Designing Agricultural Input Subsidy Programs: A System Dynamics Informed Optimization Approach for Zambia

Mrunal Shah
Purdue University

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DESIGNING AGRICULTURAL INPUT SUBSIDY PROGRAMS: A SYSTEM DYNAMICS INFORMED OPTIMIZATION APPROACH FOR ZAMBIA

by

Mrunal Shah

A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science in Industrial Engineering

School of Industrial Engineering

West Lafayette, Indiana

August 2018
THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Patrick Brunese, Co-Chair
   School of Industrial Engineering
Dr. Joaquín Goñi, Co-Chair
   School of Industrial Engineering
Dr. Steven J. Landry
   School of Industrial Engineering

Approved by:
  Dr. Steven J. Landry
   Head of the Graduate Program
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ABSTRACT

Author: Shah, Mrunal. MSIE
Institution: Purdue University
Degree Received: August 2018
Title: Designing Agricultural Input Subsidy Programs: A System Dynamics Informed Optimization Approach for Zambia.
Major Professor: Patrick Brunese, Joaquín Goñi

REQUIRED SECTION

Input subsidies have been introduced in many of the sub-Saharan countries to increase the agricultural productivity. However, these programs are very expensive and they continue to operate with no end in sight. There have been many studies evaluating of the subsidy programs, but there is a need to develop a formal design model for input subsidies. This Thesis provides a proof of concept design model for a time-bounded input subsidy program. A system dynamic framework was developed based on the in depth literature review of the learnings from the past subsidy programs. Using the relationships in the system dynamic framework, an optimization model was formulated to design the input subsidy program. The outputs based on the data from Zambia suggests that the model is functional and capable of achieving the desired goals of the input subsidy programs.
1. INTRODUCTION

1.1 Background

In 2050, the world’s population is predicted to increase from 7.6 billion to 9.8 billion (Roser, 2018). Although the rate of population growth has declined across Asia, Europe, and the Americas, Sub-Saharan Africa has seen an increase in the population growth rate. This increase in population coupled with rising incomes means increased demand for food. It is estimated that feeding the population of 9.8 billion people would require annual cereal production growth by almost one billion tons (Food and Agriculture Organization, 2009). The world faced a similar situation in the 20th century. In the mid 1960’s, Asia was dependent on foreign food aid, and hunger and malnutrition were widespread. For example, India experienced droughts in consecutive years during the mind-1960s. A report from the U.S. President’s Science Advisory Committee (1967) reported that

“The scale, severity and duration of the world food problem are so great that a massive, long-range, innovative effort unprecedented in human history will be required to master it.”

As a result, the Ford and Rockefeller foundation launched the Green Revolution, which helped in doubling the cereal production in 20 years (Hazell, 2002).

Figure 1 shows that while Asia was able to increase cereal yield from 1.02 tons/hectare (ha) in 1961 to 3.13 tons/ha in 2016, Sub-Saharan Africa still has average yield of 1.4 tons/ha. Thus, the focus has now shifted to Sub-Saharan Africa to help in increasing the food production.
Figure 1: Cereal yield from 1961 to 2016. (DataMarket, 2016)

One major reason behind the difference in the yields in Sub-Saharan Africa and Asia has been the use of fertilizer for agriculture. Fertilizers help in increasing yield by improving the soil nutrients. This increased yield typically increasing helps the revenue of farmers. Thus, if used in correct quantity, fertilizers can help in increasing the farmer’s profit. Although fertilizers have been shown to be a profitable technology, the fertilizer use in Sub-Saharan Africa has been low. Figure 2 shows the use of fertilizer across the globe. We can see that there is a substantial gap in fertilizer use in Sub-Saharan Africa and rest of the world.

One of the reasons for low fertilizer adoption is the low fertility of the soil in Sub-Saharan Africa. The soil in Sub-Saharan Africa is highly acidic and thus it would require more fertilizer to observe a yield increase. This raises the fixed costs for the farmer who is already capital constrained. Now, a positive learning and wealth effect in form of positive net returns plays an important role in increasing technology adoption. Due to low soil fertility, the farmers in Sub-Saharan Africa would have to apply more fertilizer to observe the positive learning effect. One way to cross this barrier is through government fertilizer subsidy.
In theory, a fertilizer subsidy should help in mitigating the fixed cost barrier and provide the positive learning effect to the farmer which will in turn lead to increased fertilizer adoption by the farmer. Based on the above theory, Zambia launched Fertilizer Subsidy Program (FSP) in 2003 with the goal of achieving average yield of 3 tons per hectare (MACO, 2008). Although the maize yield in Zambia has increased from 1.42 tons/ha in 2002 to 2.53 tons/ha in 2013 the FSP has faced criticism. This is because the FSP is very expensive, disrupts the private purchase of fertilizer by the farmer, and is prone to leakages. In Zambia, every kg of government provided fertilizer decreases commercial purchase of fertilizer by 0.13 kg and the FSP costs as much as 0.8% of the GDP and 37% of total agriculture sector spending (Thomas S. Jayne, Mason, Burke, & Ariga, 2018). FSP costs increased from 50 billion Zambia kwacha to 500 billion Zambia kwacha in 2013.
Thus, the FSP should only be temporary to spur adoption amongst farmers and at the conclusion farmers should obtain the required fertilizer from commercial channels rather than using the government provided fertilizer. However, in Zambia the government expenditure on fertilizer subsidy program has been increasing since the introduction rather than decreasing.

1.2 Problem Statement

While input subsidy programs can help in increasing input use and agricultural production, they are prone to leakages and private input sector disruption. Thus, there is a need to understand how the input subsidy program can be designed with a limited time horizon while increasing yield, farmer’s net return and private input fertilizer usage. I will be using a combination of system dynamics modelling and optimization to design a proof of concept model for input subsidy design to meet the above stated need using data for Zambia using from years 2006 to 2011 for validation.

1.3 Organization of Thesis

In Chapter 2, we will look at the history of input subsidy programs in sub-Saharan Africa, and learnings from impact evaluations of these programs. Chapter 3 will provide the system dynamics model and optimization model. Chapter 4 will present the results from the model and, Chapter 5 will discuss the implications of the modelling approach in this thesis and offer directions for future research.
2. LITERATURE REVIEW

2.1 Subsidy: Definition and Relevant Economic Theory

Robinson (1967) defines subsidy as:

“An act by governmental unit involving either (1) a payment, (2) a remission of charges, or (3) supplying commodities at less than cost or market price, with the intent of achieving a particular economic objective, most usually the supplying to a general market a product or service which would be supplied in as great quantity only at a higher price in the absence of the payment or remission of charges. “

Figure 3 : Economic theory of subsidy

Figure 3 helps in demonstrating the traditional economic theory behind subsidies. Let $D1$ and $S1$ be the demand and supply curve respectively for a particular good. Then point $A$ is the equilibrium point in for the good where the $Q1$ and $P1$ are equilibrium quantity and price for the good. Now if the government believes that $Q^*$ will help in meeting a particular economic objective then one way the government can increase the quantity of good demanded to $Q^*$ is by providing a subsidy of $\$ (P3-P2)$ per unit of good demanded so the total size of the subsidy program would
be $(P_3-P_2) \times Q^*$. Thus the government intervention in the form of a subsidy can help in promoting a behavior for which the social benefit exceeds private consumer benefit (Gautam, 2015). Rural farming in developing countries provides an interesting scenario where the social benefit from increased use of good can exceed private consumer benefit. Smallholder farmers in rural developing economies are stuck in a low productive (Dorward et al., 2008). Market constraints in the form of significant agriculture input costs lead to low equilibrium quantity of input used which leads to maximized but low profits and in turn leading to low input used in the next farming cycle. While using low-level input might be optimal in short run for a rural farmer, increasing input use can lead to increased productivity which can contribute to achieving national food security. Hence, the case can be made for providing a subsidy on an agricultural input to the farmer.

2.2 Input Subsidy in Sub-Saharan Africa

With the above rationale of boosting agricultural productivity, fertilizer subsidies were introduced in Sub-Saharan Africa in the 1980’s. However, these fertilizer subsidy programs were phased out in the 1990’s as a part of structural reforms by World Bank as the subsidy programs were found to be ineffective in raising productivity and creating a burden on the government spending (Bank, 2007; Kherallah, Delgado, Gabre-Madhin, Minot, & Johnson, 2002; Morris, Kelly, Kopicki, & Byerlee, 2007). One of the reasons for this ineffectiveness was the universal nature of the subsidies in the 1980’s. In 2005 freshly elected president of Malawi relaunched the FSP. The bumper harvest in Malawi that year combined with the growing confidence that the mistakes of the 1980’s universal subsidies can be avoided led to re-launch of large fertilizer subsidy programs in Sub-Saharan Africa (Morris et al., 2007). The major difference between the 1980’s subsidy programs and 2000’s subsidy programs was that the 2000’s subsidy programs were
planned to be targeted to specific groups and not to be universal. The targeting feature of the subsidies was to be coupled with private sector development and a poverty reduction plan. The three features of the 2000’s subsidy program earned it a name “market-smart subsidy” (T S Jayne & Rashid, 2013). Although there was much confidence surrounding the performance of these subsidy programs, there was also concern regarding the high cost. Some of these programs cost as much as 1% of the national gross domestic product. Thus extensive econometric evaluations were performed to measure the impact of these costly agricultural input subsidy programs. The next subsection lists some of the essential learnings from these econometric evaluations.

2.2 Learnings from the evaluations of the Input Subsidy Programs

2.2.1 Need for better targeting

Targeting was included in the market smart subsidies to make the program more cost-efficient than the universal (untargeted) subsidy programs (Banful, 2011; Morris et al., 2007). However, the targeting criteria are dependent on the objective of the program. The goal to increase agricultural productivity and reduce poverty would require targeting to poor smallholder farmers and the goal to improve food security by increasing total farm output would require targeting farms which can use inputs most efficiently (Pan & Christiaensen, 2012). In some sub-Saharan countries, the large landholding wealthy farmers were found to be more efficient than smallholder farmers (Ricker-Gilbert & Jayne, 2012). Thus, these two targeting groups may not overlap. Since most market smart subsidy programs have both poverty reduction and improving food security as their goals, there is a need for an approach that can inform policymakers on appropriate targeting to achieve both the goals (T S Jayne & Rashid, 2013).
2.2.2 Impact on private input supply system

2.2.2.1 Crowding out effect

One way government input subsidy programs can impact the private input supply system is by displacing the private input purchases. Input subsidy is provided with the aim of increasing the total input use by adding subsidized inputs on top of input quantity which the farmer usually purchases in the absence of the subsidy programs. However, it is found that in the presence of the subsidized inputs the farmer purchases less of private inputs and replaces some of the private inputs with the government provided subsidized inputs thus not achieving the expected increase in input use (T S Jayne & Rashid, 2013). This displacement of private input purchase in the presence of government subsidy program is called crowding out effect. This crowding out can lead to unsold private input stocks and low sales volume. This increases the uncertainty for private input retailers. Low revenue coupled with uncertainty disincentivizes private retailers to maintain adequate stock which in turn leads to the low availability of inputs for farmers which causes low total input use (Dorward, 2009).

2.2.2.2 Positive learning and wealth effect

If implemented correctly, subsidies can create positive learning and wealth effect among recipient farmers by generating positive net returns to inputs used (Ricker-Gilbert & Jayne, 2017). This combination of positive learning and wealth effect have been shown to establish sustained adoption of inputs even after the subsidy has been terminated (Carter, Laajaj, & Yang, 2014). Thus, this increased adoption leads to higher demand for private inputs.
2.2.3 Political economy issues

Political processes and motivations play an important role in the success of input subsidy programs. These subsidy programs are very expensive and often involve transactions between many intermediate stakeholders before the subsidy is received by the farmer. Thus this offers many opportunities for sizeable captures by many stakeholders and thus incentivize continuing the subsidy programs even after the program has served the intended purpose (Dorward, 2009). On the one hand a sizeable political commitment is required to ensure stable subsidy programs capable of creating positive learning and wealth effect to spur input adoption, but on the other hand the longer the subsidy runs more the opportunities for fraud and increased dependency on the subsidy. Thus there is a need for a specific exit strategy to be built in the design of the input subsidy program (Dorward, 2009). One possible strategy to exit the subsidy programs is by gradually increasing the working capital of the subsidy recipients (Chirwa & Dorward, 2013).

2.3 Designing input subsidy program

The above learnings suggest that input subsidy programs are not easy to design and are in fact in wicked as they sometimes have contradictory views, a large number of stakeholders involved, pose a huge economic burden, and interconnected with other problems. Thus I would like to investigate if it is possible to design a time-bounded input subsidy program which can achieve the goals of poverty reduction, food security and private sector development efficiently.

Mingers and Brocklesby (1997) suggest that a multi-methods approach can be useful in solving complex problems as different methods can be used to solve different phases of the problem. Additionally, a multi-methods approach can help in generating newer insights and increase the confidence in the results through reciprocal validation (Mingers, 2002). Thus, I use a combination of soft and hard operation research (OR) methods to design the input subsidy program. I intend to
use a system dynamics modeling, a soft OR method, to examine the relationships between the system variables and structure the problem. Based on the system dynamics model, I propose an optimization model, a hard OR methods, to decide the input subsidy allocations amongst the farmers.
3. METHODOLOGY

3.1 System Analysis and Representation

Based on the learnings from the literature review, I developed a modelling framework shown in Figure 4 using the causal loop diagramming method. Causal loop diagrams (CLD) are simple diagrammatic representations of key variables in the system. CLDs are useful in organizing thinking about and understanding the interactions between the key variables. The two fundamental components of a CLD are variables and arrows (links). A variable is a measurable factor that can influence or can be influenced by other variables. A variable can be quantitative such as profit or it can be qualitative such as trust. An arrow indicates a causal relationship between two variables. Once two variables are linked, it is essential to understand how they variables are related. If a change in one variable causes a change in other variable in the same direction, then a ‘+’ sign is put on the arrow else a ‘-’ sign is put on the arrow. The causal loop diagram consists of two loops, namely, reinforcing loop and balancing loop. The reinforcing loop is used to show represent growth or decline in the system and are thus positive feedback systems. Balancing loops are negative feedback systems. They help to represent stability or a way to reach a specific goal.

Figure 4: Causal loop diagram for the proposed input subsidy program.
The framework described in figure 4 is based on a two channel input system. In the first channel the farmer can obtain the input from the private channel at a market price. In the second channel the farmer receives a subsidy from the government at no cost. The crowding effect discussed in the literature review suggests that receiving subsidy from the government reduces the inputs purchased from the private channel, which could be considered as government interference or overreach. Thus, to ensure that the private purchases are not reduced, we introduce a condition where the farmer has to purchase at least the previous year’s level of input from the private channel. This condition is reflected in the reinforcement loop R1. The inputs obtained from government and private channel positively influence total input used. An increase in total inputs would increase the yield. Ideally, as shown in Figure 5, the yield follows the law of diminishing marginal returns. However, we are designing a subsidy program where the input use is in the growth stage i.e. stage 1 and 2 and the soil hasn’t reached the saturation stage i.e. stage 3.

![Figure 5: Yield response curve](image)

An increase in the yield increases the income. The yield also positively influences the other costs; i.e., cost associated with transportation, storage, and labor. The cost related to input purchase are
shown by input cost which increase or decrease with an increase or decrease in private input purchase respectively. The input cost and the other costs constitute the total cost for the farmer. The income and total cost determine the net return where an increase in income increases the net return whereas increase in total cost decreases the net return. The net return has a positive influence on the working capital, and an increase in working capital would increase the private input purchased next year and the cycle continues.

3.2 Decision Problem

3.2.1 Optimization reference model

The sets, parameters, and variables required to understand the mathematical relationships and constraints are as follows:

Sets

\( t \) : index for year \((t=1,2,...,T)\)

\( f \) : index for farmers \((f=1,2,...,F)\)

Parameters

\( L_f \) : Land per farmer \( f \) (ha)

\( AP_f \) : Average product of input for farmer \( f \) (kg/kg)

\( PO_t \) : Price of crop in year \( t \) (currency)

\( PI_t \) : Price of input in year \( t \) (currency)

\( E \) : Other costs per kg of crop produced (currency/kg)

\( B \) : Budget for input subsidy (kg)

\( FSG \) : Food security goal (kg/ha)

\( PO_0 \) : Price of crop in year 0; i.e., year before the subsidy program. (currency)
$PI_0$ : Price of input in year 0; i.e., year before the subsidy program. (currency)

$Y_0$ : Yield in year 0 i.e. year before the subsidy program. (kg/ha)

$Y_u$ : Yield in no input scenario (kg/ha)

**Independent Variables:**

$P_{ft}$ : Private input to be purchased by farmer $f$ in year $t$ (kg)

$G_{ft}$ : Government subsidized input provided to farmer $f$ in year $t$ (kg)

**Dependent Variables:**

$T_{ft}$ : Total input used by farmer $f$ in year $t$ (kg)

\[
T_{ft} = P_{ft} + G_{ft}, \text{ where } f = 1, ..., F, t = 1, ..., T. \quad (3.1)
\]

The total input used by the farmer is the sum of input purchased from the private channel and input received from the government.

$Y_{ft}$ : Yield for a farmer $f$ in year $t$ (kg/ha)

\[
Y_{ft} = Y_u + \left( AP_f \times \frac{T_{ft}}{L_f} \right), \text{ where } f = 1, ..., F, t = 1, ..., T. \quad (3.2)
\]

The $AP_f$ represents the amount of crop produced when an additional kg of input is applied and its estimates are based on an econometric model that controls for weather, household fixed effects, input application rate, soil acidity and type, tillage method and timing, manure application, and weeding. Thus additional crop obtained is the $AP_f \times T_{ft}$. Hence, the additional yield due $T_{ft}$ input used is additional crop divided by land size. Finally, the yield is sum of $Y_u$ and the additional yield obtained. It should be noted that the yield equation, $Y_{ft}$, is linear, which is a reasonable approximation of the first two stages of growth outlined in the previous section.
Other costs for a farmer $f$ in year $t$ (currency)

$$OC_{ft} = E 	imes Y_{ft} \times L_f, \text{ where } f = 1 \ldots F, t = 1 \ldots T. \quad (3.3)$$

$E$ includes costs for animal use, tractor use, labor, herbicides, and transportation. $E$ is calculated per kg of crop produced. The total crop produced is yield times land size. Thus, other costs is the product of $E$ and total crop produced.

Input costs for a farmer $f$ in year $t$ (currency)

$$IC_{ft} = PI_t \times P_{ft}, \text{ where } f = 1 \ldots F, t = 1 \ldots T. \quad (3.4)$$

The input costs for the farmer is the product of input price and amount of private input purchased. Market dominance is often a key feature of food chains in developing countries (FAO, 2015). Thus, we consider the producers of the inputs to be price setters and thus the price of input is considered exogenous to the model.

Total costs for a farmer $f$ in year $t$ (currency)

$$TC_{ft} = IC_{ft} + OC_{ft}, \text{ where } f = 1 \ldots F, t = 1 \ldots T. \quad (3.5)$$

The total costs for the farmer is the sum of input costs and other costs.

Income for a farmer $f$ in year $t$ (currency)

$$I_{ft} = PO_{ft} \times Y_{ft} \times L_f, \text{ where } f = 1 \ldots F, t = 1 \ldots T. \quad (3.6)$$

The income for the farmer is the product of the output price, yield, and land size. The price for the outputs in the Sub-Saharan Africa are often controlled by grain marketing boards (N. Mason, 2011). Thus, the output prices are assumed to be exogenous to the model.
NR_{ft} : Net returns for a farmer f in year t (currency)

\[ NR_{ft} = I_{ft} - TC_{ft}, \text{where } f = 1 \ldots F, t = 1 \ldots T. \] (3.7)

The net returns for the farmer is income generated less the total costs.

WC_{ft} : Working capital for a farmer f in year t (currency)

\[ WC_{ft} = WC_{ft-1} + NR_{ft}, \text{where } f = 1 \ldots F, t = 2 \ldots T. \] (3.8)

The working capital in year 1 is the income of the farmer in the year 0; i.e., the year before the subsidy program is launched. This is based on the assumption that the farmer, who are the targets of the subsidy program, are capital constrained before the subsidy program. Thus, in year 0, they use all their capital as total costs and thus the income from year 0 becomes the working capital in year 1.

Based on the relationships described above and learnings from the literature review, I develop the following optimization model. Consider a newly elected government which realizes the need and potential to increase the agricultural production in the country. The government plans to introduce an input subsidy program which should end by last year of the government’s term in office. This program is based on a single input, single output case. The objective, given by equation (3.9), is to maximize the agriculture production across all the farmers targeted over the length of the program and the decision variables are the amount of private input to be purchased by the farmer and the amount of the subsidy to be given to each farmer.

\[
\text{Maximize } \Pi = \sum_{t=1}^{T} \sum_{f=1}^{F} L_f \cdot Y_{ft} \quad (3.9)
\]
The above objective is subject to several constraints. Thee constraints are described below:

Food security constraint (kg/ha):

\[ Y_{ft} \geq FSG, \text{ where } f = 1 \ldots F. \quad (3.10) \]

A public program should be designed with a goal as that helps in measuring the success or failure of the policy (Lave, 1990). Thus, for the for input subsidy program we have the food security goal to meet \( FSG \) level of yield by the end of the subsidy program.

Working capital constraint (currency):

\[ TC_{ft} \leq WC_{ft}, \text{ where } f = 1 \ldots F, t = 1 \ldots T. \quad (3.11) \]

The working capital constraint ensures that the farmer’s costs cannot exceed his/hers working capital. This constraint can also be reflected in the balancing loops B1 and B2 in the system dynamics model.

Government subsidy constraints (kg):

\[ \sum_{f=1}^{F} G_{f1} \leq B \]
\[ G_{ft+1} \leq G_{ft}, \text{ where } f = 1 \ldots F, t = 1 \ldots T - 1. \quad (3.13) \]
\[ G_{fT} = 0 \quad (3.14) \]

The government subsidy variable in the system dynamics model is not influenced by other variables. However, to ensure that the government subsidy does not exceed the budget and is terminated in the last year of the government’s term in office the government subsidy is bounded.

Crowding out prevention constraint (kg):

\[ P_{ft+1} \geq P_{ft}, \text{ where } f = 1 \ldots F, t = 1 \ldots T. \quad (3.15) \]
The crowding out constraint ensures that there is no reduction in the farmer’s private input purchases due to government subsidy. This is reflected in the reinforcement loop R1 of the system dynamic model.

Successful exit constraint (currency):

\[ WC_{ft+1} \geq WC_{ft}, \text{where } f = 1 \ldots F, t = 1 \ldots T. \] (3.16)

A successful exit strategy for the input subsidy programs is to increase the working capital of the subsidy recipients (Chirwa & Dorward, 2013). This also helps in establishing the positive learning and wealth effect as constraint 3.16 when combined with equation 3.8 becomes \( NR_{ft} \geq 0 \). The positive learning and wealth effect, described in Section 2.2.2.2, is important for sustained adoption of inputs by the farmer. The system dynamics models shows that having positive net returns would increase the working capital. This would allow for more investment in inputs as shown by constraint 3.11.

Non-negativity constraints (kg):

\[ C_{ft}, G_{ft} \geq 0, \text{where } f = 1 \ldots F, t = 1 \ldots T. \] (3.17)

### 3.3 Formal model and Solution Method

The model to be optimized is a linear program described by the objective function (3.9) subject to (3.10) – (3.17). The model is formulated using the General Algebraic Modeling System (GAMS), and solved using IBM ILOG CPLEX solver via the NEOS Server for Optimization. CPLEX is one of the most advanced solvers for the linear optimization problems. NEOS server for Optimization provides free access to different solvers including CPLEX (Czyzyk, Mesnier, & More, 1998; Dolan, 2001; Gropp & More, 1997). NEOS was chosen for its ease of access.
3.3.1 Parameter specification

To test the usage of the proposed subsidy design model, a suitable test case is required. Zambia’s Fertilizer subsidy program can serve this purpose as its program was setup for single input; i.e., fertilizer, and single output; i.e., maize. Additionally, extensive data is available for Zambia’s program which is being utilized here.

Zambian government’s term in office lasts five years hence $T=5$. Evaluation of the fertilizer subsidy program in Zambia suggests that the subsidy should be targeted to farmers with land between 0.5-2 ha (Mason et al, 2013). Thus, in the model I consider only the farmers who own land between 0.5-2 ha. Table 3.3.1.1 distribution of smallholder households in Zambia with land size between 0.5-2 ha.

Table 1: Distribution of small holder farmers.

<table>
<thead>
<tr>
<th>Land Size (A)</th>
<th>Number of farmers (B)</th>
<th>Average product of fertilizer (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 0.99 ha</td>
<td>334,200</td>
<td>3.73</td>
</tr>
<tr>
<td>1 - 1.99 ha</td>
<td>452,364</td>
<td>3.48</td>
</tr>
</tbody>
</table>

Source: Column A and B (N. M. Mason, Jayne, & Mofya-Mukuka, 2013) Column C (W. Burke, Jayne, & Sitko, 2012)

As it can be seen, the land values are divided in ranges and not available for every farmer. I assume the farmers to be uniformly distributed in these ranges with minimum $L_f = 0.5$ and maximum $L_f = 1.9$. All the farmers with same land size are assumed to be identical and number of farmers belonging to a particular type is given by $D_f$. The distribution of targeted farmers based on
this assumption is shown in table 2. In reality, the each farmer can have a different characteristics and the farm size may not be uniformly distributed. However, if the government has data about each of the 786,564 farmer then the model proposed here is scalable to solve such a large problem. In fact, the CPLEX solver can solve models with as many as 9E+18 non zero coefficients and is limited only by memory available on the computer (“Representing very large models: 64-bit API,” n.d.).

Table 2 : Values for $L_f$, $AP_f$ and $D_f$

<table>
<thead>
<tr>
<th>$F$</th>
<th>$D_f$</th>
<th>$L_f$</th>
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Table 3 provides the values for the remaining parameters in the model. These values are based on data from Zambia from 2006 to 2011.

Table 3: Parameter specification

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4. RESULTS AND DISCUSSION

The results presented in this chapter are based on the proof of concept design of input subsidy program described in Chapter 3. The parameters described in Section 3.3.1 are based on certain assumptions on the distribution of land size of the farmers. Since land size, $L_f$, is part of the objective function the results presented in this chapter cannot be compared directly with the results of historical Zambian Fertilizer Subsidy program. Thus, the analysis is focused on the checking if the expected behavior is achieved from the results.

4.1 Total fertilizer used

One of the key reasons to introduce a fertilizer subsidy program is to increase the total fertilizer used. Low fertilizer use has been pointed out as a key reason behind low productivity (Kihara et al., 2016). The model is expected to increase the total fertilizer used over length of the program and this behavior can be observed from Figure 5. The marked difference in total fertilizer applied between farmer group 15 and farmer group 1 is due to difference in land size. The key is that the increase is observed in all farmer groups, and the average fertilizer applied increases from 54.86 kg in year 1 to 689.97 kg in year 5.
Although an increase in fertilizer use is expected, this increase should be accompanied by an increase in private fertilizer purchased so that the government can effectively leave the market at the end of the program. Figure 6 shows that private purchases of fertilizer increases every year for each farmer group and the average private fertilizer purchased increases from 31.66 kg in year 1 to 689.97 kg in year 5. Firstly, these increases would help in achieving the goal of private sector development. Secondly, the increment also reflects that there is no crowding out of private fertilizer purchases. Also, as expected, the total fertilizer used in year 5 is equal to the private fertilizer used in year 5.
Figure 7: Private fertilizer used per year

The model outputs the quantity of private fertilizer to be purchased by farmer and quantity of subsidized input to be given to the farmer every year. One might argue that the farmer might not end up actually buying the suggested amount of fertilizer from the private channel. A plausible reason could be that the farmer may not know the correct quantity to purchases. The government can make a condition that it will provide the subsidy only if the farmer buys the suggested quantity from the private channel. However, effectively monitoring this condition might be challenging for the government. To solve this issue the government can combine the two channel market into a single channel market. Consider the case of farmer group 1 who are expected to purchase 14 kg of fertilizer from private channel at 486.809 Zambian Kwacha (ZMK)/kg and receive 9.8 kg of subsidized fertilizer from the government. The fertilizer cost for the farmer would be 14 * 486.809
+ 9.8 * 0 = 6,811.4314 ZMK. Instead of the two channels, the government can provide a single fertilizer subsidy coupon of 23.8 kg for 6811.4314 ZMK or 286.0744 ZMK/kg. This may help in ensuring that the farmer buys the private fertilizer and ends up using the optimal quantity of total fertilizer. The coupon would also assist in coordinating the supply chain by making sure the right amount of fertilizer are available at the demand points.

In the proposed subsidy model, the government provides the subsidized quantity for zero charge throughout the subsidy program. Sub-Saharan countries in the past have proposed a subsidy program where the government provides a price subsidy; i.e., the government would pay some share \((z\%)\) of the price and farmer has to pay the remaining \((1-z)\) %. The government would then reduce the value of \(z\) and finally end the program with \(z = 0\). In Zambia, the original design suggested 75-50-25-0 as the values of \(z\) over the proposed length of the program. Firstly, this exit strategy was never actually implemented and secondly, this values of \(z\) are not backed with any formal method. We can use the voucher presented earlier to find out the actual value of \(z\) for each year. Consider the case of farmer group 1. This group gets the coupon of 23.8 kg for 6811.4314 ZMK. Based on the actual market price of fertilizer 23.8 kg would cost 11,586.0542 ZMK. Thus, the government’s share of the total fertilizer cost becomes \((11,586.0542 - 6,811.4314) \times 100/11,586.0542 = 41.2\%\). Figure 7 shows the government’s share of total fertilizer cost over length of the proposed program.
We can see the government’s share for each farmer group decreases over year and the average share decreases from ~ 42% in first year to 0% in the last year. As mentioned earlier, these numbers are not sufficient to compare directly with the original numbers of the program as the results are based on the assumption of uniform distribution of small holder farmers. These results show that model follows the expected behavior. The government’s share of total fertilizer used follows the behavior of the actual subsidy design and an important point is the decreasing share is based on a formal analysis.

4.2 Yield

Section 4.1 illustrated that the total fertilizer use increases over the length of the program and based on the system dynamic framework the yield should also increase over the years. Figure 8
shows that the yield for each farmer group increases over the length of the program and the average yield increases from approximately 1,424 kg/ha in year 1 to approximately 3,430 kg/ha in year 5. The food security goal for Zambia fertilizer subsidy program was to achieve yield of 3,000 kg/ha by the end of the program and Figure 8 shows that the goal is, indeed, achievable in year 5. However, this is subject to the assumptions made earlier.

Figure 9: Yield per year

4.3 Income and net returns

Another goal of the Zambia’s fertilizer subsidy program was to increase the incomes of the farmers. Figure 9 shows that the income for each farmer group increases over the length of the program and the average yield increases from 1,223,074.242 ZMK in year 1 to 5,028,349.447 ZMK in year 5. Ideally, the net returns of the farmer should also increase every year. Figure 4.3
show that the average net returns increase from 123,761.2584 ZMK in year 1 to 2,073,885.28 ZMK in year 5. However, from Figure 10, we can see that there is a small decrease in the net returns in the year 2. This is because the net return is negatively affected by increase in yield due to higher other cost \((OC)\) and also due to fertilizer input costs \((IC)\). Hence, there is a need to consider fertilizer prices endogenously while designing the subsidy program.

Figure 10 : Income per year
An optimization framework presented in this thesis could be used as a decision support tool to inform the policy makers. In a system like an input subsidy program, where there are many variables and stakeholders, it is possible the actions of the decision makers can lead to unintended consequences. However, if the actions are based on a framework then the decision-maker can trace the issue in the system, and re-run the analysis.

In case of the input subsidy program, the Zambian government during the planning period (i.e., year 0) can use the optimization framework to decide the values for private inputs and government inputs to be allocated to the targeted farmers in order to reach the goal by the end of the fifth year in office. However, after the first year of the program (i.e., at the end of year 1), the government may have collected data on the agricultural outcomes (e.g., yield, farmer profits, and income), which could be used to compare with the predicted system performance from the proposed decision model. If performance were significantly different, the decision makers could
utilize the causal loop model to assess where the system differed from expectation, and if needed, the model could be reassessed with new input data to replan the remaining periods. For example, the government discovers that the yield did not increase as much as expected then it can check if the estimate for average product was incorrect. Alternatively, other interventions could be planned for variable within the system that are out of the scope of the model. For example, if the take up rate of the voucher is low then the subsidy may be increased in the following year. This process could be repeated for years 2, 3, and 4 to increase the likelihood of the success of the subsidy program.

At the end of the program, there are two likely cases. The first is that the goal was not ultimately achieved for the target group. In this case, the government can revise and rerun the program for the same target group or the government can decide to allocate the ISP budget to other programs e.g. infrastructure development. If the goal was achieved for the target group then a) the government can rerun the program for same target group but update the goal so as to move from stage 1 to stage 2 in Figure 5, or b) the government can change the formation of the target group so as to include other farmers who are in the stage 1 of the yield response curve, or c) if the government finds that the farmers have achieved stage 3 i.e. saturation stage of the yield response curve then it can decide to allocate the ISP budget to other programs.
5. CONCLUSION AND FUTURE RESEARCH

5.1 Conclusions

Input subsidies have been introduced in many of the sub-Saharan countries to increase the agricultural productivity. However, these programs are very expensive and they continue to operate with no end in sight. There have been many studies evaluating the outputs of these subsidy programs, but there is, to the authors’ knowledge, no known attempt to develop a formal design model for input subsidies.

This thesis provides a proof of concept design model for a time-bounded input subsidy program. A system dynamic framework was developed based on the in depth literature review of the learnings from the past subsidy programs. Using the relationships in the system dynamic framework, I formulated a linear program to design an agricultural input subsidy program. The model was run using data from Zambia from the years 2006 to 2011. Based on the output analysis presented in Chapter 4, the model is functional and capable of achieving the desired goals of the input subsidy programs. In addition, prospective strategies for usage of the system dynamic and optimization models in decision support over the length of the program are also discussed.

5.2 Future research

The linear program developed to design the input subsidy is based on the single input, single output case. This can be generalized to multiple input, multiple outputs. In addition, the prices of inputs and outputs were considered to be exogenous to the model as they are often controlled by external boards in the developing countries. However, modelling the prices endogenously would allow more control and certainty on the net returns of the farmers. Such a change would likely lead to the model having nonlinear structure, which would also require further
consideration for its usage in decision support. Further, soil dynamics were not taken into consideration. In the future, one can model the changes in the soil organic matter over time due to fertilizer use. Also, it would be beneficial to take into account the environmental effects of applying large amount of fertilizer over time. Finally, additional work in validation using field experiments is recommended.
REFERENCES


DataMarket (2016). Cereal yield (kg per hectare) [Data file]. Retrieved from https://datamarket.com/data/set/13ed/cereal-yield-kg-per-hectare#!ds=13ed!ffj=5o.68.2w.y.6g&display=line


U.S. President’s Science Advisory Committee (1967). The World Food Problem: A report of the President’s Science Advisory Committee. Washington D.C.