimated to behave like a liquid. This way the load on the bearings, motor, and frame was calculated. Soaked Lodgepole pinecones have half the density of water. When spinning the drum, the pinecone mass will flow inside the drum. To provide an even drying process on every cone, SeedEx needs to guarantee a consistent concoction of the loaded mass inside the drum. Therefore, fins were added inside the drum.

In this design the motor, radiator, fan, and, piping for the airflow direction were added. The opening section of the drum was then redesigned before manufacturing, simplifying the handling and increasing the clearance of the drum inside the hexagon. After the first conducted experiment of the system, bottom rails for standard 1/1 Gastronorm stainless steel containers were installed to catch the seeds and reduce heat loss.

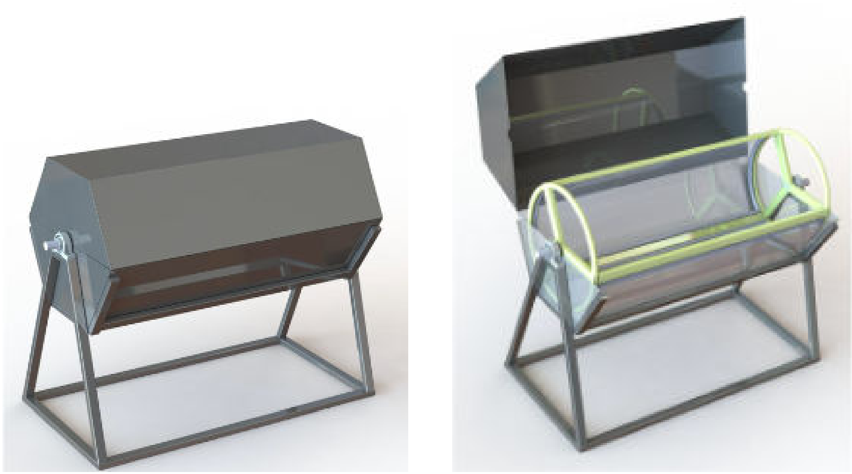
3.2 Design Parameters

From the Functional Requirements listed in section 2, a list of Design Parameters is developed while following the Independence Axiom and the Information Axiom [6], as shown in table 1.

Starting with the top-level Design Parameter "$\mathbf{DP}_0$ Fan with a radiator to blow hot air and dry the pinecones. Motor for rotating the drum. Mesh to separate the empty pine cones from the seeds. The opening section of the drum is at a height of 1.125 m above the ground." and decomposing into further DPs, as summarized in table 2:

$\mathbf{DP}_1$ Water radiator and electric fan

Hot geothermal water at 80 °C with a flow rate of 0.05 L s^{-1} flows through the 2.5 kW radiator and exchanges heat with the passing air from the



(a) Closed while in operation and dispensing seeds.

(b) Open for loading of cones.

Figure 4: CAD 3D Models of final design show cover positions of extractor.

Table 1: Top level FR-DP mapping.

	Functional Requirement	Design Parameter
1	Drying pinecones	Water radiator and electric fan
2	Add kinetic energy to pinecones to separate the seeds	Electric motor, Gearbox and Mesh with 8×8 mm holes
3	Allow one person to load and unload	Machine opening 1.125 m above ground and unloading through gravity

$240\,\mathrm{m^3\,h^{-1}}$ fan. This heated air is at 48 °C fulfills CON_5 and dries the pinecones.

DP$_{2.1}$ Electric motor and gearbox

A 1.1 kW electric motor with a maximum rpm of 1445 and a gearbox with a 1:67 ratio. Bring the pinecones in motion by spinning the drum at 10 rpm, so the seeds fall out. The powertrain provides 500 N m of torque which was chosen by the following equation:

$$T_{\text{requirend}} = m_{\max} x_{\max} g \tag{1}$$

where $T_{\text{requirend}}$ is the maximum torque required, $m_{\max}$ the highest possible loading weight with a safety factor of 2, $x_{\max}$ is the maximum lever arm as shown in figure 5, and g is the gravitation constant. The

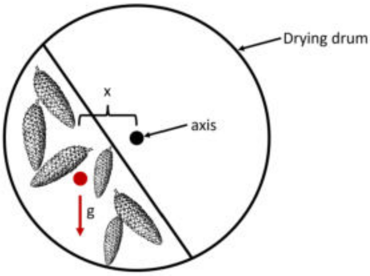


Figure 5: Estimated behavior of the pinecones inside the drum with resulting torque

Table 2: Second level FR-DP mapping.

	Functional Requirement	Design Parameter
1	Drying pinecones	Water radiator and electric fan
2.1	Add motion to the pinecones	Electric motor and gearbox
2.2	Strain seeds from pinecones	Mesh with 8×8 mm holes
3.1	Allow one person loading	Machine opening at 1.125 m above ground.
3.2	Allow one person unloading	Unloading through gravity

approximated values result in:

$$T_{\text{requirend}} = (250\,\mathrm{kg})(0.18\,\mathrm{m})(9.8\,\mathrm{m\,s^{-2}}) = 441\,\mathrm{N\,m} \tag{2}$$

As shown in Figure 5, the lever arm reaches its maximum when the pinecones accumulate on one side of the drum.

DP$_{2.2}$ Stainless steel mesh
Stainless steel mesh made out of 1 mm thick wire with square holes of 8×8 mm. This mesh is wrapped around the drum, holds the pinecones and lets seeds fall through to the bottom. The size of 8×8 mm was recommended by the IFS as the ideal size to let the seeds fall through, but stop even the smallest pinecones.

DP$_{3.1}$ Machine opening for loading at 1.125 m above ground.
The height of the frame with wheels is designed to be 0.9 m above ground. The loading height ends at 1.125 m. so the loading is comfortable and ergonomic [11].

DP$_{3.2}$ Unloading through gravity.
The machine has an open bottom. By turning the drum 180 degrees from the loading position with the removable section removed, the pinecones fall through the bottom into a collection box.

Figure 6: First Test of SeedEx at Reykjavík University's power and energy lab.

3.3 Design Matrix

The top and second level design matrices [12] were developed as shown in Equation 3 & 4. This matrix is uncoupled, i.e. diagonal matrix, meaning by varying one DP each FR can be changed without affecting other FRs [12]. Therefore, it is possible to work on individual DPs simultaneously. This simplifies the optimization of the system.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} FR_1 \\ FR_{2.1} \\ FR_{2.2} \\ FR_{3.1} \\ FR_{3.2} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_{2.1} \\ DP_{2.2} \\ DP_{3.1} \\ DP_{3.2} \end{Bmatrix} \tag{4}$$

4 Results and Discussion

In this chapter, the results of the different tests are shown and discussed. This was conducted starting with the FEM simulation of the frame, followed by the testing of the drying system, and concluding with the testing of the whole machine in operation.

4.1 Frame FEM simulation

The frame was simulated in Autodesk Inventor 2021 bearing a load of 6.25 kN split between the pillow block-bearing seats. This is equal to 2.5 times the

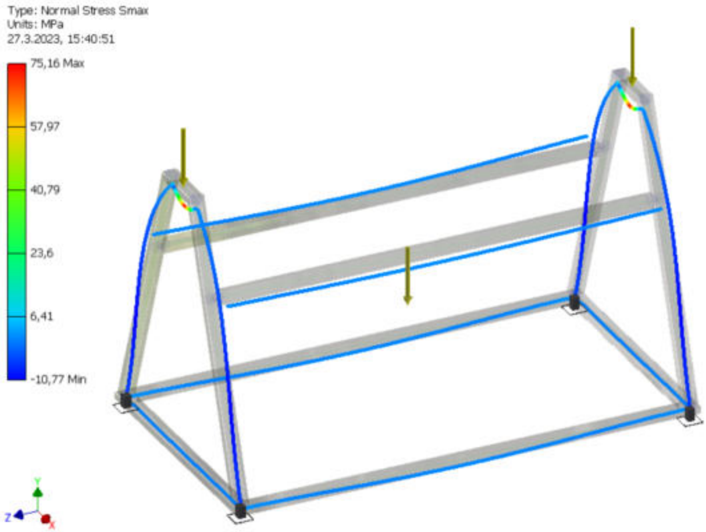


Figure 7: FEM simulation of the frame with loading equal to 2.5 times the expected loading

expected loading. The expected loading was calculated from the weight of the drum 50 kg with the maximum allowed amount of pinecones at 200 kg. This results in a force of 2.5 kN acting on the bearing seats. As can be seen in Figure 7 the max von Mises stress did not exceed 75 MPa on the bearing seats. Given that the yield strength of 304 stainless steel is 205 MPa, the frame experiences no fatigue under the expected operation. The load is estimated to remain below half the yield strength. The deformation with the expected loading is 0.0372 mm as can be seen in Figure 8. The observed deformation in the real unit was too small to measure with the available tools, as it was less than 1 mm.

4.2 FR_1 test: Airflow and air temperature (Radiator and Fan)

The fan and the radiator were tested together to evaluate the range of temperature and airflow expected from this module. The steady temperature at the final location will be 10 °C with a relative humidity of 80 %. The relative humidity will drop to 14 % after the air is heated to 40 °C according to the psychrometric chart. Therefore, the relative humidity should not affect the process. The radiator was connected to the water source with a water flow of $0.16\,\mathrm{L\,s^{-1}}$ at 52 °C, and high water flow was required to compensate for sub 70 °C water at the university. The fan was set to a max setting of $230\,\mathrm{m^3\,h^{-1}}$. The fan and the radiator were connected with a pipe so that the fan blows air through the radiator. The in- and outflow temperatures of air were measured with a DTP6 thermometer, and the air velocity was measured with AN310

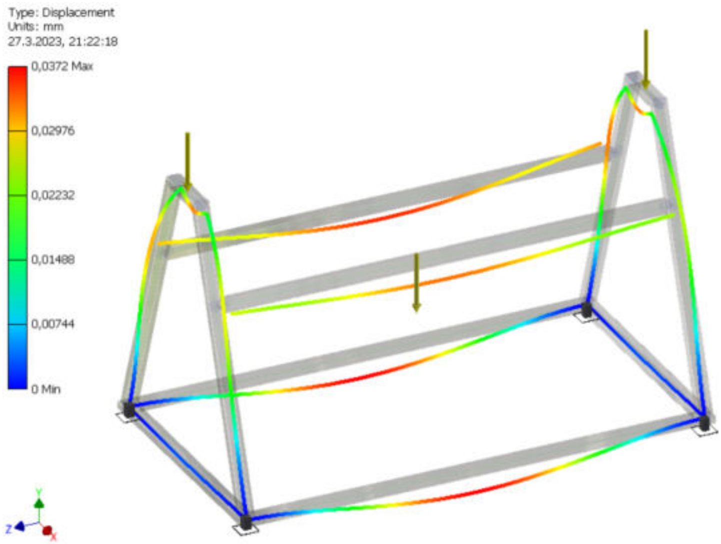


Figure 8: FEM simulation of the deformation in the frame with the expected loading

Anemometer. The temperature of the discharging water was 50 °C. The inflow air temperature was at 20 °C and outflow at 42 °C. The airflow dropped to $150\,\mathrm{m^3\,h^{-1}}$ due to the pressure drop in the radiator. The air temperature for pinecone drying must not exceed 50 °C. Given access to hotter water, the desired temperature will be easily reached even with ambient temperatures of 10 °C according to the data from this test.

4.3 Functional testing of the system with 100 L/50 kg of pinecones

To begin system testing, the pine cones were soaked for 24 hours. Afterward, they were loaded into the machine and dried with a continuous rotation of 10 RPM at 40.3 °C. After 20 hours, 70 % of the pine cones got dry and opened up. The data log of the first 60 minutes can be seen in Figure 9. The temperature in the air duct reached a horizontal asymptote after 16 minutes. The measured data was:

- The air temperature inside the drum was 41.8 °C.
- The ambient temperature was 3 °C.
- The water temperature going in was 75 °C.
- The water temperature going out was 59 °C.
- The airflow was $155\,\mathrm{m^3\,h^{-1}}$.
- The water flow was $0.04\,\mathrm{L\,s^{-1}}$.

The remaining unopened 30 % of the pinecones are due to the cones' level of serotiny. These pine cones will be reentering the process, as they require

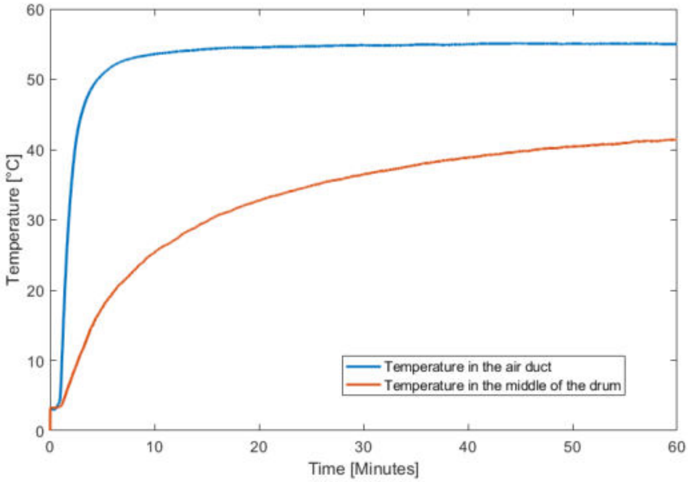


Figure 9: SeedEx heating up at the 3 °C greenhouse with 80 °C water

multiple pre-soaks before they open up during the drying process. The unloading through gravity worked as desired and the machine was unloaded in under 10 seconds. Adding 4 min and 50 s for the loading process, the labor work was reduced by 92 % in comparison to the current IFS process (60 min).

This testing evaluated all the FRs, from loading the machine in the beginning to unloading the machine after the drying and seed separation was done.

5 Conclusion

Replanting trees is increasing in importance due to global warming and preservation of biodiversity. The IFS is responsible for the required Russian Larch, Alaskan poplar, Sitka spruce, and Lodgepole pine tree seeds in Iceland. The government agency is extracting seeds with two machines from pinecones in a labor-intensive process. By using Axiomatic Design the CNs of the IFS were identified and entirely accomplished in a simplified and independent design. This enabled SeedEx modules to develop over the design process without affecting others. The Seed Extractor (SeedEx) dries pinecones (CN_1) and separates the seeds (CN_2) in one process, while additionally enabling one person to unload and load the machine (CN_3). SeedEx is performing a convection drying process with a water heat exchanger and an industrial fan. The pinecones are secured in a cylindrical drying drum, which consists of a 8×8 mm square hole mesh and a removable section. The drum is brought into circular motion by an electric motor. This motion is forcing the small seeds to be released from the pinecone and fall through the mesh and out of the machine. The loading and unloading mechanism of the drum consists of one removable section of the drum. The section enables one average-height person to remove it for loading and unloading at a height of 1.125 m, while the unloading process is executed by gravity by turning the open drum 180 degrees, reducing the labor work by 92 %. The implementation of the cylindrical drying drum results in the maximum width to fit through 85 cm doors (CN_5), while at the same time providing five times the stated minimum loading capacity of 50 L (CN_7). The customer budget of 500 000 ISK was not exceeded, as the cost of building the machine resulted in 490 000 ISK (CN_4). At the same time, reliability in unheated greenhouse conditions was accomplished by choosing 304 stainless steel for the components (CN_6). The major challenge was combining the process into one machine. SeedEx accomplished all CNs in the conducted experiment. 70 % of the pinecones opened up and released the seeds over a time of 20 hours which fulfills (CN_1).

Overall, in addition to the fulfillment of customer needs, the designed SeedEx contributes to the acceleration of reforestation efforts and strengthens the conservation of biodiversity.

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