Development and evaluation of an improved maize silo to advance food security in Uganda

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Abstract: Maize is a major agricultural resource for smallholder farmers in East Africa, providing both food and income. However, poor post-harvest management leads to about 20% and 30% loss of maize grains, thereby aggravating hunger and poverty. Reducing post-harvest losses in maize is an essential component in any strategy to make more food available without increasing the burden on the natural environment. The current metal silo storage methods do not offer significant protection against insect and mould infestation. In addition, they often experience temperature fluctuations, grain lumping and caking due to moisture condensation at the inside silo wall. This study focuses on developing an improved metal silo to prevent grain damage due to rodents, insects and caking. The research covers all the necessary design considerations, construction and methods of using the silo for maximum results. The improved metal silo is 87% efficient in reducing insect infestation, significantly reduces temperature fluctuations and completely prevents grain caking or lumping. The silo is used indoor and recommended to enclose...
a candle with the grains for maximum efficiency. The silo is economically affordable and increases farmers’ income through reducing post-harvest losses.

**Subjects:** Preservation; Processing; Product Development; Structural Mechanical Engineering; Engineering Economics

**Key words:** Maize metal silo; double-wall; candle; sawdust

1. Introduction

As the global population increases, there is a corresponding increase in food demand. In many cases, there is sufficient crop production but due to the lack of sustainable storage facilities, food insecurity still exists. Thus, there is a quest for innovative means of preserving grains especially through home-grown solutions that uses locally sourced materials. In East Africa, the situation is the same for all grains including maize. Notably, maize (*Zea mays* L) is a major staple food for a large proportion of the East African population (Z. Gitonga et al., 2015). Its consumption has increased over the years as population increases and as people change their consumption habits (Daly et al., 2016). It has a larger quantity of carbohydrates and significant proportions of proteins, vitamins and fats contained in the kernels (Suleiman, 2016). This makes it compete favourably as an energy source with root and tuber crops. In Uganda, maize is sold mainly for food in households, schools, relief by World Food Programme (WFP) or exported to neighboring countries such as Tanzania, Kenya, Rwanda and Burundi (Daly et al., 2016). However, farmers are unable to meet the ever-increasing demand and compete favorably in the market due to grain storage losses (Kimenju et al., 2009). In order to fight food insecurity, reducing post-harvest losses that amount to 30% of staple food grains through modern storage techniques is of critical importance (Abebe et al., 2009).

There are a number of traditional storage methods still being used by farmers such as floor storage, bags, granaries, jars, baskets and pots. These do not insure maize against damage by insects, pests, rodents and moulds (Yuya et al., 2009). Currently, metal silos are the predominantly used techniques for grain storage in East Africa (Z. Gitonga et al., 2015). However, metal silos have had little success in preventing insect infestation due to air leakage into the silo (Babangida & Yong, 2011). In addition, they often experience temperature fluctuations especially in warm and humid climate (Adejumo, 2012). More so, caking and lumping usually occur on the walls as a result moisture condensing on the inner surface of the cold wall. The condensing moisture is absorbed by the adjacent grains resulting in either sprouting or mold growth resulting in grain deterioration (Adejumo, 2013). The damaged grains usually have reduced nutritional values, low viability and reduced weight that frequently fetch low market prices (World Bank, 2011).

1.1. Post harvest losses and trend in grain storage technologies

Post-harvest losses have been studied for a long period of time across the globe (Affognon et al., 2015; Kaminski & Christiaensen, 2014; Tefera, 2012). According to Kaminski and Christiaensen (2014), post-harvest losses for maize grain are up to 1.4–5.9 % at country level among the countries considered for the study including Uganda, Malawi and Tanzania. In both East and Southern Africa, the most important staple food is maize but has however undergone serious post-harvest losses in the past resulting in the reduction of farmers’ incomes (Z. M. Gitonga et al., 2013). Uganda’s economy is highly dependent on agriculture and yet still is a major driver for growth and food security (Kaminski & Christiaensen, 2014).

Most post-harvest losses arise from insect infestation, rodents attack, poor storage facilities and moisture conditions (Tefera, 2012). According to FINTRAC (2016), 20–50% of on farm post-harvest losses arises from insect infestation. The losses incurred on farm for maize farmers in Uganda is up to 6% of the stored quantity while may reach 100% in some cases (Omotilewa et al., 2016). In addition to the above causes of post-harvest loss, it is noted that the length of storage also increases the grain deterioration and thus reducing the potential market price. Investment in
efficient on farm storage facilities is therefore required to improve the shelf life of grains after harvest.

Methods for grain protection against insect infestation range from use of traditional methods like woven sisal sacks, insecticides, biological treatment and hermetic technologies. Hermetic storage technologies (HST) work on the principle of oxygen deprivation thus making the storage facility free from molds and insects. Hermetic storage technologies involve air tight bags made from various materials the most common being polypropylene & polyethylene, other technologies involve use of a metal or plastic silo. Various methods for storing grains have been employed in developing countries and sub-Saharan Africa. The traditional methods of grain storage in East Africa with main focus on Uganda involve the use of a granary (mud and grass thatched houses) normally raised from the ground to prevent rodent intrusion (Baributsa & Njoroge, 2020). The traditional methods are however inefficient and cannot fully protect the grains against insects and rodents (Z. M. Gitonga et al., 2013; Simon, 2015). Other methods involve the use of simple sacks, while others involve treatment of the grain with insecticide prior to storage. The treatment with insecticide is iterative as it should be repeated at least every three months. Additionally treatment with insecticide has a downside as improper use may lead to food safety issues (Baributsa & Njoroge, 2020; Talukder, 2009).

Farmers in Kenya have adopted hermetic storage technologies, particularly the hermetic bags to store mostly maize and with an increased return on investment (Baributsa & Njoroge, 2020). However, 13.5% of users of the HST in this study had issues with reduced grain quality and poor quality of the hermetic bags which led to insect infestation and rodent attack. Using a randomized control trial method, Omotilewa et al. (2018) investigated the effect of use of improved storage technology (hermetic bags) on food security in Uganda with results showing a 61-70 % reduction in storage losses. The hermetic bags despite being efficient were small to accommodate the farmer’s produce. A study conducted in Kenya indicated the effectiveness of metal silo technology in protecting maize against pests (Z. Gitonga et al., 2015). Metal silos are an effective technology as they facilitate longer and safer storage periods (SDC, 2008). Additionally metal silos offer a range of sizes for farmers, thus enabling them to store as much grain as possible (Simon & Groote, 2010).

It is projected that by 2050 the world population will be 9 billion, therefore a 70% increase in food production is required (Tefera, 2012). In order to efficiently accommodate the growing population, measures involving reduction in post-harvest losses should be adopted to counter balance with the increased need for food production. According to World Bank (2011), reduction in post-harvest losses at household level will help in improving food availability and enhancing household income. Design of efficient and improved storage technologies such as metal silos that are cost effective and efficient can highly contribute to enhancing food security both globally and locally. This is because by using efficient storage technologies, the farmers are in position to store their food for longer periods and cater for the periods of scarcity. The limitation of the previous studies that this paper seeks to overcome is that other studies have not shown any concern lumping and cake formation.

Therefore, this paper focuses on the development of an improved indoor metal silo for maize grain storage with complete air-tight locking device aimed at reducing post-harvest losses due to insects, rodents, molds and caking in Uganda. The research covers all the necessary design considerations, construction and methods of using the silo for maximum results. It also encompassed the performance and economic evaluation of the device.

Following this introduction, the materials and methods are presented in section two, the results and discussions are presented in section three while section four focuses on the conclusions and recommendations drawn from this study.

1.2. Materials and methods
The silo was designed to be indoor to prevent corrosion of the construction material since it is metallic. The most important design considerations included: space since it was indoor, silo
capacity, weight, manufacturability, maintenance, durability, strength, safety, availability and cost of construction materials. Throughout the design of the silo, the use of standard parts was emphasized where possible. The silo was designed to store 200 kg of maize grain. The sources of the materials are given in Table 1.

### 1.3. Design of the silo drum or shell

The silo wall was made cylindrical to effectively resist pressure caused by grain loading through development of circumferential and hoop stresses. Cylindrical sections occupy less space and require fewer joints during construction hence increasing the strength of the drum with minimum thickness. They also provide an easier way of loading and unloading of the grains from the silo.

The height and diameter of the silo wall were determined based on the volume or amount of grain stored as in equations 1 and 2.

\[
V = \pi r^2 h_1 + \frac{1}{3} \pi r^2 h_2
\]

(1)

But,

\[
V = \frac{m}{\rho}
\]

(2)

Where,

- \(V\) = volume of the silo \((m^3)\)
- \(m\) = mass of the stored product \((kg)\)
- \(h_1\) = height of the silo wall \((m)\)
- \(r\) = radius of the silo \((m)\)
- \(\rho\) = Density of the stored material \((kg/m^3)\)
- \(h_2\) = height of the hopper \((m)\)

The pressures distribution due to charging, discharging and at rest conditions of the silo were determined. The vertical pressure was calculated using Janssen's equation in equations 3, 4 and 5 (Nakashima, 2010);

| S/N | Material                  | Source                        | Use                                           |
|-----|---------------------------|-------------------------------|-----------------------------------------------|
| 1   | Galvanized iron           | Roofings outlet, Tororo       | To construct the silo drum and the hopper    |
| 2   | Mild steel angle bars     | Steel and Tube outlet, Tororo | To construct the support frame                |
| 3   | Rubber fittings           | Tororo city tyres centre     | To make inlet and outlet seals                |
| 4   | Saw dust and wood shavings| Tororo furniture workshop    | To provide the insulation so as to reduce temperature fluctuations inside the silo. |
\[ P_V = \frac{\gamma R}{\mu K} \left( 1 - e^{-\mu x} \right) \]  \hspace{1cm} (3)

\[ K = \frac{1 - \sin \phi}{1 + \sin \phi} \]  \hspace{1cm} (4)

\[ R = \frac{D}{4} \]  \hspace{1cm} (5)

Where,

\[ P_V = \text{vertical pressure (Nmm}^{-2}\text{)} \]

\[ R = \text{Hydraulic radius of horizontal cross section of storage space (m)} \]

\[ \mu = \text{Coefficient of wall friction} \]

\[ x = \text{Depth from surface of stored material to point in question (m)} \]

\[ K = \text{Lateral to vertical pressure coefficient} \]

\[ \gamma = \text{Weight per unit volume for stored material (Nmm}^{-3}\text{)} \]

\[ D = \text{Diameter of the silo (m)} \]

\[ \phi = \text{Angle of internal friction (°)} \]

The horizontal pressure, \( P_H \) (Nmm\(^{-2}\)) of a unit area at depth \( x \) (mm) from the free surface was obtained from equation 6.

\[ P_H = k P_V \]  \hspace{1cm} (6)

The friction force, \( P_f \) (Nmm\(^{-2}\)) of a unit area of silo wall at depth \( x \) (mm) from the assumed free surface was computed from equation 7.

\[ P_f = \mu P_H \]  \hspace{1cm} (7)

The static unit pressure, \( P_o \) (Nmm\(^{-3}\)) normal to the surface inclined at angle \( \alpha \) to the horizontal at depth \( x \) below the surface of stored material was obtained from equation 8.

\[ P_o = P_H \sin^2 \alpha + P_V \cos^2 \alpha \]  \hspace{1cm} (8)

The silo was designed for concentric discharge, hoop stress, \( \sigma_H \) developed from concentric discharge were obtained from equation 9 (Nakashima, 2010).

\[ \sigma_H = \frac{P_H D}{2t} \]  \hspace{1cm} (9)

The thickness of the silo wall using buckling stress and the hoop stress at cylindrical wall (Carson & Jenkyn, 1993) as in equation 10.

The critical elastic buckling stress, \( \sigma_{cr} \) is given by:

\[ \sigma_{cr} = \frac{E t}{\sqrt{3(1-\nu^2)} R} \]  \hspace{1cm} (10)

Where,
σₐ = the critical elastic buckling stress (N/mm²)

E = Elastic modulus (N/mm²)

t = Cylinder thickness (mm)

r = Cylinder radius (mm)

v = Poisson's ratio (unitless)

1.4. Design of the hopper
The hopper made of galvanised iron was made in conical shape because conical shapes facilitate smooth flow under gravity. According to Beakawi Al-Hashemi and Baghabra Al-Amoudi (2018), the sloping angle of the hopper should be at least 5° greater than the angle of repose of the stored maize grains to facilitate smooth solid flow. Based on field observations, the angle of repose for maize ranges between 16° and 30.2° (Bhadra et al., 2017). The meridional tensile stress and the circumferential hoop stress were calculated from the equations 11 and 12 (Nortje, 2002).

\[ F_m = \frac{P_D}{4s\sin\alpha} + \frac{W}{nD\sin\alpha} \]  (11)

\[ F_t = \frac{P_D\sin^2\alpha + P_D\cos^2\alpha}{2s\sin\alpha} \]  (12)

Where,

W = weight of the stored grains in the hopper

\( F_t \) = Tangential force due to circumferential hoop stress (N)

\( F_m \) = Meridional tensile force (N)

D = Diameter of the top of the hopper (m)

The hopper’s minimum diameter was determined from equations 13 and 14 (Chase, n.d).

\[ d = H(\theta) \frac{\text{CAS}}{\rho g} \pi r^2 \]  (13)

\[ H(\theta) = 2 + \frac{\theta}{60} \]  (14)

Where,

\( \text{CAS} \) = Critical applied stress which is a function of the material's flow function and flow factor \( \theta \) = semi included angle.

From the design chart for symmetrical slot outlet hoppers for solid flow, CAS was determined to be 2.8766 (Nakashima, 2010; Reed & Duffell, 1980).

1.5. Design of the support/frame
The support structure was designed to carry all the load above it and to resist the stress of the stored material. According to Khurmi and Gupta (2003), compressive stress in the support frame is calculated from equation 15.
\[
\sigma = \frac{\text{applied load}}{\text{crosssectional area}}
\]  

(15)

1.6. The fabrication and description of the metal silo

Galvanized iron was selected for the silo shell due to its strength to withstand forces and pressures, corrosion resistance and availability. In this study, mild steel was used to fabricate the support frame based on its ability to withstand compressive forces, availability and reduced cost. Wood shavings and saw dust were selected for insulation due to its low conductivity and availability. The silo consists of the following (Figure 1).

(a) The cylindrical double wall; sawdust is placed between the two thin galvanized iron walls. The wall holds the stored grains and prevents temperature fluctuations.

(b) Inlet cover and outlet; these have rubber seals and locking mechanisms to tightly cover the charging and discharging points respectively to provide a controlled airtight atmosphere

(c) Support frame; to provide support to the different parts of the silo and for repositioning the silo. It also fitted with a lubricated ring allowed uniform agitation of the silo to further prevent grain lumping and caking.

(d) Conical hopper; to allow free flow under gravity of the grains during discharging

Different fabrication and machining methods such as cutting and bending were used in the production of the different parts of the silo. Joining of the silo parts was made by seaming, riveting, brazing and welding. Painting of the prototype was made to give a better surface finish.
1.7. Performance evaluation of the machine

The candle test was carried out to test for the sealing efficiency of the silo. A candle was enclosed inside the silo and observed (Anne et al., 2018). This was tested three (3) times and for each test a stopwatch was started to determine the duration taken from the closure of the silo to the time the candle goes off.

To test for insect infestation, dried grains with moisture content of 13.9% wet basis were sampled and loaded into the silo. The moisture content was measured using a mini digital hygrometer due to its simplicity, accuracy and reliability (Tubbs et al., 2017). Ten (10) samples of 0.25 kg were made and enclosed in the silo together with a burning candle. The average number of live weevils per kilogram of grain were obtained. After 35 days the grains were off-loaded from the silo and the number of live insects in each sample determined. The silo efficiency in protecting grains against insect infestation was calculated from equation 16. This methodology was used due to its wide use by researchers as a simple and accurate method to determine insect infestation in a closed silo (Anne et al., 2018; Babangida & Yong, 2011).

\[
\text{Efficiency} = 1 - \frac{\text{no of live insects per kg after loading in the silo}}{\text{number of insects per kg before loading in the silo}}
\]  \hspace{1cm} (16)

The same procedure above was repeated with the same grain batch (same insect infestation). For this test, the burning candle was not enclosed with the grains and the number of live insects per kg were recorded after 35 days of storage. To test for temperature fluctuation protection, the internal silo temperature was measured at eight hours interval for 15 weeks using thermocouples and a data logger of model TC-800D. The ambient temperature was measured using a digital thermometer. The initial grain temperature was 20.8°C. Agitation was done once in a week for a minimum of 30 minutes.

1.8. Economic analysis

This project was economically evaluated by calculating the payback period and the net present value (NPV) of the project as the methods of the project evaluation (Garg, 2016). The total cost of the silo was calculated from the sum of cost of materials used and the labour costs incurred during fabrication of the silo. The annual depreciation of the silo was calculated using the straight line method in equation 17 (VCCL (Vancouver Community College Learning Centre), 2013).

\[
\text{Annual depreciation} = \frac{I_0 - I_t}{t}
\]  \hspace{1cm} (17)

Where,

- \( I_0 \) = initial cost of the silo (Uganda Shillings)
- \( I_t \) = value of the silo after time (Uganda Shillings)
- \( t \) = useful life of the silo (years)

The interest rate of 15% per annum was used as per the Central Bank of Uganda

\[
\text{Interest} = \text{interest rate} \times \text{initial investment cost}
\]  \hspace{1cm} (18)

The Total annual non-cash fixed cost was calculated as the sum of total annual depreciation cost and interest whereas total annual cash fixed cost considered only insurance. Since the silo is a structure prone to risks, the insurance was estimated as 0.25% of the total investment (Winckler & Boshoff, 2017). The operational costs were estimated as 5% of the initial investment of the silo. This included labour and repair costs. Therefore, the expected annual increase in revenue due to the use of the silo was estimated at 81,400UGX by taking the percentage savings from general grain losses during traditional storage of maize which could be reduced by the improved storage of
the silo. The difference between the losses due to the silo and the average losses due to traditional storage methods was assumed as the savings due to the silo in equation 19.

\[
\text{Expected increase in revenue} = \text{percentage savings} \times \text{total sales}
\]  

(19)

The Payback Period, Return on Investment and Net Present Value were calculated using the equations 20, 21 and 22 respectively.

\[
\text{Payback period (years)} = \frac{\text{initial investment}}{\text{annual increase in revenue} - \text{operating cost}}
\]  

(20)

\[
\text{Return on Investment} = \frac{\text{annual increase in revenue} - \text{operating cost}}{\text{initial investment}}
\]  

(21)

\[
\text{Net Present Value} = \sum^0 V - I_0
\]  

(22)

1.9. Limitations and future scope of the study

The new design is entirely based on maize grain properties. For it to be adapted to other grains, further studies need to be carried out. In addition, the silo is designed for household applications, its applicability for industrial purposes needs to be studied. Also, this research did not consider testing the viability of the stored grains. This is planned for the next phase of research.

2. Results and discussion

The results of this research are presented in this section and are discussed in comparison with other similar studies.

2.1. Components’ dimensions

The diameter of the silo wall was calculated as 0.6 m and the total heights as 0.9 m and 0.3 m using equations 1 and 2. The diameter is small enough to facilitate indoor storage and the height is sufficient for easy loading and discharging of maize grains from the silo. The vertical, horizontal pressure and static design and frictional force exerted on the silo wall as shown in Figure 2 are recorded in Table 2 as calculated from equations 3, 6, 7 and 8. According to equations 9 and 10, the

Figure 2. Pressure distribution on the silo wall.
Silo wall thickness was determined as 0.524 mm to withstand all the calculated pressures. However, a standard thickness of 0.8 mm was adopted during construction of the silo. A 45° hopper angle greater than the maize grain angle of repose was adopted to facilitate smooth solid flow during silo discharge. The hopper’s minimum outlet diameter was determined from equation 13 as 300 mm. In order to determine the support frame design, a total compressive stress of 3.0153 N/mm² from the weight above the support was determined from equation 15. The result is far less than the compressive stress of the selected mild steel justifying the use of the material. Three 40 × 40 × 3 mm angle bars were selected, 0.9 m high based on the average waist height of a person for easy unloading of the grain from the silo. The complete results of the dimensions are shown in (Figure 3).

| Depth (mm) | PV (N/mm²) | P_a (N/mm²) | PH (N/mm²) | Cd | DPV (N/mm²) | DP_a (N/mm²) | P_f |
|-----------|------------|-------------|------------|----|-------------|--------------|-----|
| Top       | 900        | 0.004383    | 0.002906   | 0.001429 | 2.004       | 0.006576     | 0.005824 | 0.000672 |
| Middle    | 1000       | 0.004665    | 0.003093   | 0.001521 | 1.780       | 0.006999     | 0.005506 | 0.000715 |
| Bottom    | 1100       | 0.004920    | 0.003262   | 0.001604 | 1.500       | 0.007381     | 0.004893 | 0.000754 |

2.2. Silo performance
From the candle test the following durations of 20, 23 and 17 minutes were recorded as the time taken before the candle goes off. The candle going off indicated that after an average of 20 minutes the oxygen in the silo had been burnt and there was little or no oxygen entering the silo.
indicating an airtight atmosphere. Insect infestation reduction efficiency of the silo was tested for 35 days of grain storage and results recorded in (Table 3)

On average, six (6) live insects per kilogram were found after 35 days of grain storage with a candle enclosed in the silo after loading. Using equation 16 this amounts to 87% efficiency. The high efficiency of the silo in reducing infestation shows that this new design will certainly overcome the problems of infestation identified by Baributsa and Njoroge (2020) in the use of HST within the region. However, when the candle was not enclosed in the silo, twenty-nine (29) live insects per kg were found on off-loading representing an efficiency of 37% after 35 days of grain storage. This implies that for the silo to be used efficiently, a candle has to be enclosed together with the grains in the silo after loading (Anne et al., 2018). The candle reduced oxygen concentration increasing carbon-dioxide concentration with in the silo hence suffocating the insects since there is no gas exchange between silo and the outside surrounding due to airtightness. This is in accordance with the observations of Anne et al. (2018) that the use of lighted candle prevented the infestation of insects in stored grains.

The mean weekly temperatures recorded by the thermocouple showed a slight and insignificant temperature gradient ranging from 25.5°C to 26.5°C silo wall to centre and 24.9°C to 26.1°C from bottom to top whereas the ambient temperature ranged from 20°C to 29°C. The significant variation in temperature between the inside and outside with almost constant temperature inside the silo indicates that saw dust is effective in insulating the silo walls. Compared to the observations by Adeduntan and Falayi (2017), the double wall filled with sawdust significantly reduced temperature fluctuation by 68%. There was no grain caking or lumping observed after the 15 weeks making the designed silo an effective storage facility of maize grains. This can be greatly attributed to the good insulation provided by the double walls and saw dust. Furthermore, the weekly agitation of the silo on its lubricated ring reduces the risk of lumping or caking. Moreover, it is recommended that the moisture content of the maize should be checked before loading to avoid moulds which should be within the acceptable range (12.8%–15.2% wet basis) of moisture content for maize (Codex Alimentarius Commission, 2017).

2.3. Economic performance, environmental and social impact of the new design
Economically, the silo is affordable to both low and middle-income farmers in Uganda with a total cost of 293,000 UGX ($80) (Table 4) and at an average annual depreciation of 28,860 UGX ($7.8) calculated according to equation 17. The Expected annual increase in revenue due to the use of the silo was estimated at 81400 UGX ($22) using equation 19 and with a payback period of

| Sample (1/4 kg) | Number of live insects |
|----------------|------------------------|
|                | Before | After |
| 1              | 13     | 2     |
| 2              | 12     | 1     |
| 3              | 14     | 2     |
| 4              | 10     | 0     |
| 5              | 9      | 0     |
| 6              | 12     | 1     |
| 7              | 8      | 0     |
| 8              | 12     | 3     |
| 9              | 12     | 2     |
| 10             | 13     | 3     |
| **Average**    | **11.5** | **1.4** |

NB: Average number of live weevils before loading per kg of grain = 11.5×4 = 46 insects
Table 4. Total cost of the silo

| Item                          | Cost UGX |
|-------------------------------|----------|
| Materials (galvanised Iron)   | 150,000  |
| Mild steel angle bar + flat bar | 43,000   |
| Transport                     | 20,000   |
| Labour                        | 80,000   |
| **Total cost**                | 293,000  |

4.5 years. The net present value discounted for 10 years was calculated as 913,609 UGX ($253) (Table 5) with a revenue sensitivity margin of 44.5%. An NPV greater than zero, implied that the silo is economically viable. However, the sensitivity margin is high indicating that the silo ceases to be economically viable for low storage volumes of maize grain. In addition, the silo is worth investing on by a farmer since its calculated return on investment (ROI) is 22% as per equation (21). Similarly, a ROI on maize silos of about 13–80% has been reported in East African region which shows that this new design is economically feasible (Baributsa & Njoroge, 2020). Notably, increasing the capacity of the silo to store larger quantities of grains would also help in increasing the ROI.

The silo design will significantly contribute to the wellbeing of the farmers through improved quality and quantity of the stored grains as well as increased bargaining power. Therefore, the maize market prices will be well managed by farmers instead of businessmen who seek higher profits by taking advantage of the farmer’s lack of storage facilities.

In addition to promoting food security for households and improving farmer’s incomes, the design and fabrication of the new design will provide jobs for skills men in fabricating these metal silos (Manandhar et al., 2018). Furthermore, it avoids the use of insecticides that have more adverse impacts on both environment and human health. On the other hand, the new design could have a negative impact on biodiversity as it can kills both useful and harmful insects found in the stored grains.

The results of this study and this new design fulfills the criteria of an ideal grain storage technology for smallholder farmers in Uganda and other East African countries since it can maintain the good quality of grains, prevents lumping and cake formation, reduce grain storage losses, mechanically durable, and it is cost-effective and air-tight (Manandhar et al., 2018). In addition, Omotilewa et al. (2018) already identified that improved post-harvest storage technologies of maize will play an important role in the adoption of new maize varieties. It is expected that this new design will enhance the adoption of new varieties since it overcomes the challenges of smallholder farmers.

Table 5. Economic parameters of the silo discounted for 10 years

| Year | Narrative       | FV      | DF  | PV    |
|------|-----------------|---------|-----|-------|
| 0    | Initial investment | (293,000) | 1   | (293,000) |
| 1–10 | Fixed cost      | (145,450) | 5.0188 | (729,984) |
| 1–10 | Variable cost   | (14,650)  | 5.0188 | (73,525)  |
| 10   | Salvage value   | 10,500   | 0.2474 | 2,598   |
| 1–10 | Revenue         | 400,000  | 5.0188 | 2,007,520 |
|      | **NPV**         |         |      | 913,609 |
2.4. Conclusion and recommendations

The design and construction of an indoor silo was successfully done, the silo was tested and found to be 87% efficient in reducing insect infestation. The study shows that enclosing a candle with the dry grains gives maximum efficiency and agitation of the silo by rotating it over the lubricated ring for at least 30 minutes weekly prevents caking and lumping of the grains. In addition, caking and lumping is further prevented by the double wall filled with sawdust that prevents temperature fluctuations and moisture condensation at the inside wall of the silo. The economic analysis of the silo shows that the silo is affordable and increases farmers’ income through reducing post-harvest losses. The silo is expected to improve food security for small holder farmers especially in Uganda through guaranteed storage of food grains during off-season.

The improved metal silo maintains the quality of stored products, permits effective non-residual fumigation, avoids use of insecticides and reduces losses significantly since the rodents are sealed off and insects are suffocated. This will lead to high quantitative and nutritive value of grains leading to increased bargaining power for market prices by the farmers. It also ensures long term storage thereby leading to food security in the off-season periods and enabling farmers to take advantage of fluctuating grain prices. The silo therefore, has a tremendous positive impact on the incomes and standards of living of the farmers in Uganda. The design can be adapted to many other countries and easily scaled for 50–2000 kg capacity.

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Conflicts of Interest
The authors declare no conflicts of interest.

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