



# **Maize Losses During Storage: A System Dynamics approach to the Food Reserve Agency Case in Zambia**

By

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## **Abstract**

Agricultural development in sub-Saharan Africa is seen as the key pathway towards economic development. Among sub-Saharan countries, Zambia stands out for its agricultural production potential, and has in the past decade, managed to reach the status of a maize surplus producer. Such increases in maize production have been supported by two government subsidy programs: the Farmer Input Subsidy Program (FISP) and the Food Reserve Agency (FRA). The drastic increases in production experienced in the 2010-2013 period, brought severe unintended consequences for the FRA in the form of budget overshoots and excessive maize storage losses. As considerable as these maize losses during storage are (estimated at 32% in 2013), little is certain regarding their causes and possible solutions. This research project provides a tool that helps explain the high losses of maize in the FRA storage system and that allows for the identification and assessment of alternative strategies that could prevent/mitigate the occurrence of such a problem in the future. This was achieved through a system dynamics and case study approach, relying on a system dynamics simulation model that integrated the causal mechanisms leading to maize losses during storage and the specific circumstances of the FRA case. Such an approach permitted the identification, description and simulation of the phenomenon in a consistent, coherent and transparent manner. It was found that maize losses during storage can be described as the result of the interaction of two variables: inventory age (time of storage) and storage method. It was also found that these two variables are the result and consequence of inventory management and investment decisions within the FRA, and as such within its control. Through the analysis of the main feedback loops of the model and the analysis of two possible FRA growth scenarios, leverage points that could reduce weight losses were identified and tested. In a non-saturated maize market scenario, reducing the national reserve size and switching the capacity investment decision from sheds to silos are viable options. In a saturated maize market scenario, switching the capacity investment decision from sheds to silos is viable to some extent, but in this case, the only fundamental solution lies in fostering export mechanisms.

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## **List of Acronyms**

ATP: Available to Promise

CLD: Causal Loop Diagram

CSO: Central Statistical Office (Zambia)

FAO: Food and Agriculture Organization

FISP: Farmer Input Subsidy Program

FRA: Food Reserve Agency

IAPRI: Indaba Agricultural Policy Research Institute

KMT: Kilometric Ton

PICS: Purdue Improved Crop Storage

RMSE: Root Mean Squared Error

SFD: Stock and Flow Diagram

SSA: Sub-Saharan Africa

USAID: United States agency for international development

WFP: World Food Programme

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## **Chapter 1: Introduction**

### **1.1 Research Topic Introduction and Motivation**

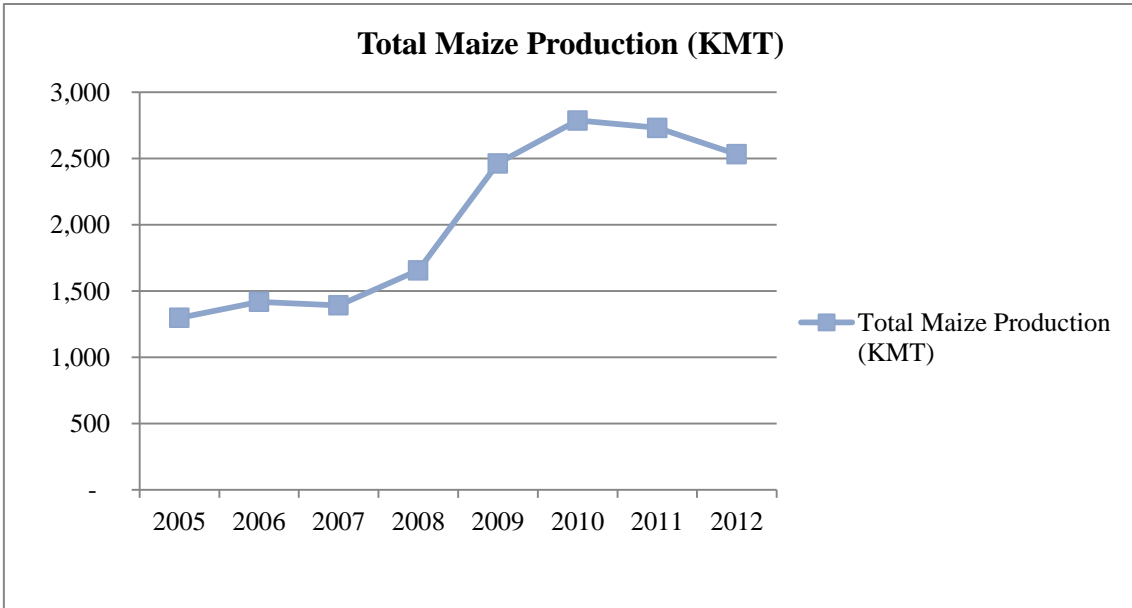
Poverty incidence in rural Zambia in 1991 was estimated at 88%. Nine years later, in 2010, poverty incidence in rural Zambia remained at a staggering high level of 78% (Tembo & Sitko, 2013).

It is in the light of these alarming and persistently high levels of rural poverty, that fostering the agricultural sector of the Zambian economy remains as a priority within the national economic development agenda. The selection of this particular strategy is justified when considering the fact that approximately 73% of the Zambian workforce is employed in the agricultural sector (Chiwele et al, 2010); most of which is comprised of smallholder farmers sourcing approximately 88% of the total national production but only contributing with 13% of the national GDP (Tembo & Sitko, 2013). This particular mix of high workforce occupation and low GDP contribution presents itself as a high priority development area.

The current national development strategy focuses its efforts on increasing crop production (predominantly maize production) at a national level through two programs: the Farmer Input Support Program (FISP) and the Food Reserve Agency (FRA). The FISP program devotes its efforts to raising agricultural productivity by providing subsidized inputs (mainly fertilizers) to smallholder farmers in order to increase crop yields. The FRA on the other hand was established in 1996 to serve as a national food reserve, with the objective of providing a last resort market to marginalized producers; in 2005 its activities were expanded for the FRA to participate in large scale grain marketing (Mason & Myers, 2011), and serve as a price stabilizing entity, both for producers and consumers.

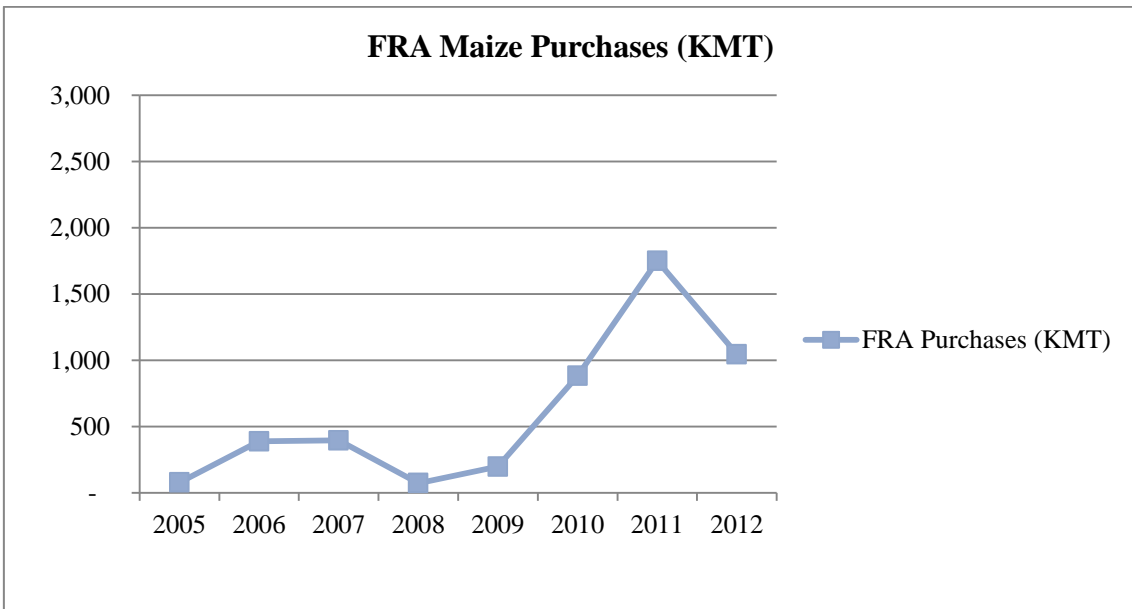
The expenditure for these two programs has continuously increased during the last ten years. At the same time, their success and effectiveness remain ambiguous. During the last ten years, maize production at the national level increased considerably (Figure 1). On an absolute level, that is, without taking population and thus demand growth into account, FISP and FRA thus achieved their core output objective, namely that of fostering the agricultural sector through increased maize production levels.





**Figure 1: Total Maize Production (Sitko & Tembo, 2013)**

However, the increase in production by 115% between 2005 and 2010 entailed severe overshoots in these programs' budgets, (Sitko & Tembo, 2013) in particular in the FRA, since it bought most of the bumper harvest's surplus production (Kuteya & Sitko, 2013) (Figure 2).



**Figure 2: FRA Maize Purchases (Kuteya & Sitko, 2013)**

The sudden and drastic increase in purchases (2,227% from 2005 vs 2011) by FRA (figure 2) caused several unintended consequences such as high levels of storage losses (estimated at 32% in 2013), significant financial losses due to highly subsidized pricing

structures, and unusually high operating costs (Sitko & Kuteya, 2013), all which summed up to a severe budget overshoot in 2011. Despite of the severe and constant budget overshoots, as well as the expression of concern from the Zambian agricultural ministry regarding the FRA's sustainability (Sichinga, 2013); the Zambian government has not taken any major steps in terms of reducing the FRA's volume of operations. Currently investment plans within the FRA point towards further expansions of their activities within the Zambian maize market (FRA, 2015).

Given this likely scenario, in which the FRA continues to expand its activities, the reported levels of maize losses during storage represent a clear opportunity area for improvements through which the FRA could set itself into the direction of less financially burdensome operations. In order to contextualize the magnitude of the FRA losses during storage (32% in 2013) it is enough to compare them to the estimated losses of the Zambian private storage sector of about 5% (Kuteya & Sitko, 2014); the room for improvement and risk reduction is appalling.

It is also relevant to mention that high food losses during storage not only have a direct economic impact through inefficient budget expenditure, but also strongly impact national food security by reducing overall food availability and food access in the form of price increases (Affognon, 2015). The Zambian food security reality also demands for action in reducing storage losses of maize in the FRA, when pondering that total population undernourishment stands at 48.3% (FAO, 2014). Reducing food losses during storage, in what is the biggest maize marketing organization of the country would undoubtedly benefit the food security situation of the country.

It is within this context, and the national pursue of establishing Zambia as the region's "breadbasket", that uncovering, describing and analyzing the mechanisms that cause maize losses during storage at a national level becomes essential, first to understand the causes of the reported high loss levels and second pin point leverage points and alternative strategies to reduce them.

## **1.2 Research Objective and Research Questions**

The objective of this research is therefore defined as: provide a tool that helps explain the high losses of maize in the FRA storage system and that allows for the identification

and assessment of alternative strategies that could prevent/mitigate the occurrence of such a problem in the future.

The main questions this research aims to answer in order to fulfil the research objective are:

1. What causal mechanisms/theories are described in the existing maize loss during storage literature?
2. How can these mechanisms be integrated into a coherent and consistent framework?
3. How can these mechanisms be quantified for the specific case of the FRA in Zambia?
4. What alternative strategies or management practices can contribute to mitigating future maize losses during storage given the specific case of the FRA?

### **1.3 Research Methodology and Strategy**

The employed method in this study is quantitative system dynamics modelling within a case study and theory building strategy (Repenning, 2002). The combination of this method and research strategy is grounded in the specific circumstances of the research context: scarce and disperse data and gaps in the existing theoretical frameworks to assess food loss from an aggregate and systemic perspective.

The combination of this method and research strategy is appropriate given the nature of the system dynamics method itself, which relies on the iterative formulation and testing of dynamic hypotheses, which constitute theories about the occurrence and management of a specific dynamic problem. This notion of continuous theory building and testing in the system dynamics method is supported by Sterman's take on good modelling practice: "Instead of viewing validation as a testing step after a model is completed, they (good modelers) recognize that theory building and theory testing are intimately intertwined in an iterative loop" (Sterman, 2001:850). This statement serves as a basis to justify the fact that system dynamics modelling normally utilizes a combination of case study and theory building strategies. The testing of the hypothesized theories (in the form of a dynamic hypothesis or model structure) is further validated through the specifics of a case study (in the form of quantifying the model to analyze the behavior a dynamic hypothesis or model structure gives rise to).

A hybrid case study and theory building strategy using archival research, quantitative data induction and expert validation provides triangulation to the research process. In order to stress the importance of triangulating in case study approaches from a methodological perspective, we can refer to Saunders et al: “Triangulation refers to the use of different data collection techniques within one study in order to ensure that the data are telling you what you think they are telling you.” (Saunders, Lewis & Thornhill, 2009: 146).

This versatility and robustness in formulating and testing assumptions lies in the core of the system dynamics modelling methodology since a system dynamics model provides a framework with which to elaborate and test hypotheses in a coherent and transparent manner; these hypotheses are continuously tested and validated until confidence in them is reasonably established. This is supported by Sterman’s take on the modelling process: “Modeling is a continual process of iteration among problem articulation, hypothesis generation, data collection, model formulation, testing, and analysis” (Sterman 2000:104).

The combination of quantitative system dynamics modeling within a case study and theory building strategy corresponds very closely to the approach followed by Reppenning (2002), first by extensively reviewing relevant literature on the topic, secondly by integrating this existing research and data into a coherent system dynamics model and finally analyzing the behavior of the system dynamics model in order to provide a “new level of specificity” on both the maize weight loss during storage subject as well as on the specific FRA maize weight loss during storage case.

In terms of data sources and data collection, the main quantitative data sources come from archived research (IAPRI, USAID and FAO) as well as the FRA website and Zambian newspaper articles. The working papers available at the Indaba Agricultural Policy Research Institute (IAPRI) provided most of the required quantitative data for the calibration of the model, this data include: FRA purchase volumes, national maize production figures, smallholder sale figures, etc. Newspaper articles provided estimates on the missing pieces of information, those which are not normally tracked by any research institution, or simply not publicly available, such information includes: FRA storage capacity figures, estimates on maize losses during storage, FRA storage capacity investments, etc. Qualitative data used for the building of the system dynamics model

was mainly drawn from existing literature, which will be addressed and discussed in section 1.4 of this document.

Once the system dynamics model was finalized, a disconfirmatory interview (Andersen et al. 2012) was held with a Zambian agricultural expert, during this interview the model and its simulation results were presented to the expert. This process provided strengthened confidence in the model's structural validity as well as further detailing the calibration of previously relatively uncertain parameter values.

## **Chapter 2: Literature Review**

Within the scope of this research two main literature subtopics were reviewed: cereals postharvest loss literature and descriptive literature on Zambian agriculture and the FRA. It is important to note that although this literature review is presented in a specific order; the actual review of the subtopics was, at some stages, carried out simultaneously. This permitted for the review of the cereal postharvest loss literature to be focused the work that proved most relevant to the Zambian reality. Subsection 2.1 is aimed at broadly answering the first research question: What causal mechanisms/theories are described in the existing maize weight loss during storage literature? Subsection 2.2 describes the reviewed literature characterizing the FRA storage system.

### **3.1 Cereal postharvest loss literature**

The initial literature review was focused on that describing how weight losses in cereals can be determined from a technical perspective. Within this context we can set as a basis the work of Harris & Lindblad (1976). This technical manual describes the principles of the main post-harvest losses assessment methods from a food system perspective, or in different words, it describes postharvest losses by contextualizing them to the specific stage of the food value chain stage in which they occur. This work also contains a description of the most used loss assessment methods, their general principles and specific considerations. The review of this literature provided a general understanding of how postharvest losses happen, what are the basic considerations to achieve standardized measurements and the practical implications of such measurement methods. The understanding of these principles is basic in order to understand the further reviewed experimental research on the subject, more specifically, when facing

the need of interpreting experimental research, its results and the further translation of them into a tool that can coherently and consistently represent them.

Another key piece of the reviewed cereal postharvest loss assessment literature was the work carried out by Rembold, Hodges & Bernard (2011) in *The African Postharvest Losses Information System*. This work focuses on the description of a postharvest assessment information tool aimed at estimating cereal postharvest losses in the Sub-Saharan African region. This information tool bases its estimates on best available data or literature; with which country and region specific profiles are generated. The original design of the tool was aimed at having these profiles periodically updated to reflect the changes in the specific circumstances that might affect the levels of loss in the different stages of the food supply chain. A general description on how the profiles are generated and what are the main factors driving cereal losses proved useful in the forming of a causal theory and its translation to a system dynamics model. The main limitation of this specific tool within the Zambian context lies on the fact that the best available estimates within the tool were those of the work of Lars-Ove Jonsson and Kashweka K (1987). These estimates only relate to weight losses during the harvest and drying stages of the postharvest chain. Estimates during the storage phase are non-specific to the Zambian context. This fact further stressed the need of covering this knowledge gap in literature with the specifics of the Zambian circumstances, which have very much changed since 1987. As a complementary document to this work, Hodges (2013) compiled

After reviewing how postharvest losses are assessed both from a technical and practical perspective, attention was placed on literature that could provide specific measurements on storage losses of maize in Zambia. In this matter the work that served as a reference point is the meta-analysis carried out by Affognon et al (2015) in *Unpacking Postharvest Losses in Sub-Saharan Africa: A Meta-Analysis*. This work summarizes through a meta-analysis the research concerning postharvest losses in six different sub-Saharan countries: Benin, Ghana, Kenya, Malawi, Mozambique and Tanzania. Despite the fact that research in Zambia was not included in this meta-analysis, the general characteristics of the sub-Saharan context still served as a good reference point for the Zambian case since their climatological, biological and technical similarity due to their geographical vicinity is significant. As previously stated, this paper served as a reference point in order to set the limits of possible losses during storage for maize. This

meta-analysis also stressed the importance of both maize and storage losses within the sub-Saharan postharvest losses agricultural systems since 80.4% of all found loss estimates were related to storage and 43.2% of the analyzed studies were performed on maize.

The previously mentioned literature served as the basis of understanding of how cereal losses occur, how are they measured and understand relevant attempts of assessing them. It also served as a context setter in order to understand the possible levels of losses during storage in the sub-Saharan region.

Once these concepts were understood, the literature review moved on to finding relevant quantified estimates of maize losses during storage within Zambia. No Zambia specific literature was found. What was found was the work of De Groote et al (2013) in *Effectiveness of hermetic systems in controlling maize storage pests in Kenya*, in which six different storage methods for maize are experimentally evaluated. The evaluation of these storage methods is done by measuring the incurred weight losses of different maize samples over a six month period. This work is extremely useful since the main tested storage methods correspond to those most widely used in Zambia: polypropylene bags with or without pesticide treatment and hermetic silos. The drawback of this specific experiment is that the maize samples were artificial infested with large gran borers (LGB); the occurrence of this specific pest in Zambia is highly uncertain. On the bright side, the artificial infestation levels, in the evaluated storage methods most widely used in Zambia was initially controlled either by oxygen depletion (silos) or by the effect of the pesticide (polypropylene bags), which reduced its influence of on the weight losses. The specific use and integration of the results of this experiment in the loss estimation model are thoroughly discussed in appendix B. Other maize weight loss specific literature that was reviewed and contributed in the form of grounding points for the model's loss estimates include: Tadele, Mugo & Likhayo (2011), Hodges (2013) and Harris & Lindblad (1976).

Detailed knowledge and a complementary summary of the sub-Sahara African reality on maize weight losses during storage can be found in Tadele (2012).

### **3.2 Zambian Agricultural Sector and the FRA Descriptive Literature**

The literature review and data collection on this subtopic was thorough and extensive and it can be organized for clarity purposes in two main streams according to its sources: IAPRI and USAID.

The IAPRI literature is mainly composed by working papers addressing different policy opportunity areas within the Zambian agricultural sector. Most of these papers contain research on the effects of current government programs (namely FISP and FRA) on aggregate agricultural productivity levels, crop yields, market prices development, etc. Most of the quantitative data available in these working papers is based on data collected through annual crop forecast surveys and postharvest surveys. The results of these surveys characterize the annual specific situation of the Zambian agricultural sector and provide estimates on production levels, FRA purchases, commercial sector purchases, household demographics, etc. The data of these surveys' served as the main source of quantitative information for the calibration of the model's parameters. Recently (March 2015) the subject of maize loss in the FRA storage system caught the attention of the IAPRI and a paper relating high levels of food loss, with its probable causes and possible solutions, was published (Chapoto, A. Chisanga, B., Kuteya, A., Kabwe, S, 2015). In this paper the importance of high stock levels in the FRA after bumper harvest purchases is outlined in terms of its consequences towards maize loss and budget stress. The authors depict several short term options to alleviate the problem, such as price discounts or food donations to the World Food Program (WFP) and proposed the reform of the FRA marketing activities altogether as a longer term viable option. Despite being arguably feasible options, the proposed long term solution does not address the persistent behavior of the FRA from a systemic perspective, it addresses it from a political reform perspective by suggesting to reduce the purchases of the organization (by limiting its overall marketing attributions) and as a consequence inclining towards the liberalization the maize market.. In terms of scenario evaluation, the current thesis opts at analyzing solutions form an alternative management practices and strategies perspective, setting out of scope politically driven solutions.

The main piece of literature from USAID on the Zambian agricultural sector (and more specifically on maize) can be found in *Staple Foods Value Chain Analysis – Country Report - Zambia* (USAID 2009). In this work a general overview of the maize value



chain is presented along with its main limitations and opportunity areas. Despite of being published in 2009, a time by which bumper harvests hadn't occurred yet, some of the persistent problems in the value chain were already noticed by the research team and most importantly as they reported: *"Disturbing features of the agricultural sector are... harvest losses reported in the food balance sheet due to poor storage, purchases of poor quality grain and possibly to inaccurate record keeping or mismanagement of stocks. In 2007/08 ... over 94,000 tonnes of maize were estimated to be lost after harvest in 2008"*. This observation is not only useful in terms of reinforcing the notion that data found on newspapers reporting high levels of maize loss within the FRA storage system was indeed a plausible claim, but also provided through a partially quantified value chain analysis, which was helpful in order to establish causal relationships in the system dynamics model.

Finally it must be stated that FRA and Zambian food loss during storage specific literature is extremely scarce, most of the reviewed literature addressed different opportunity areas of the Zambian Agricultural sector, but with only one work focusing on the FRA's behavior and its relationship storage losses. This situation strikes as surprising when considering that the FRA bought close to 80% (weighted average) of all marketed maize in Zambia within the first three marketing years of consecutive bumper harvests (2009-2011) and estimates of its losses go as high as 32%. The present literature review included approximately 45 documents from which pieces relating to the FRA and its probable losses during storage were distilled into the database presented in appendix E.

### **Chapter 3: Model Description**

After the literature review was concluded, and the relationships between the specific situation of the FRA and possible factors driving maize losses during storage in such conditions were identified and understood, a system dynamics model that could represent such relationships in a coherent and consistent manner was built. The aim of building this system dynamics simulation model is mainly to provide an answer to the second research question of this thesis. As such this and chapter 4 provide a partial answer to the question.

### **3.1 Model Assumptions**

#### **1. - Only weight losses caused by biodeterioration are considered.**

Within the food loss academic field two types of losses are normally acknowledged: quality and weight losses.

Weight losses refer to the “reduction of the physical substance of the product”. (FAO, 1994) while quality losses refer to “the exterior aspect, shape and size, as much as the smell and taste”... “These losses are quantifiable only on condition that criteria or standards of quality have been previously established” (FAO, 1994).

Since the relationship between quality losses and its possible opportunity costs is highly uncertain (Hodges, 2014) the current model will focus on explaining weight losses since its effects (financial losses and food insecurity) are certain.

It is also important to note that during the postharvest chain, losses can also be classified according to its causes as referred by Hodges (2013):

- Scattered or spilt grain
- Biodeterioration as a consequence of insect, mold or animal activity.

Scattered or spilt gran during storage is not considered in this thesis.

#### **2. – Export volumes are externally driven, the decision to export is not.**

The calculation for available inventories for exports is based on the same method used by the Zambian Central Statistical Office (CSO, 2013), which relies on parameters such as available inventories, local demand, desired reserves, etc. During the 2009-2012 period, available maize volumes that could be exported (according CSO’s method), exceeded actual exports. This apparent data incongruence can be explained by the fact that FRA maize is not regionally competitive due to highly subsidized purchasing prices which cause high export parity prices (Auckland, Chisanga & Sitko, 2014), hence limiting export volumes to its full potential. Another limiting factor towards unfulfilled potential exports lies on common government decrees banning exports during the analyzed period. Since the main objective of this research effort is not to estimate the effect of either of such factors on exports, these limits to exports are assumed as external parameters (independent variables).

### **3. –Purchasing volumes are externally driven, as is its decision.**

It is not the aim of this research to explain the dynamics driving the purchasing decisions of the FRA. The aim of this research is to uncover and analyze how these specific purchase volumes are related to maize weight loss in storage. Uncovering the mechanisms behind these decision rules, which are mainly driven by market dynamics, is an effort that would require the investment of additional time in the form of research efforts currently not available for research project.

### **4. – All maize is mixed (conditioned) before selling.**

Weight and quality losses in maize are closely related. As weight losses increase due to biodeterioration factors it is assumed that quality losses will too increase. As low quality maize is difficult to market, it is common practice to mix grain in order to homogenize its quality (Hodges, Bernard & Rembold, 2014). This is reflected in the model by discounting maize from the FRA inventory at its weighted average age, not through a First-in First-out (FIFO) policy.

### **5. – Purchases and local market releases are assumed constant throughout the marketing season.**

Both purchasing and local market releases (sales) are assumed to be constant throughout the marketing year. The main reason of this modelling choice lies on the added simplicity of analysis that this assumptions generates as well as the added ease of incorporating maize weight loss research and management practice decisions into one coherent framework. What this model aims at representing is the average behavior of the FRA through a marketing season and an estimation of their maize losses during storage from an aggregate perspective. Adding seasonality considerations to these two variables would open the door to a very different level of aggregation, one that should also consider spatial factors in order to be coherent and consistent; given the available time for this research effort, these dimensions were excluded from the analysis.

## 3.2 Model Structure

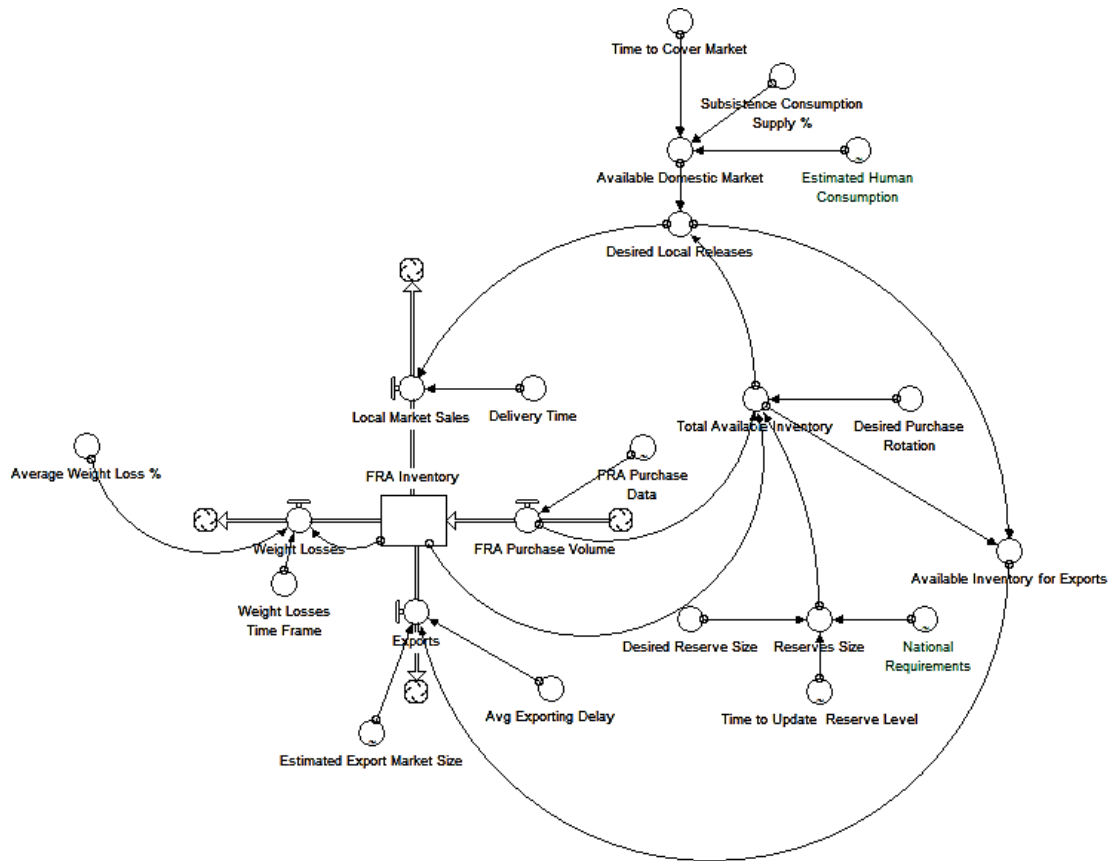
### 3.2.1 Detailed Sector Description

Model structure from a system dynamics perspective can be defined as the set of stocks, flows and auxiliary variables by which the representation of any particular system is achieved. Model structure represents both the qualitative dimension of the system, through the causal linking of variables, and its quantitative dimension, through the formal definition of these causal links through equations.

In the case of quantitative system dynamics modelling, stock and flow diagrams are the tool by which model structure is defined, represented and evaluated. Stocks are variables in which quantities accumulate over time. Flows are the variables affecting stocks and through which accumulation or depletion of stocks occur. Auxiliary variables serve either to represent external parameters (parameters outside of the system's influence) or as the intermediate steps by which stocks and flows affect each other through feedback mechanisms. Auxiliary variables add conceptual clarity to the model by describing the intermediate steps by which stocks and flows are related. For more information of stock and flow diagrams chapter 6 of Sterman's Business Dynamics book is particularly useful (Sterman 2000, Ch. 6).

In order to describe the structure of the system, attention will be firstly placed on describing the different sectors of the model individually. Secondly the overall unified structure of the model will be described in terms of how sectors interact with each other from a feedback loop perspective.

**Figure 3** shows the sector of the model that regulates the FRA inventory and will here forth be referred as the inventory management sector.



**Figure 3: Inventory Management Sector**

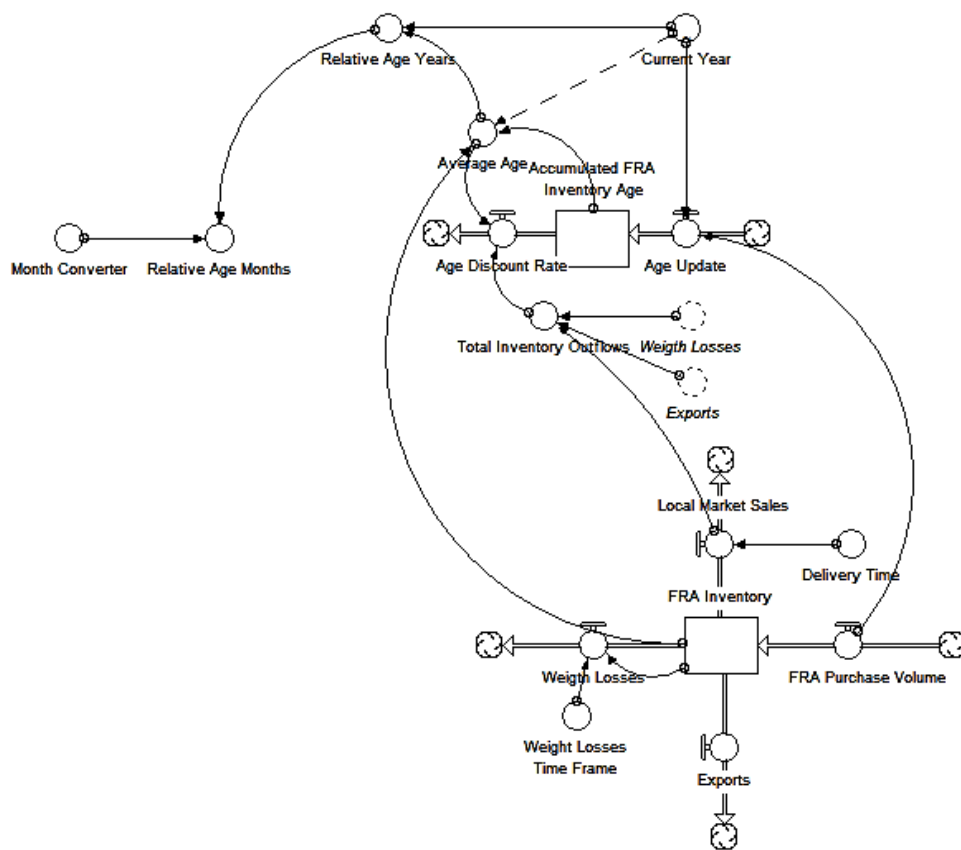
This structure is very straight forward; it represents the FRA inventory as a stock that accumulates the FRA purchases (in KMT/year) over the course of a marketing season. The outflows of the FRA inventory are divided in order to correctly represent the different factors and decision rules that drive them. Local market sales for an instance are a function of the desired local releases, which is in turn a comparison between the total available inventory and the available domestic market. What this outflow represents is a very basic decision rule: local market sales will only occur when the FRA inventory is above its average desired reserves size and up to a volume no bigger than the local available market.

The export outflow is ruled by another very simple decision rule drawn from the reviewed literature (CSO, 2013), which basically states that the FRA will first supply the local market and whatever product is left will be considered as available inventory for exports. This outflow is also regulated by an external limiting factor in the form of an estimated export market size.

Finally the weight loss outflow depends on two factors: the FRA inventory and a decay rate that is captured through a variable called average weight loss %. This formulation is also drawn from the idea that weight losses in absolute terms (mass/year) happen as a consequence of a relative weight loss percentage (which is dependent of several risk factors and the length of exposure to these factors) and the size of the inventory, these ideas can be found both in the works of Harris & Lindblad (1976) and Hodges (2013).

To briefly summarize this sector, the main idea is that the accumulation of inventory in the FRA storage system is driven by the balance of supply (through purchases), demand (through local market sales and exports) and the level of weight losses.

The next part sector to be described is the part of the model that estimates how long the inventory has been in storage; this sector will be referred to as the age accumulation sector and can be seen in isolation in the upper side of figure 4.



**Figure 4: Age Accumulation Sector**

What this structure provides is a way of estimating the age of the FRA inventory. This is achieved first by taking purchases and registering their entry date by multiplying them by the current simulation time and accumulating them in a stock. If this new stock,

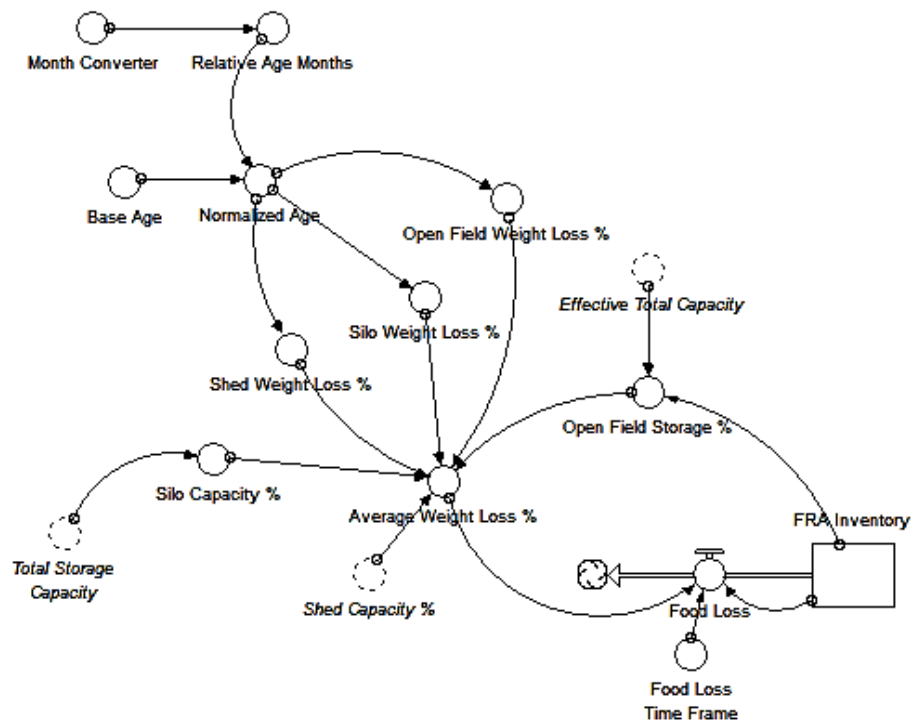
called Accumulated FRA Inventory Age is divided by the actual FRA Inventory stock, the resulting measurement would be the average age of the stock or in different words, the average time at purchases were registered. When sales or losses happen, the Accumulated FRA inventory Age, should have discounted the proportional age related to that volume sold or lost. This is when assumption 4 (maize is mixed before selling) becomes most relevant, since age is discounted by multiplying all of the FRA inventory outflows, times the calculated average age of the stock. The detailed implications and validation of this particular structure were thoroughly tested and validated and are discussed in chapter 3 of this thesis.

Once the general structure governing the average age parameter is set, we can compare this value to the current simulation time. What results of this comparison is called the relative age of the stock which gives an approximation in relative terms (to the current simulation time) of how old the FRA inventory is.

Once the relative age of the FRA inventory is known, an estimation of the weight losses can be partly determined. The calculations of weight losses in this model are based on the idea that two factors drive them: the different risk factors this inventory has been exposed to and the length of exposure to these risks. The length of exposure to risk is assumed to be the length of stay within the FRA storage system. The different risk factors to which the inventory has been exposed to are closely related to the storage technology in which they are stored. In this regard a differentiation can be made between two main storage technologies: hermetic and non-hermetic storage. Hermetic storage relates to all those technologies that rely on two basic concepts to diminish the risk of exposure to bio agents responsible for deteriorating maize: the first of these concepts is the denial of access to the product, the second is known as the oxygen depletion process. Access denial is basically not allowing external agents (rodents, weevils, moths, etc.) to access the product. Oxygen depletion is the process by which oxygen within the specific container (silos, PICS bags, bag silos, etc.) is withdrawn until living organisms cannot longer sustain themselves. Hermetic storage is a particularly effective technology for maize and it allows for very long storage periods if correctly utilized. Non-hermetic storage technologies encompass those technologies such as polypropylene bags, traditional crib storage, shed storage, etc. These technologies mostly rely on the use of insecticides to prevent the development of molds or insect attack to the product. Within the FRA the most widely used storage technology

are polypropylene bags, these bags are kept either in sheds or in the open field and covered with plastic tarpaulins (when the available storage capacity is not enough). The FRA also has silos at their disposal, but it is estimated that only 50% of them are currently on use (expert's estimate).

The specific structure used to capture the weight loss phenomena can be seen in figure 5



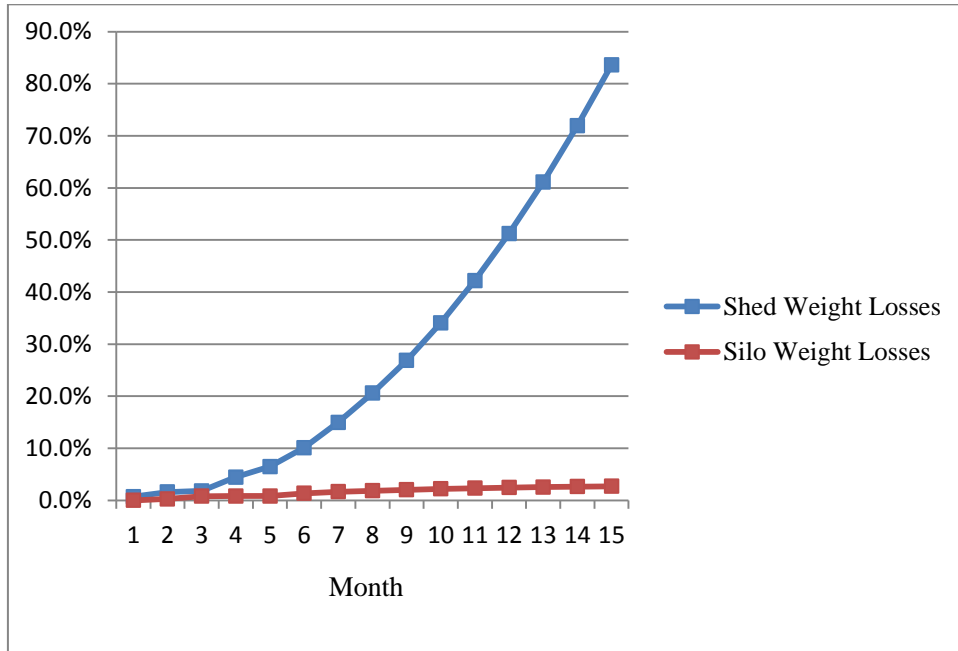
**Figure 5: Weight Loss Sector**

Picking up from the last sector's description, the relative age is normalized in order to use it as the input to the analytic functions representing the development of weight losses over time for each storage method. These analytic functions are then averaged through the percentage each storage method represents in terms of its share on total storage capacity through the variable called average weight loss %. It is assumed that silos and sheds will be used to its full effective capacity first and whatever excess of inventory remains is placed in open field storage. The specific analytic functions determining weight losses for silos, sheds and open field storage were derived from the work of De Groote et al (2013) and Harris (1976).

The final idea to round up the description of this specific section of the model is that shed and open field storage methods lead to exponential weight losses over time. Silos on the other hand lead to almost constant weight losses, and of a far lower scale. The



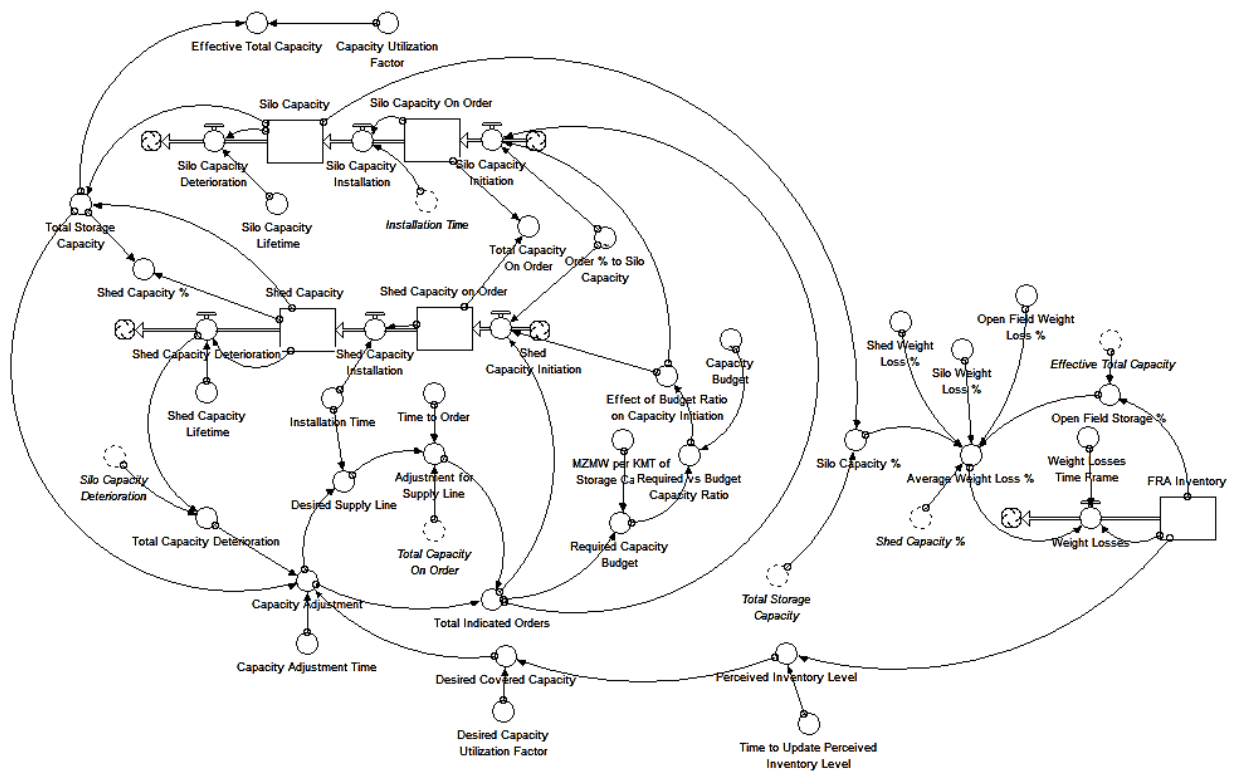
analytical functions used for sheds and silos are presented in figure 6. For open field storage no data was found, hence they were assumed to be 5% higher than those of the sheds.



**Figure 6: Shed and Silo Weight Loss Curves**

For the specifics on how the analytic equations for the weight losses were arrived at, please refer to appendix B.

Finally, the structure that models how capacity develops within the FRA is presented in figure 7. This structure is an adaptation of the one presented in Sterman's Business Dynamics (2000, Ch. 20, p. 806)



**Figure 7: Capacity Build-up Sector**

The starting point of this structure is the level of inventory within the FRA. This model assumes the FRA sets their desired capacity for covered storage (sheds and silos) based on how much inventory they hold and adjust it towards a *Desired Capacity Utilization Factor*. This desired capacity utilization factor represents, in the form of a percentage, the level of utilization deemed as ideal for their storage system. This assumption is based on information found in the FRA Investment plan in Developing Storage Facilities 1 statement (FRA, 2015), a document in which it is detailed the investment plans for the near future within the agency. Once a desired level for capacity is defined, it is compared to the total capacity currently available (both in sheds and silos) plus the needed adjustment for capacity that is lost due to deterioration. This comparison is done in the variable named *Capacity Adjustment*. Once the total capacity adjustment is known, it is re-adjusted so it considers what is already on order and yet to be installed. This is done in order to avoid over or underinvestment. This needed re-adjustment is calculated in the variable named *Adjustment for Supply Line* and integrated with the original *Capacity Adjustment* in the variable named *Total Indicated Orders*. The total indicated orders represent the actual needed amount of new capacity to be invested in order to achieve the *Desired Covered Capacity* target.

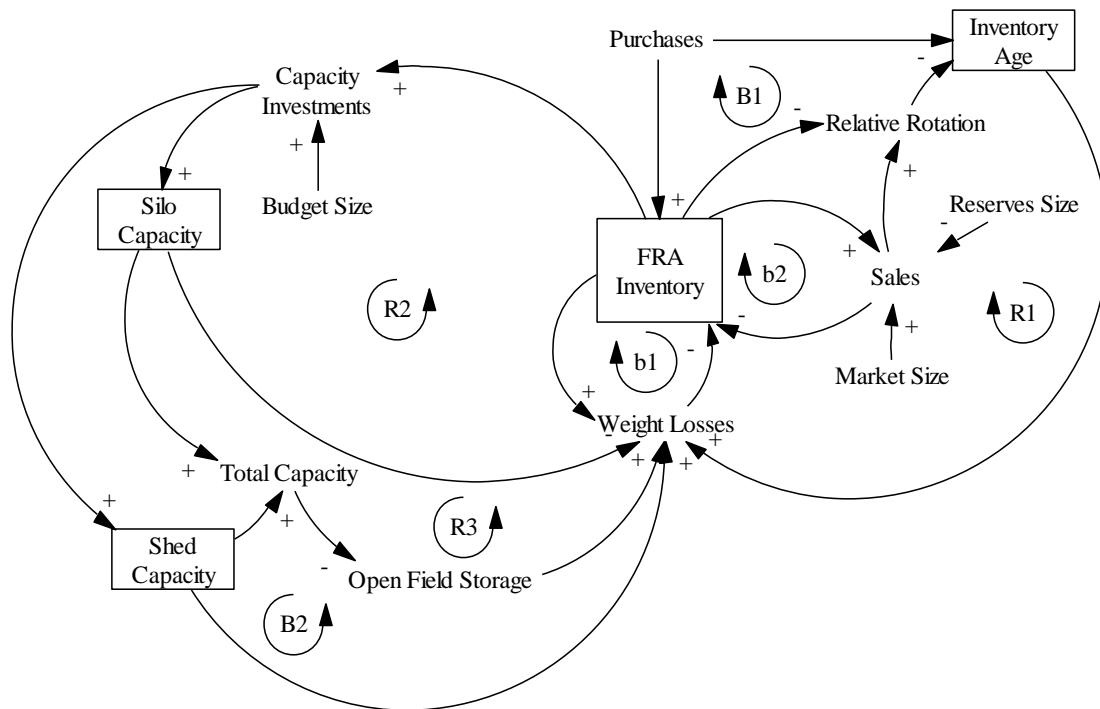
After the total amount of capacity to be invested in is known, it is translated into a *Required Capacity Budget* and compared to the actual estimated *Capacity Budget*. This comparison (represented in the variable *Required Capacity Budget Ratio*) is then modeled as a multiplicative effect that will reduce the actual investments by the same proportion by which they exceed the budget. In simpler terms, capacity investments cannot exceed the allocated budget for capacity. The size of the estimated capacity budget was derived from the actual capacity increases in the FRA and the estimated costs for these investments.

Finally, since no information on how the decisions of attributing investments to either silo or shed capacity was found, it was simply modelled by assuming a certain predefined fraction of the budget is attributed to each.

On a side note and as previously mentioned, the structure of a quantitative system dynamics model is not fully defined by only considering the causal links represented in a SFD. The specific equations and parameters characterizing this causal links are also a fundamental component of the structure since these elements determine the polarity of the loops, their strengths and hence the system's behavior. For further reference regarding the equations of this model please refer to appendix C; also a complete integrated view of the model can be found in appendix A.

### **3.2.2 Feedback Description**

In order to provide a general description of the model in terms of its main feedback loops it is necessary to simplify its representation. This simplification will be done through a causal loop diagram (CLD) shown in figure 8.



**Figure 8: FRA Weight Loss CLD**

When analyzing this diagram it is extremely important to note that the polarities of the relationships (denoted by + and - signs) are in some cases defined from a benchmarking perspective, that is, when comparing its effect in terms of best available options. This specific way of defining the polarities and how to interpret them will be further clarified once the description of these specific feedback processes is done.

The first feedback loops to be described are the two minor balancing loops or first order controls (b1 and b2). Minor balancing loops are characterized by self-influence; that is, the level of the stock through which the feedback loop is formed, determines its own level without the influence of any other stock. Minor balancing loops, also known as first order controls, only contain one stock within their structure.

The b1 minor balancing loop describes the relationship between weight losses and inventory; the more inventory the FRA has, the higher absolute weight losses can be, the higher absolute weight losses are the less inventory there is. The b2 minor balancing loop englobes all of the sales decision rules driven by the inventory following this logic: the more inventory the more sales, the more sales the less inventory, and the less inventory the less sales. Assuming everything else remained equal these two minor balancing loops would drive the system to different desired levels. The b1 loop, given enough time, would take the inventory to minimum levels, those implicitly determined

by the maximum loss rate. The b2 loop would drive the inventory to the predefined reserves size.

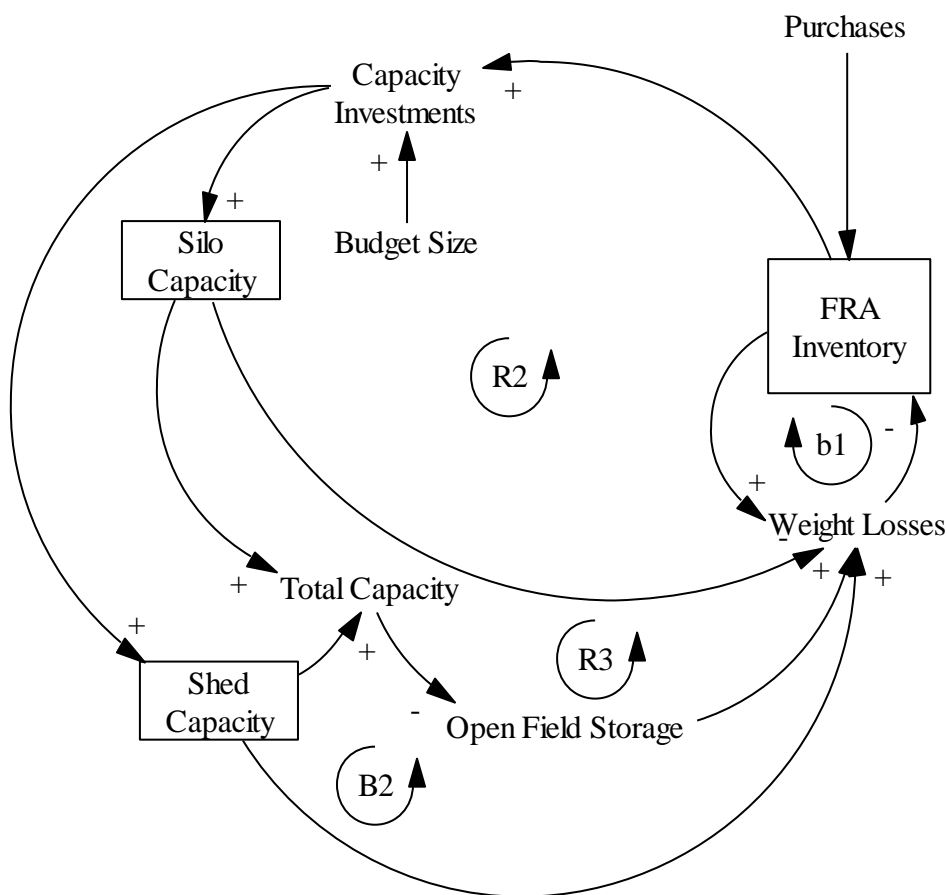
Now the description of the feedback loops will be focused on the mayor feedback loops. These feedback loops are characterized by having two or more stocks within their structure. Mayor feedback loops are responsible for delays and most of the dynamic complexity in systems.

We will start with the B1 balancing loop which relates the FRA inventory and its age through a new parameter called relative rotation. This new parameter is not explicitly modelled as such in the stock and flow diagram presented in the previous subsection. Its function within this CLD is to establish that inventory age is implicitly a function of inventory and sales levels. What this B1 loops says is the more inventory the less relative rotation, the less relative rotation the more inventory age, the more inventory age the more losses and the more losses the less inventory, which would in turn cause more relative rotation. The implications of this loop are in general terms, and everything else remaining equal, that inventory age would be balanced or driven towards a certain stable age, which would be determined mainly by the maximum possible amount of weight losses. An additional implication of this loops is that no matter how much time it passes, given a certain level of sales and purchases, the relative rotation of the inventory would eventually stabilize and as a consequence its age; the only situation in which the inventory age would endlessly grow, would be when having a relative inventory rotation of zero, something not possible in this model given the b2 control loop.

Next the R1 reinforcing loop will be described. The logic behind this loop is the following: the more inventory age the more weight losses, the more weight losses the less inventory, the less inventory the less sales, the less sales the less inventory rotation and the less inventory rotation the more inventory age. On a first impression this loops strikes as evidently vicious, one leading towards a downwards spiral of increasing age and decreasing inventories through losses. What must be considered is that this loop affects both inventory and inventory age through the relative rotation variable, the same variable through which the previously described B1 loop affects these two stocks. The strongest loop will determine the overall behavior of inventory age. In this regard it is relatively simple to determine which loop will have precedence by looking at the variable in which the loops diverge and the looking again at the point in which they

converge again. Both loops take different paths after the inventory variable and rejoin in the relative rotation variable. This realization gives a good indication of which loop will dominate the other. While the B1 loop affects relative rotation directly and with negative polarity, the R1 loops affects it indirectly and in a positive polarity. While every change in the inventory will have a direct balancing effect on relative rotation through the B1 loop, the R1 loop will only provide a fraction of that same impact in a reinforcing fashion; the first order control loop of sales (b2), reduces the overall possible strength of R1

Once the feedback processes of the inventory management and inventory age structure have been described, attention will be shifted towards the left side of the CLD which represents the capacity buildup structure of the model (figure 9)



**Figure 9: Capacity Build-up CLD**

This structure has three major feedback loops R2, R3 and B2. The description will start with the R2 reinforcing loop, which logic is the following: the more inventory the more

capacity investments, the more capacity investments the more silo capacity, the more silo capacity the less weight losses. For the R3 reinforcing loops the logic is the same as for R2 with the difference that the decision to invest in silos or sheds leads to more total capacity which decreases the need for storing product in the open field. Less open field storage leads to less weight losses.

For the B2 loop is when things get a bit tricky; although the logic is the same as that of the R2 feedback loop, the difference of sign in the last link to weight losses is justified by defining it through a benchmark approach. What is meant by this is that although more shed capacity would lead to less weight losses that is a relative statement, less losses compared to what?, if the comparison is done against open field storage, it is true, less losses would occur, if we compare it to silo investments, more losses would occur. Here is when the decision of defining this polarity in terms of best available options becomes relevant, this final link was defined considering not the worst possible option but the best one, in this case silos. The main justification of this choice relies on the gap between differences in losses between each method, while sheds and open field storage experience similar levels of weight losses; silos present a far superior alternative. In other words, the decision to invest in sheds rather than in silos produces higher weight losses and hence the polarity between shed capacity and weight losses is set as positive.

### **3.2.3 Model calibration**

The base simulation run of this model can be split up in three main periods according to their level of certainty. This level of certainty is related to the amount of data that supports them in terms of possibilities of validation. The first period starts in year 2005(simulation start year), the year in which the FRA started expanding its role as a maize marketing entity in Zambia and it ends in year 2012, the year in which the availability of complete data series ends. The second period starts in year 2012 and ends in year 2015. For this period, the available data comes as single figures and was not available for all external parameters; hence some of them run under assumed probable values during this period. The third period starts in year 2015, the last year for which some form of data is available, and ends in year 2030, the year which marks the end of the simulation. Over this period all external parameters are based on probable value assumptions that will be described when pertinent. For the complete parameter specifications, please consult appendix C.

It should also be noted that years in this model do not represent calendar years, but marketing season years. For example, year 2005 in the model should be interpreted as the period that starts on May 2005 and ends in April 2006. All tables and data series should be interpreted in this same manner.

As for the units of measurement it is also important to mention that all weight figures (purchases, sales, weight losses) are represented in thousand metric tons (KMT). Capacity figures are also considered in thousand metric tons.

## **Chapter 4: Validation**

Model validation will be described along the suggested lines of Barlas (1996) and focusing on 5 main validation categories: Unit consistency, parameter-confirmation, structure confirmation, structure-behavior and behavior (pattern and point check) tests.

### **4.1 Unit Consistency**

Each variable in the model is defined so as to represent a “real world” equivalent. Since variables are related with each other, and take as input through defined equations other variables within the model, the simulation software can check the consistency of such relationships in terms of their units through dimensional analysis.

In the present case, there is not much added value in detailing a dimensional analysis of every unit and equation of the model; hence the simulation software’s “check units” function will be used to assess’ unit consistency (figure 10).



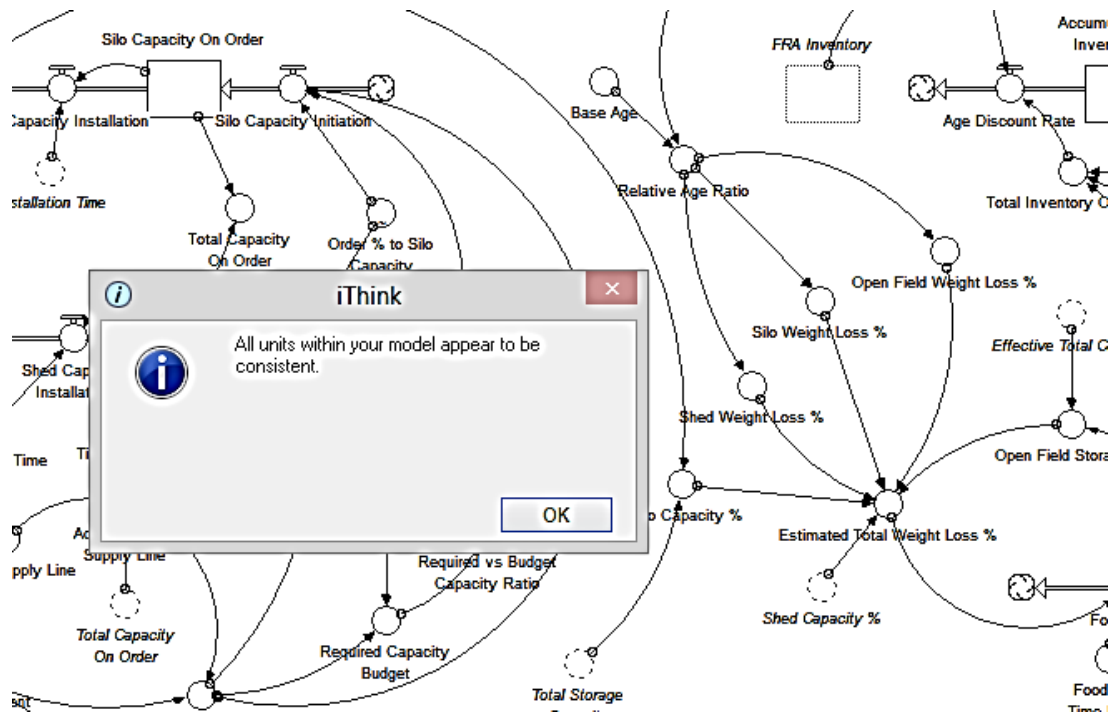


Figure 10: Unit Consistency Check

## 4.2 Parameter-Confirmation

Unit consistency checks are only suitable and useful once every variable of the model has been checked for “real world equivalents” through a parameter-confirmation test (Barlas, 1996). All variables passed this test for the exception of one which will be discussed.

Within this context the model presents one limitation in the specific case of the non-linear functions used to estimate the different values of weight losses per year. The currently utilized method of normalizing the inventory age (in months) and then using it as an input to a non-linear equation yields non dimensional units. This non-dimensional output or percentage is then returned to the time unit of the model through a dummy variable (a variable without a “real world” counterpart) in order to comply with dimensional consistency. The reason behind this is that the modelling of these non-linear relationships through a unit consistent causal structure is absolutely out of the scope of the current research since it would require for the modelling of the biological phenomena that causes maize weight losses over time, something irrelevant towards the fulfillment of objective of this research effort. Within the level of aggregation of this

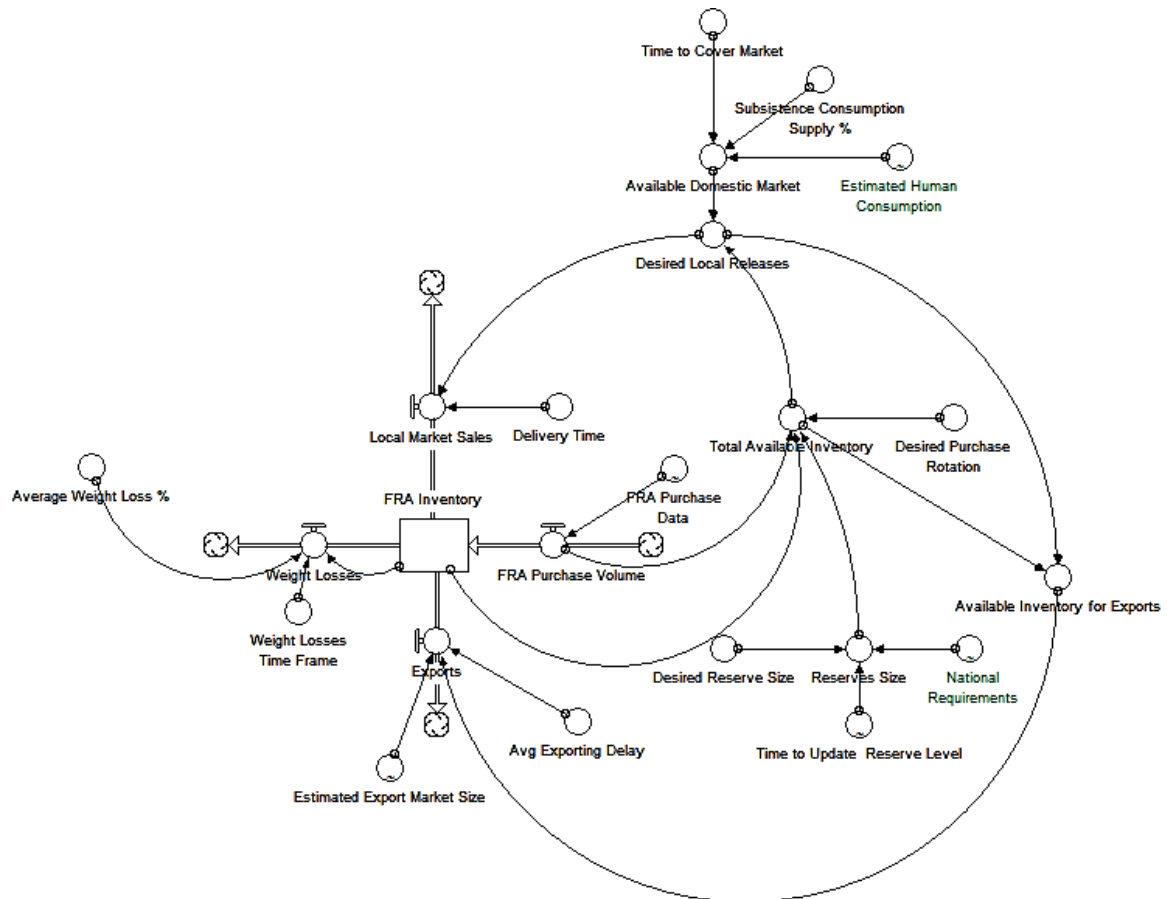
model, the chosen approach to model this specific phenomenon is, for practical reasons, both as justified as necessary.

### **4.3 Structure Confirmation**

Referring to Barlas (1996, pp189-190): “Direct structure tests assess the validity of the model structure, by direct comparison with knowledge about real system structure. This involves taking each relationship (mathematical equation or any form of logical relationship) individually and comparing it with available knowledge about the real system.”

In this regard all of the equations in the model were elaborated in such a way that they represent “real world” general decision rules through robust assumptions. To exemplify what is meant both by general decision rules and robust assumptions, some of the most important relationships will be explained on these terms.

The first piece of the model to be analyzed will be the structure and equations representing the general decision rules of the FRA’s inventory management process (figure 11).



**Figure 11: Inventory Management Sector (validation)**

In order for this analysis to be meaningful from a modelling perspective; attention should be placed on those variables endogenously modeled. In this specific piece of structure there are three main endogenously modelled variables: *Total Available Inventory*, *Desired Local Releases* and *Available Inventory for Exports*. The variable *Total Available Inventory*, represents the entire inventory that should be available for the FRA to dispose of, this includes both the consideration of inventory as well as the known purchases at that specific time minus the desired level of reserves. This equation was adapted from that used within normal inventory management practice (i.e. when calculating ATP inventory). This variable simply represents what the FRA knows will have at a specific point in time and that can be released without compromising the desired level of reserves.

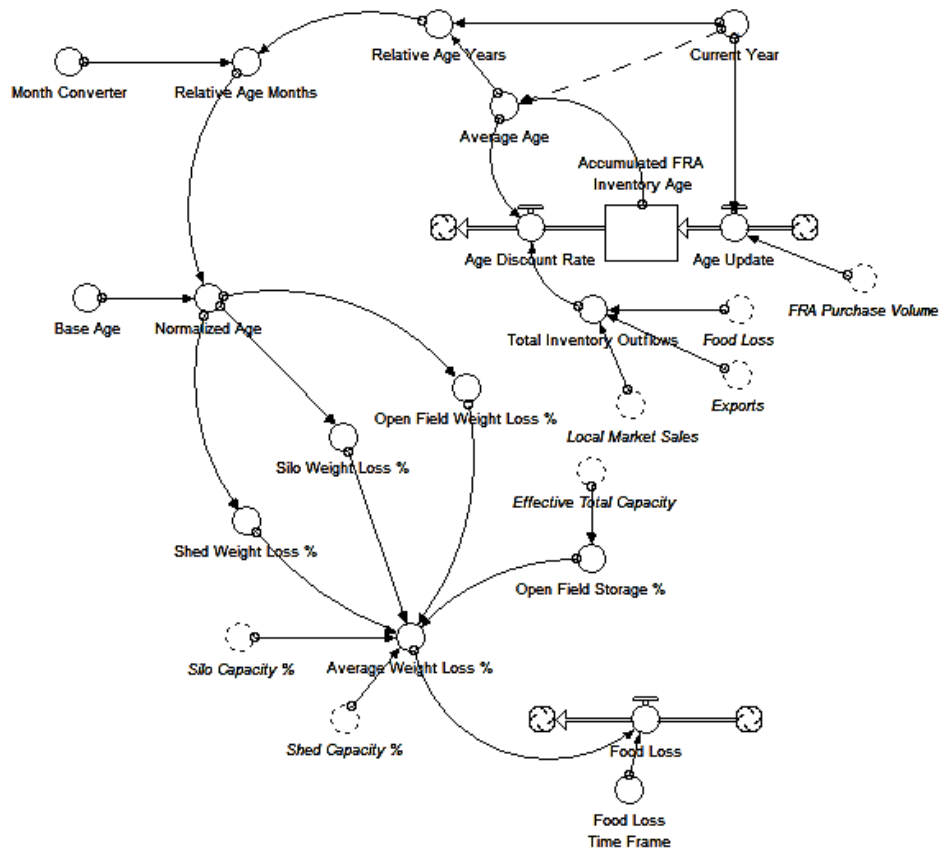
The variable called *Desired Local Releases* is modeled by taking the minimum value between *Available Inventory* and *Available Domestic Market*; the logic behind this decision rule is quite simple: the domestic market will not take more maize than what it

can consume and the FRA will give preference to the local market. This assumption was verified through the disconfirmatory interview with the Zambian agricultural expert.

It is assumed that if the calculated available inventory has a higher value than what the local market is able to consume, the FRA will consider exporting the surplus. This assumption complies with the way the Zambian CSO calculates the potential commercial exports in the country's food balance sheet (CSO, 2013). Again, not all of the inventory that is available for exports will be exported; as explained in the model's assumption's section (assumption 2).

All of the previously utilized equations and causal relationships were, as described, based on very simple decision rules such as calculating available inventories, placing the sales preference on the local market and only in surplus periods considering exporting.

Another piece of the model whose structure confirmation test will be discussed is that representing the inventory aging mechanism and its relationship towards the estimated levels of weight loss. Figure 12 shows a modification of the structure of the model in which some variables were eliminated and the section is isolated in order to narrow its analysis.



**Figure 12: Age Accumulation Sector (validation)**

Only once the structural validity of the stock management structure is reasonably established the analysis of this mechanism becomes pertinent, since this piece of the structure is entirely determined by the flows governing the *FRA Inventory* stock. These flows dictate the behavior of this structure's main stock: the *Accumulated FRA Inventory Age*. As previously explained in chapter 2, the use of this stock is to estimate the minimum age the *FRA Inventory* will acquire over the course of a season and presenting it through the variable called *Relative Age*.

The basic assumption on which the accumulation of this stock relies is that whenever a purchase is made, this purchase volume is “tagged”(or registered) with the date it was purchased in; this is captured by multiplying the purchase volumes times the current model's time. Conversely, when inventory depletion occurs (through local market sales, exports or weight loss), the stock's age is discounted; this is done by multiplying the sum of all *FRA Inventory* outflows by the average age (or entry date) of the inventory.

By dividing the value of the *Accumulated FRA Inventory Age* stock by the actual *FRA Inventory* an estimation of the FRA inventory's average age (or average entry date) is generated. By comparing this average age (or entry date) to the current simulation time, an approximation of the stock's age in years is generated. The validity of this section of the model is entirely dependent on the appropriateness of the previously discussed assumption 4 (chapter 2): all maize is mixed (conditioned) before selling. This assumption when analyzed in "real world" terms is challenged in the times in which the FRA inventory has low age values, since it would be hard to imagine that conditioning or mixing or maize would be required to homogenize its quality when it hasn't suffered any quality losses. When this assumption becomes relevant is when the extreme cases of accumulation of inventory and age accumulation happen; this is when the cases in which high weight losses also happen and hence when this assumption becomes very appropriate and the most useful.

Once an approximation of the age of the FRA Inventory is generated, a level of expected weight loss per different storage method is associated to the inventory. These different weight loss values are then averaged into one according to the share of the FRA Inventory each represents, giving priority to the both Silos and Sheds, that is, whenever the FRA Inventory is equal or below the *Effective Capacity* value, *Open Field Storage %* (maize kept outside of storage structures) is assumed to be zero. The support of this idea is that inventory will always be sought to be under the best possible storage conditions and the fact that open field storage is an emergent strategy to deal with capacity constraints and deemed as a last resort option.

For a review on the structural validity of the capacity build-up section of this model please refer to Sterman (2000, ch.20), as this structure is common standard within the system dynamics practice, and its discussion in this thesis wouldn't contribute any new knowledge.

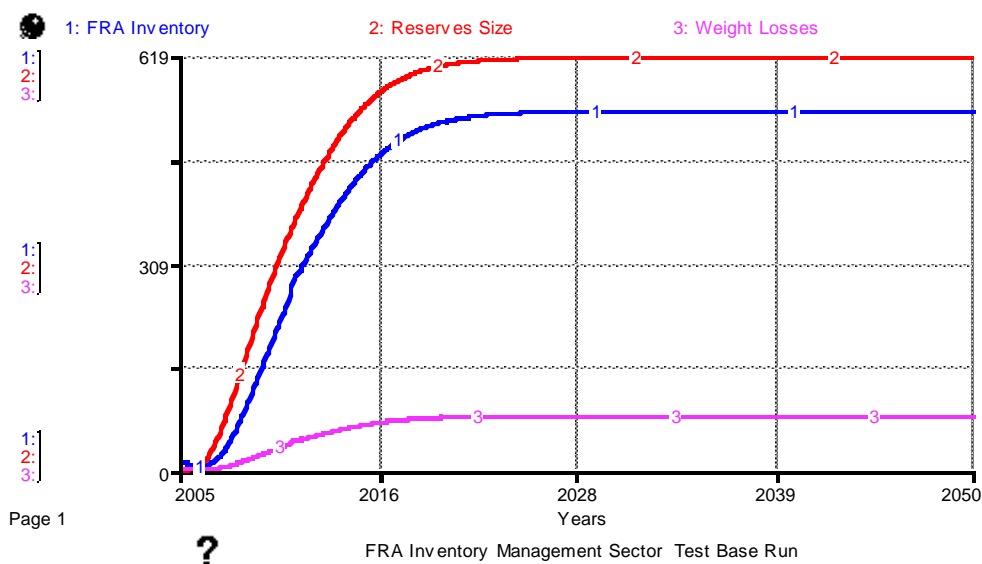
#### **4.4 Structure Oriented Behavior Validation**

The specific structure oriented behavior tests hereby presented were carried out by isolating each specific sector from the rest of the model and testing its behavior under extreme conditions as well as by modifying certain inputs and then confirming the expected patterns and scale of the behavior of the outputs. Analyzing each of the

model's sectors independently and in isolation simplifies their analysis and narrows down the possible sources of unexpected behavior.

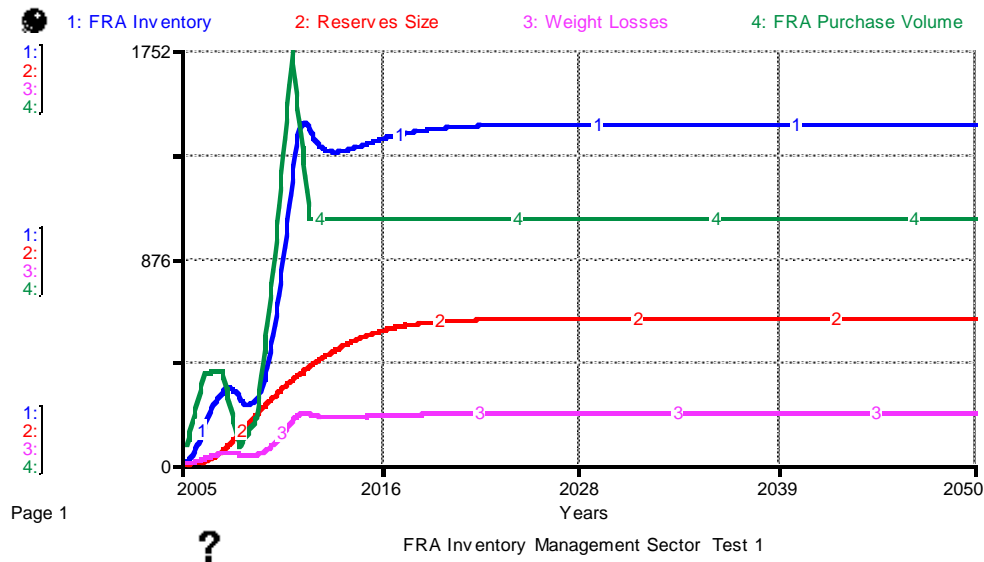
As the previous subsection, this validation test focused mostly on the FRA inventory management structure and the age accumulation structure.

Figure 13 shows the behavior obtained from the first run test of the isolated FRA inventory management sector. In this specific run, weight losses of the inventory were assumed at a constant rate of 15% and the *Possible FRA Market* as unrestricted (all available maize can be placed on the local market). This particular run, which will serve as a basis for comparisons, behaves as expected. The *FRA Inventory* stock follows the *Desired Reserves* parameter which serves as its target. An interesting analysis highlight is that the *FRA Inventory* value never reaches the exact value of *Desired Reserves* because of what is known as a “steady state error”, which is an implicit consequence of the assumption that the FRA doesn't take into account weight losses when calculating the *Total Available Inventory*. This assumption was confirmed by the *Zambian agricultural expert* whom was consulted, and stands as a better option than its alternative, which would be assuming the FRA has a weight loss tracking/prediction information system and that this information is taken into account to update the *Total Available Inventory* on a nationwide basis.



**Figure 13: Inventory Management Sector- Test Base Run**

To exemplify one of the performed tests, the equation for *Total Available Inventory* was modified so it wouldn't consider the purchase volumes when calculating the *Total Available Inventory*. The results of this test (Test 1) are shown in figure 14

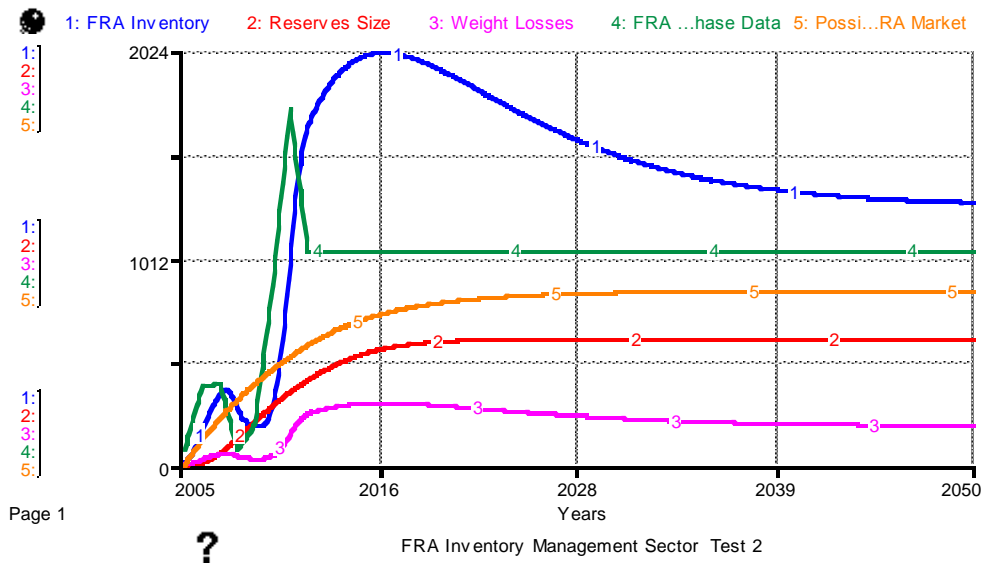


**Figure 14: Inventory Management Sector- Test 1**

This figure tells two things, first and most importantly, it tells us that considering purchases as part of the *Total Available Inventory* is essential in order to regulate the *FRA Inventory* stock variable so it is adjusted to the *Desired Reserves* target level. Second it shows an error of the expected magnitude and direction. The *FRA Inventory* stock experiences a steady state error of the exact magnitude of the purchase volume, something that would contradict practice when considering that this specific run assumes an unrestricted market size. What this specific run shows is basically that without considering purchases as a part of the decision of the available volume to sell, the FRA would perpetually keep stocks above their desired reserve's size .

For the next test the equations were returned to those of the base run and a restriction over the size of the *Possible FRA Market* was placed. Exports were restricted to zero as well. The results of this test (Test 3) can be seen in figure 15.

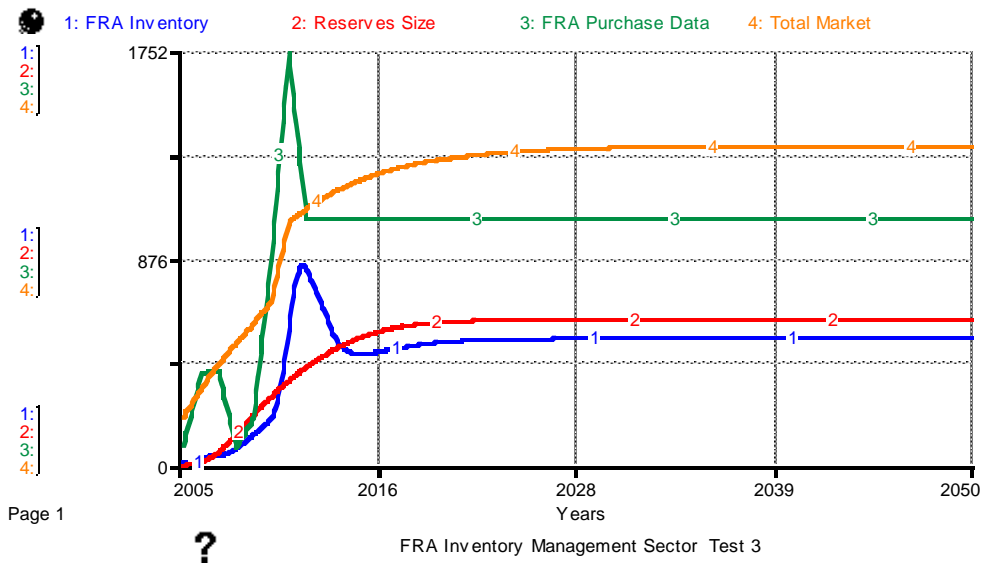




**Figure 15: Inventory Management Sector- Test 2**

As expected, the *FRA Inventory* drastically rises above its target level (*Reserves Size*) since purchases are well above the placed restriction on the market. To simplify: more product than what can be sold is purchased. The slowly declining behavior in the *FRA Inventory* is caused by the assumed constant weight losses. The assumption of constant weight losses, which disregards how long the product has been held in storage, is utterly unrealistic from a conceptual level; maize has a lifetime and cannot be stored indefinitely. This simple, yet important finding further stressed the need of devising a mechanism to estimate a measurement of the inventory's age and use it as a basis for the estimation of weight losses.

The final test that will be discussed for this sector is shown in figure 16. In this test the *Estimated Export Market Size* variable was set to those levels used in the working model, clearing the way for the inventory to return to its target level.

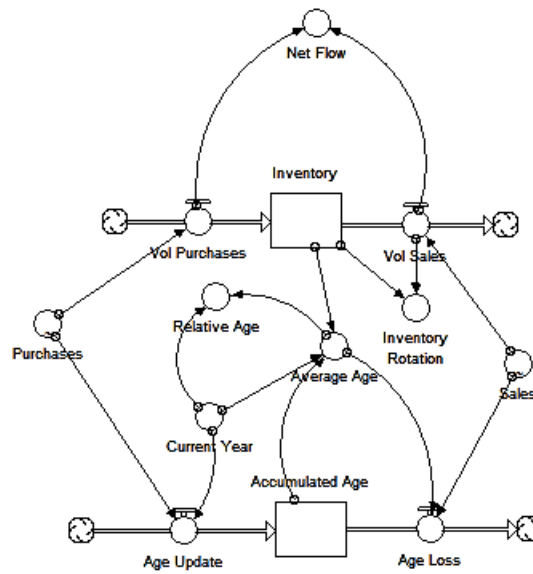


**Figure 16: Inventory Management Sector- Test 3**

When the purchases exceed the total market size (domestic plus exports market), the inventory overshoots its target; once purchases fall below the total market value the inventory returns to its target.

Similar tests were performed for other extreme cases such as setting very low or high parameter values in the restrictions over the local market, export markets, reserve sizes, etc. The model in its final formulation behaved in an appropriate manner.

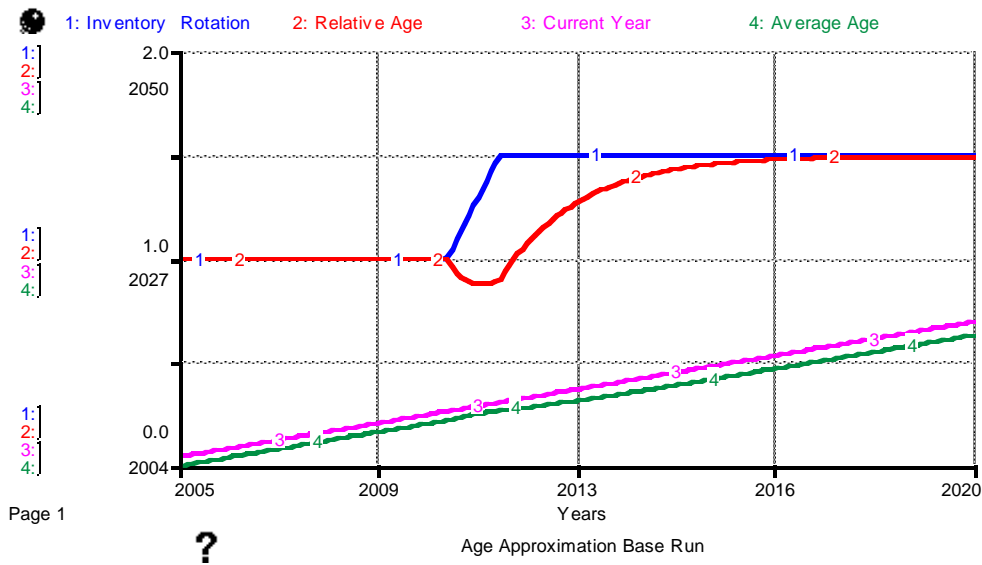
Once confidence was established on the structure managing the FRA Inventory, attention was shifted towards testing the mechanism that approximates the age of the inventory. In order to do so, a conceptual version of this section of the model was tested in isolation.



**Figure 17: Age Accumulation Sector (Conceptual validation)**

Figure 17 is in concept (and formulation) the same structure used in the final version of the model. It consists of two sets of stocks and flows; one set accumulates the physical inventory of maize and the other set keeps track of the “accumulated age” associated to the physical stock. The *Accumulated Age* variable is calculated by multiplying purchases by the current simulation year and accumulating them in a stock, the stock is depleted by multiplying the sales volume times the calculated average age. Age is added with the value of current simulation time, age is discounted at the weighted average of the stock’s age.

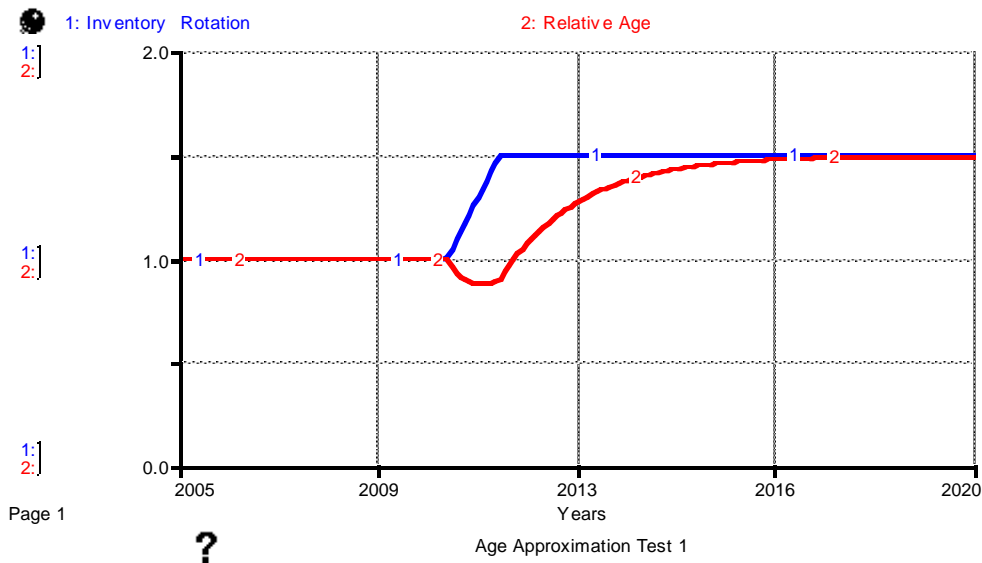
In order to test the validity of this structure’s concept figure 18 will be used to exemplify the base run. During this run purchases and sales are set at a constant value of 10 (KMT/year), the initial value of the *Inventory* stock was set to 10 (KMT) and the initial value for the *Accumulated Age* stock is set to 20040 (10 KMT\*2004).



**Figure 18: Age Accumulation Sector- Base Run**

The results of this base run might strike as obvious, given the initial value of the *Inventory* stock of 10, purchases values of 10 and sales of 10, the relative age of the stock remains constant at a value of 1. The *Relative Age* parameter, as previously mentioned, is defined as the difference between the average age of the stock (the division of *Accumulated Age* by *Inventory*) and the current simulation time. The initial value of the *Accumulated Age* stock was calculated so that it would represent the value of a one year old age stock.

As a first test, purchases were increases to 15 (KMT/year) during one year in 2010, and then returned to the previous value of 10 in 2011 while everything else remained constant. The results of this test can be seen in figure 19.

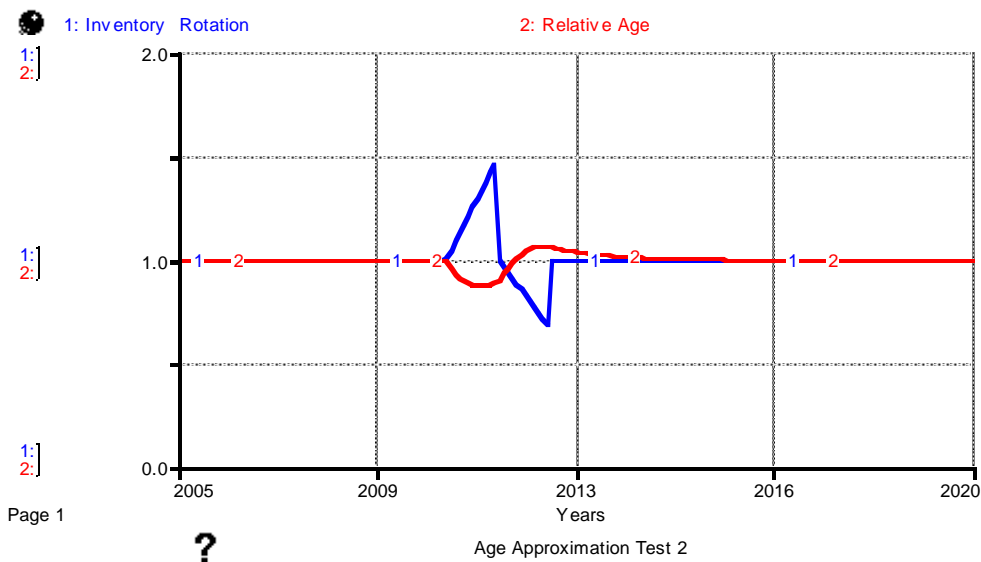


**Figure 19: Age Accumulation Sector- Test 1**

The variable of interest in this figure is *Relative Age* since this is the actual estimation of the inventory’s age with respect to the current simulation year. A new variable was added to this graph called *Inventory Rotation* which is defined as the division of *Inventory* by *Sales*, this variable’s formulation is commonly used to estimate the time it would take a stock to deplete, and would in some cases, provide a good estimator of the age of a stock. This variable would provide another reference point in determining the appropriateness of the current approximation through this *Relative Age* variable.

From this test a somewhat unexpected pattern emerges, the variable *Relative Age* initially decreases. One would expect that the age of the inventory, given higher purchases and the same level of sales, would increase. If we analyze it in detail though, it is completely logical for the variable to initially decrease since the addition of new inventory actually decreases its average age; it is only after time has passed (with the same level of sales) that the variable’s value should increase. This is where the proposed formulation results extremely useful and definitely more appropriate than the commonly used *Inventory Rotation* formulation. Whereas *Inventory Rotation* would provide an estimate of an inventory that’s 1.5 years old at year 2011 (one year after the increase in purchases), *Relative Age* correctly represents an inventory that’s one year old, one year after the increase in purchases with an initial reduction in its average age due to the addition of newer inventory. It is only after 2011 that *Relative Age* starts rising until it reaches a steady state value of 1.5 years.

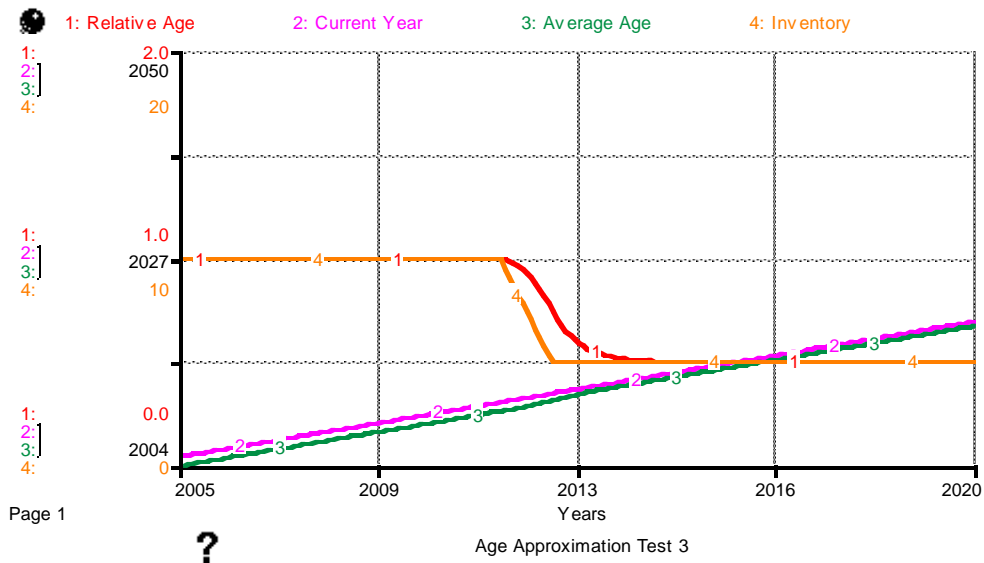
In figure 20 the results of a second test are presented. The only difference regarding the previous run (test 1) is that sales are increased in 2011 to 15 (KMT/year) in order to return to the steady state observed in the base run, and analyzing if the pattern that emerges is adequate or not.



**Figure 20: Age Accumulation Sector- Test 2**

As seen the resulting behavior is in line with what is expected, a stock that initially becomes younger (on an average) due to the increase in purchases, but ages as time passes. With the modification of the sales level, the steady state of *Relative Age*, does not remain at 1.5 years as in the previous run, it goes back to 1 years as expected. It is interesting to compare both graphs, and observe that inventory rotation does not correctly represent age in yearly changes since it would imply considering that the change in sales and purchases has an immediate effect on the age of the inventory, something that strengthens the notion that the current proposed structure is a more adequate approach.

Finally the results of test 3 on this section of the model are presented in figure 21. For this particular run, all parameter values were returned to those of the base run and an increase from 10 to 15 (KMT/year) in sales in 2010 was set; sales were returned to 10 (KMT/year) in 2011 and afterwards. The purpose of performing such a test is analyzing what are the implications of a market that allows higher sales than the purchases, and the effect of the depletion process of inventory on the relative age variable.



**Figure 21: Age Accumulation Sector- Test 3**

As expected the relative age parameter is reduced to .5 years; this can be easily interpreted as a consequence of reducing the value of the inventory from 10 to 5 (KMT) in comparison to the level of sales which are set at 10 (KMT/year). What is also interesting is the comparison of this behavior to that obtained from test 1, in which the increase in purchases had a delayed effect on the inventory's age; in the present case, sales have an immediate effect of the inventory's age, reducing it. This makes absolute conceptual sense if we consider that when sales are done, it is assumed that new maize is mixed with old maize; an increase in sales would carry out more old maize with them, hence reducing the average age of the stock. Basically, what this test confirms is that this structure appropriately accounts for the fact that older inventory is on an average sold first (through mixing), a fundamental assumption of this model.

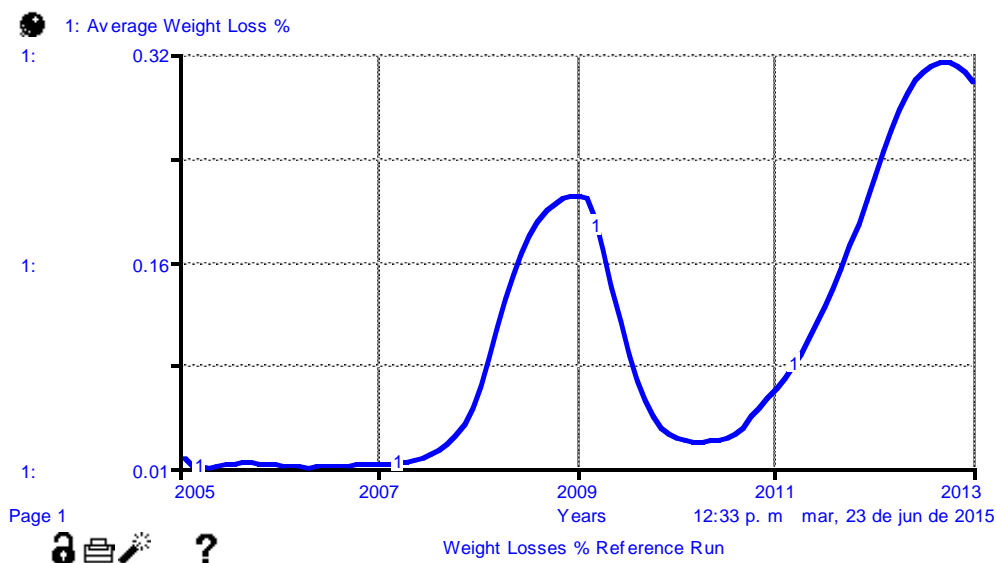
#### 4.5 Behavior Pattern and Point Check Tests

The main purpose of performing behavior pattern and point check tests on a simulation model is to establish how well does the model reproduces the behavior of its variables of interest in both a quantitative and qualitative manner.

In the case of the problem this model aims at reproducing, namely maize weight loss at the FRA storage system, there is no available formally measured quantitative data. This does not mean the obtained behavior cannot be assessed for its validity, it only means the level of uncertainty cannot be explicitly defined in quantitative or statistical terms.

What can be done is assessing its validity in terms of how well the produced patterns manage to express its known qualitative behavior.

In this regard, what is known in qualitative terms about the behavior of weight losses of maize within the FRA is that they reached a peak of about 32% in 2013 (Chapoto et al, 2015). It is also known that under normal circumstances, private sector storage facilities in Zambia experience losses of about 5% per year (Kuteya & Sitko, 2014);. These two values set the reference for possible minimum and maximum values for weight losses during storage In the FRA. Connecting these pieces of information gives us a picture of what could be expected in terms of qualitative pattern development for storage losses in the FRA for the analyzed reference period (2005-2012): rising weight losses in stored maize, going from an initial level of 2% - 5% in 2005, up to an expected peak of 32% in year 2013. Figure 22 shows the simulation base run of the relative weight losses during storage from 2005 to 2013.



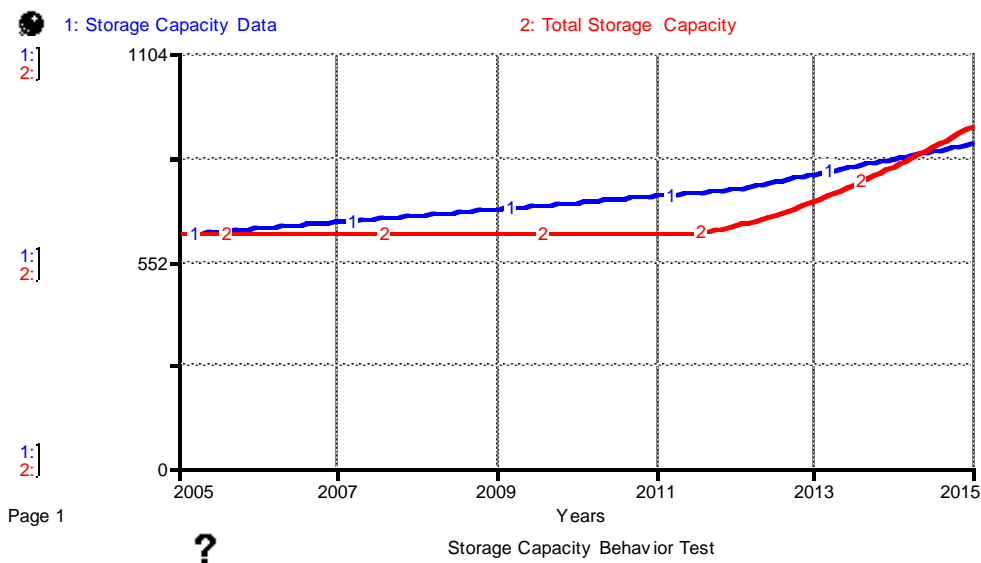
**Figure 22: Average Weight Loss % (Validation)**

This behavior reproduces adequately and in general terms the previously defined pattern: low losses for the initial period rising from about 1% in 2005 to 30% in 2013. On a side note, it must be clearly stated that this run does not involve any sort of calibration in the parameter values of the model; all of the parameter values are set to those values found in literature, archived data sets, etc. It is on my personal view that a clear and transparent model can be put to better use than a perfectly calibrated one, and as such, it was within my judgment to not further calibrate it. This behavior pattern is the result of the previously validated structure and as such, replicates its assumptions;



this is also something that must be present at all times when putting this model to a use, this model is as robust and accurate as its core assumptions.

As previously explained, these levels of food loss are the consequence of several endogenously driven factors; such factors will be compared to available data. To start, the simulated storage capacity will be compared with available data in figure 22. The data used for this comparison is based on the numbers found in Mutumweno (2013) and the FRA website. These two sources provided with three reference points in time for the years 2005, 2012 and 2015; the intermediate points were assumed to behave linearly.

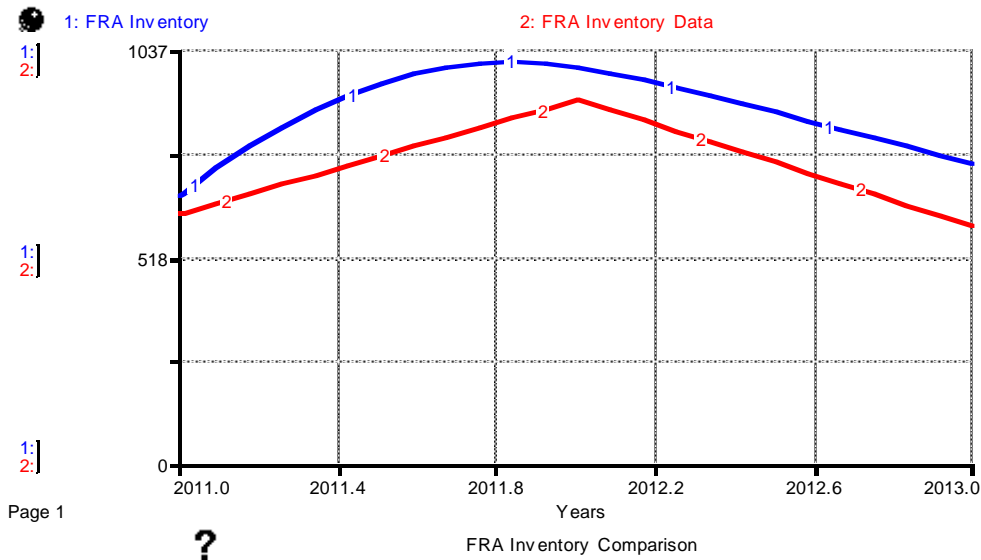


**Figure 23: Storage Capacity Behavior Validation**

In order to evaluate the difference between both curves R-squared will be used. In this case the R-squared value relating both series is .86. Although not being a perfect fit and given the overall qualitative similarity between both data series the fit is deemed as sufficiently good.

The final variable to be tested for its behavior validity is the FRA stock. Data series for this variable could not be found. The only available data was recently provided in the form of an estimation of the carryover stocks for the 2013/2014 marketing season in Chapoto et al (2015) and set at 597 KMT. Estimates of carryover stocks for the 2011/2012 and 2012/2013 seasons were also available (Reuters, 2012, Sichinga, 2013 p. 4). The R-squared between both series was calculated in order to assess the difference between the curves and its value stands at .90. Although being only three data points, this period stands as the most relevant period in terms of storage losses. During this

period the FRA inventory reached historical maximums and this is when storage losses were reported in alarming high levels. In figure 24 the two data series are plotted for this period and it can be seen that the trend, scale and timing of the peaks, match relatively well when comparing them.



**Figure 24: FRA Inventory Behavior Validation**

It is very important to understand that the formal data sources available to construct this model were very limited. Most of the calibration of the parameters was done through second-hand data and approximations through regressions/extrapolations performed by the author and as such the refinement of certain parameters stands as an opportunity area of the model. A positive aspect that certainly reduces the extent of this limitation is that every variable of this model has a reference to the best available data source; this provides the model with very specific and accurate grounding points to reality. These data sources can be found in appendix E.

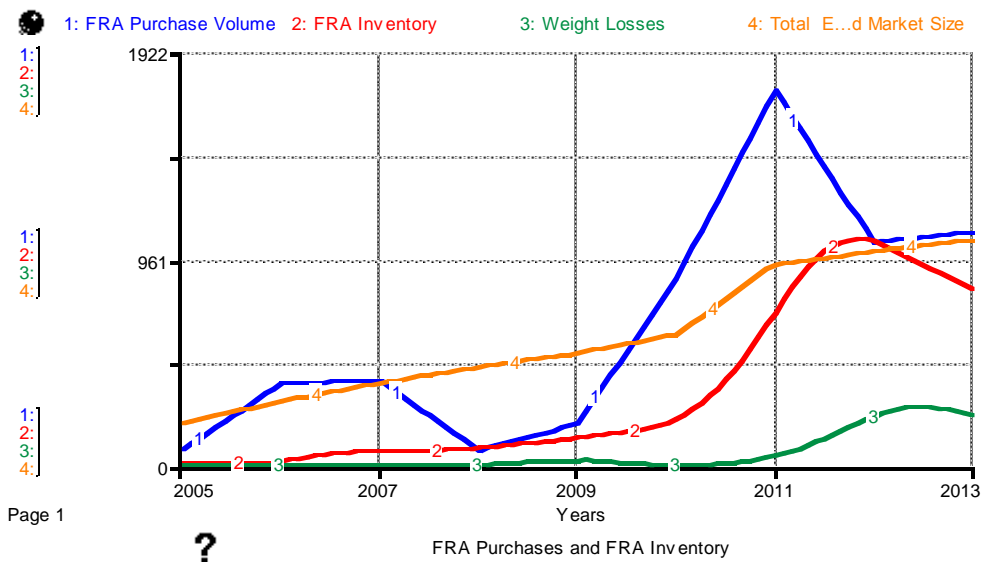
As a conclusion and in a general sense, this simulation model can adequately quantify the mechanisms that characterize the general behavior of the FRA and as a consequence appropriately estimate the levels of weight loss of maize during storage.

## Chapter 5: Behavior Analysis

After discussing the model's structure both in a detailed and general fashion as well as its validity, the scene is now set for the description of the behavior of the main variables

of interest of the model and the description of the specific circumstances of the FRA case which lead to such outcomes. The analysis will focus on the description of how the main variables driving weight losses developed and why they developed in such a way.

The starting point of the behavior analysis will be the same as the starting point of the FRA operations: purchases and its implications towards inventory levels.



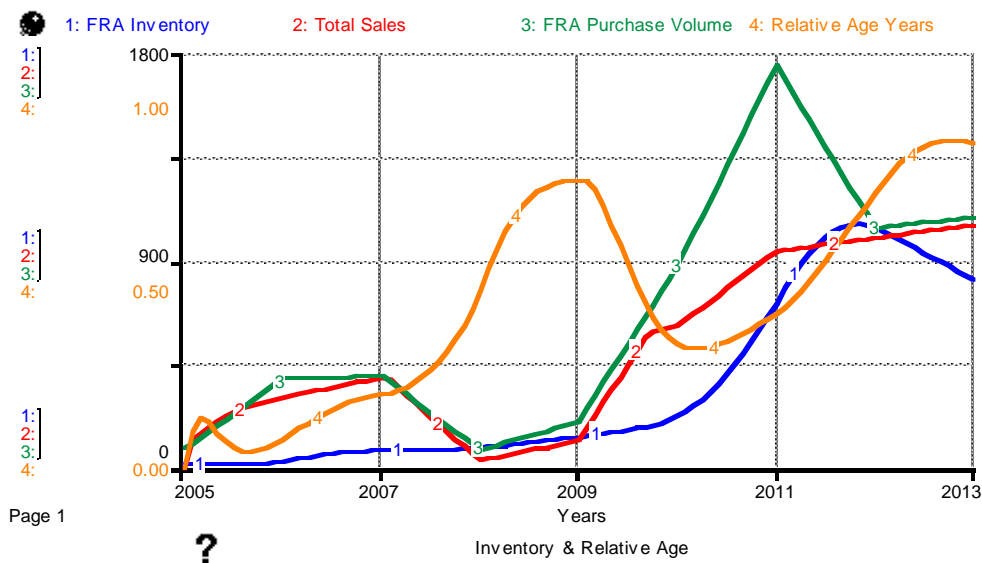
**Figure 25: Purchases and FRA Inventory**

What can be seen in figure 24 are the relatively simple implications of the purchasing behavior of the FRA. During the initial period (2005-2010), the domestic and foreign markets were sufficient for the FRA to offload the maize they had bought, keeping the inventory levels at relatively low levels. When the second bumper harvest happened in 2010, the FRA reacted by purchasing unprecedented volumes of maize, these purchases exceeded the total available market for the maize to be placed in. As a reaction, the FRA exported some of their excess maize, this can be appreciated in the sudden increase in the total estimated market size variable in 2010. Nonetheless, this increase was not sufficient to offload enough maize from the inventory which led to an exponential increase in the inventory. This excessive increase of maize was compensated by an increase in weight losses during storage as well as by the eventual reduction in purchases. By 2012 the total market size was about the size of the purchases, and weight losses started declining as maize was either sold or wasted.

This situation portrayed in figure 24 can be summarized quite simply: the FRA expanded its activities and started big scale maize marketing activities from 2005 till

2010. During the initial phase the total available market was big enough and inventory could be easily placed in the market. In 2010 the second consecutive bumper harvests came and with it a massive increase in purchases. These purchases were performed in a limited market environment, which lead to excessive inventory accumulation since maize demand was not high enough. This drastic accumulation of inventory didn't come with very high losses of maize, which caused an eventual decline in inventory levels.

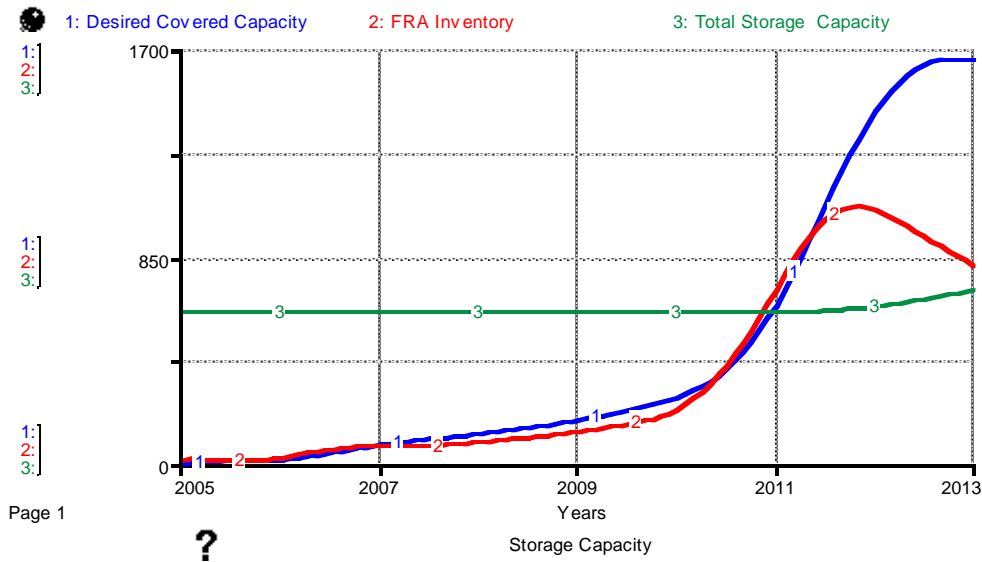
Figure 25 shows the development of the estimation of age of the FRA stock during this time period. Initially the inventory's age is assumed to be zero.



**Figure 26: Inventory and Relative Age**

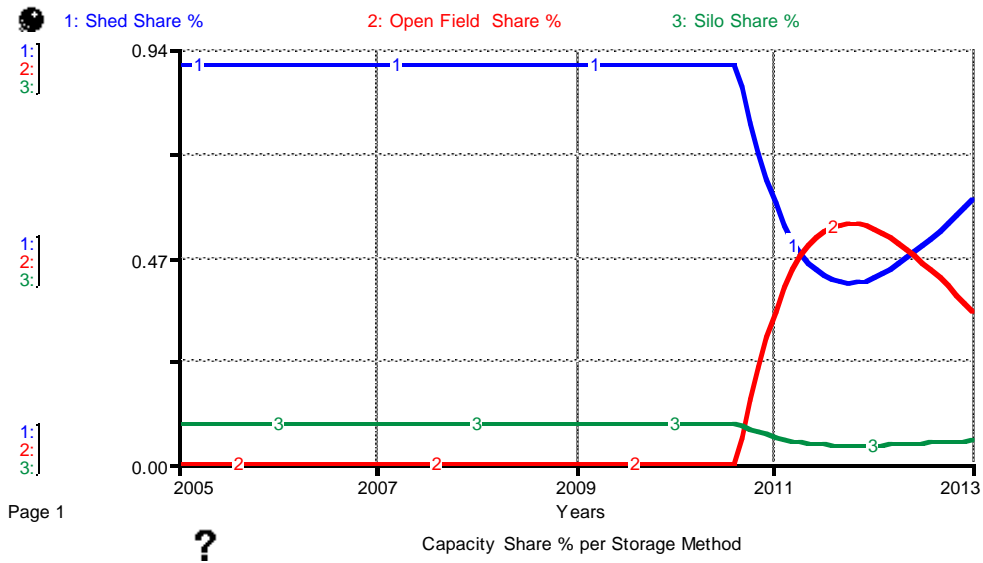
The first important analysis point in this graph is the first bump in age experienced from 2008 to 2010. The combination of low sales, low purchases and a relatively high level of desired reserves led to aging stock. Once the purchasing volume started increasing in 2009, the new inventory that flowed into the FRA storage system temporarily reduced the inventory's age. This age decrease caused by more purchases didn't last for long. As time passed, the amount of purchases proved excessive and while they were impossible to place in any market, inventory levels again rose. This sudden increase in inventory levels and the low rotation of the inventory caused the second bump in inventories age. An important thing to notice is that while both age bumps are of a similar magnitude, the consequences of them are over a very different level of inventory. While the first age bump referred to only 127 KMT, the second age bump was associated to 1043 KMT.

As mentioned before weight losses are modeled as a function of the time the inventory's age and the storage method/technology in which it is stored. In order to complete the picture of how weight losses rose to such levels in the FRA, figure 26 will be used to analyze the development of the available capacity in the FRA.



**Figure 27: Storage Capacity (Behavior)**

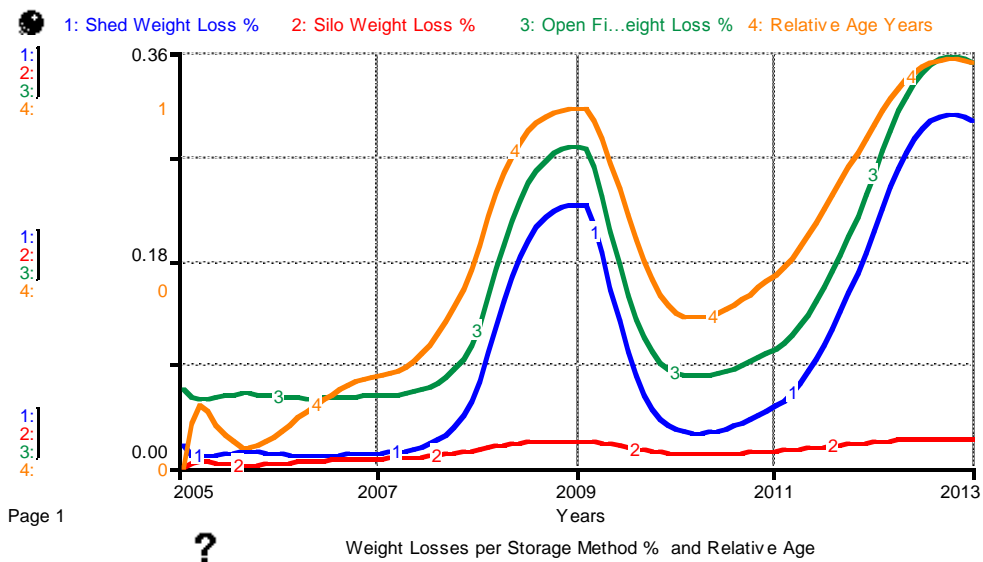
As inventory builds up the desired capacity follows; this desired capacity value is not reached since budget constraints and time delays slow down the process of actually getting capacity built up. In order to cope with this lack of capacity in the 2010-2013 period, open field storage appeared as an emergent strategy. The development of the relative share (in %) of employment of the different available storage methods within the FRA can be seen in figure 27.



**Figure 28: Capacity Share % (per storage method)**

This sharp increase in open field storage happens when the inventory exceeds the available capacity. As the inventory starts its decline from its 2011 peak the open field storage share % drops as well.

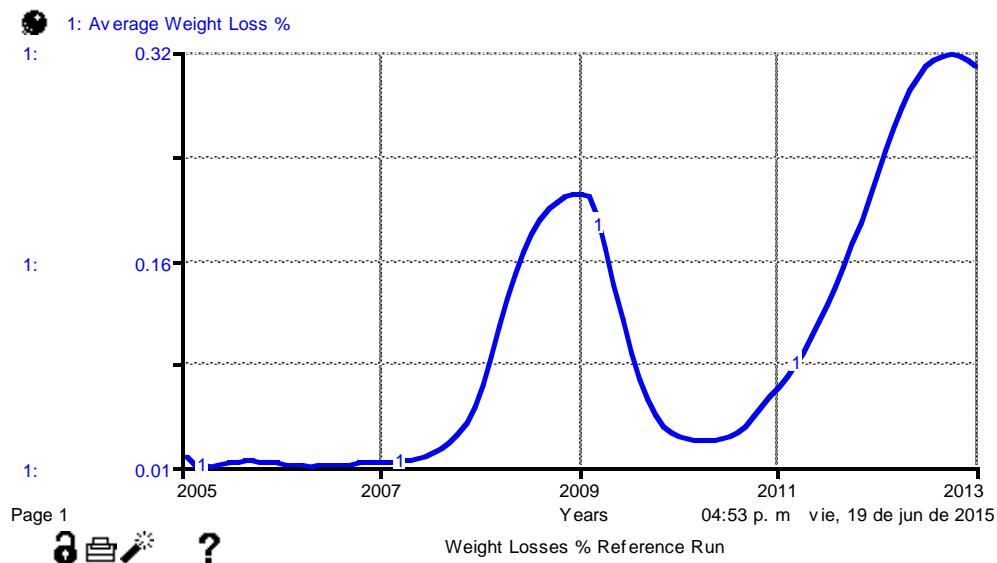
The shares of the different storage methods are used to weight and average the analytic functions of weight loss. The behavior of each estimated weight loss curve per storage method as well as the relative stock age can be seen in figure 28.



**Figure 29: Weight Losses per Storage Method (%) and Relative Age**

By looking at this graph we can easily tell that the shape of the curves behavior is dictated by the average age of the inventory. Each different storage method

Finally if each of these curves is multiplied by its specific share (figure 27), the final result is the relative weight losses of maize in storage.



**Figure 30: Weight Losses % (Reference Run)**

## Chapter 6: Scenario and Policy Analysis

Once confidence has been built in the constructed system dynamics model, and once it has proven to be a valid tool to estimate weight losses during storage in the FRA system, the design and testing of policies that could mitigate the problem (or its risk) in the future is now possible and pertinent. This particular chapter is aimed at providing an answer to the fourth research question of this thesis.

In order to test and asses possible policies that could steer future expected system behavior into more desirable outcomes, it is basic to first explicitly define the characteristics of the expected future circumstances under which the system's response will be tested. In this regard, it is always a difficult task to predict how those external parameters affecting the system will develop in the future. In order to overcome this difficulty the testing of policies will be done considering two scenarios which are deemed as plausible but result in very different outcomes. These two scenarios will be described in the next subsection.

For a full running version of the simulation model please refer to appendix D.

## 6.1 Scenario Description

The base scenario (or 2.7% growth scenario) has the following characteristics regarding the external factor affecting it:

1. Foreign and domestic market sizes are expected to growth at a 2.7% yearly rate. This growth rate is based on population growth estimates (African Development Bank Group, 2015).
2. Population shifts from rural to urban areas are not considered. These shifts could affect the proportion of maize consumed by rural populations before entering the market. If a mayor population shift is to happen, the domestic maize market would be expected to increase for the FRA.
3. The reserves size remains at a level of three months' worth of national consumption.
4. Overall national consumption also grows at the same rate as the population (2.7% per year).
5. Investments on silos and sheds maintain the same historical estimated proportion (91% to sheds, 9% to silos)
6. Purchases grow at the same rate as national population growth (2.7% per year). This implies one of two things: either that agricultural output also grows at a 2.7% per year rate and the FRA remains as the major marketing organization or that despite higher growth rates in the agricultural sector the FRA purchases increase at a lower rate and their dominance in the maize market gradually decreases.
7. The capacity budget grows at the same pace as purchases; at a 2.7% per year rate.

The desired economic growth scenario (or 7% growth scenario) has the following characteristics:

1. Points 1 to 5 remain as in the base scenario (2.7% growth scenario)
2. Purchases grow at a 7% per year rate. This number is considered as it is the last available estimate for desired economic growth (Hill, 2015). Being a major contributor to economic growth in Zambia, agriculture should at least grow at this rate for the target to be met.



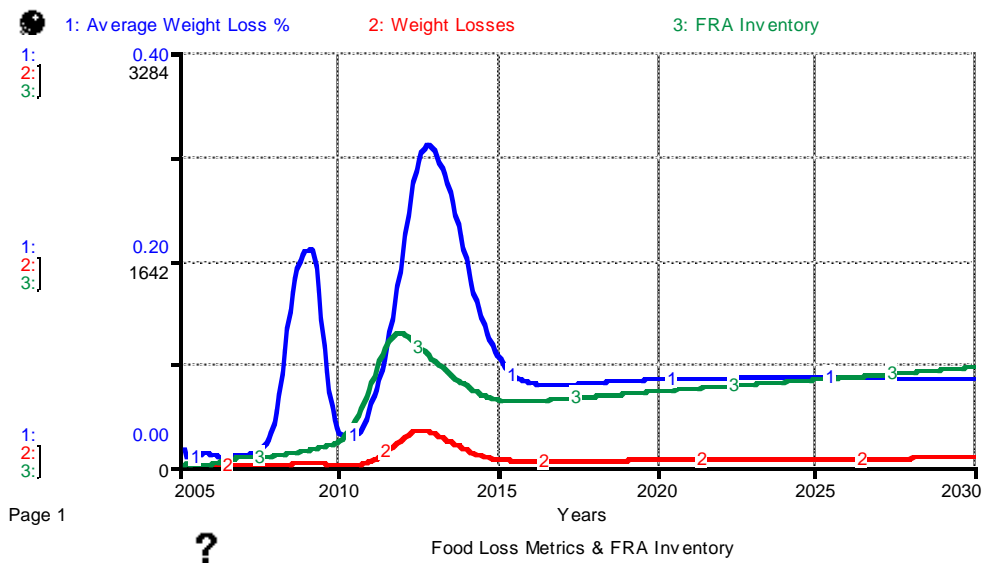
- The capacity budget grows at the same pace as purchases; at a 7% per year rate.

As general considerations:

- The behavior of all parameters before 2012 is the same for both scenarios; changes in the assumptions come into effect after this year. All of the major effects of the change in parameters come after year 2015.

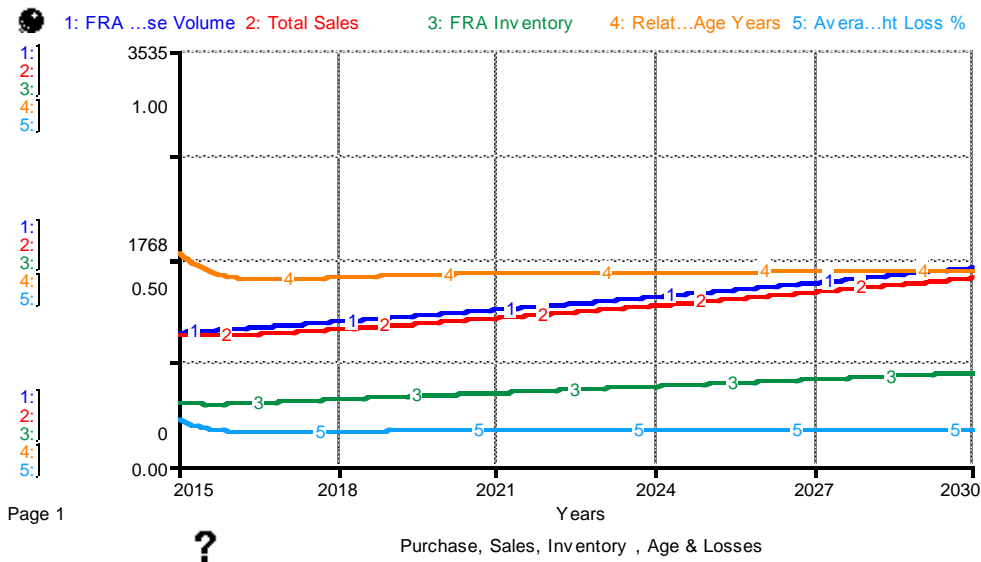
## 6.2 Base Scenario (2.7% growth Scenario)

This scenario portrays the decision of mimicking population growth as a strategy in terms of growth management within the FRA. The idea of this scenario is testing what would happen in terms of weight losses during storage, given that the FRA doesn't expand its activities in comparison to the expected growth in the available markets. It is clear though, that the purchasing decisions of the FRA has an influence on the overall agricultural industry, and as such the conclusions drawn from this analysis should be taken with caution and always considering the implications and assumptions of both the model and the scenario design (Chapter 6, Section 6.1 & Chapter 3, Section 3.1). It is also clear that the FRA purchasing decisions and market behavior in general are most likely to be part of a complex feedback process that also includes production levels; this feedback process is not considered since it is out of the scope of this model.



**Figure 31: Food Loss Metrics & FRA Inventory (2.7% Scenario)**

Figure 31 shows the most important variables to be tracked and which will serve as the reference point in the assessment of possible policy options. The behavior of these variables is self-explanatory; after the year 2015 weight losses stabilize at a level of approximately 9%. This stabilizing effect is explained by the behavior of the main variables driving inventory age (figure 32):

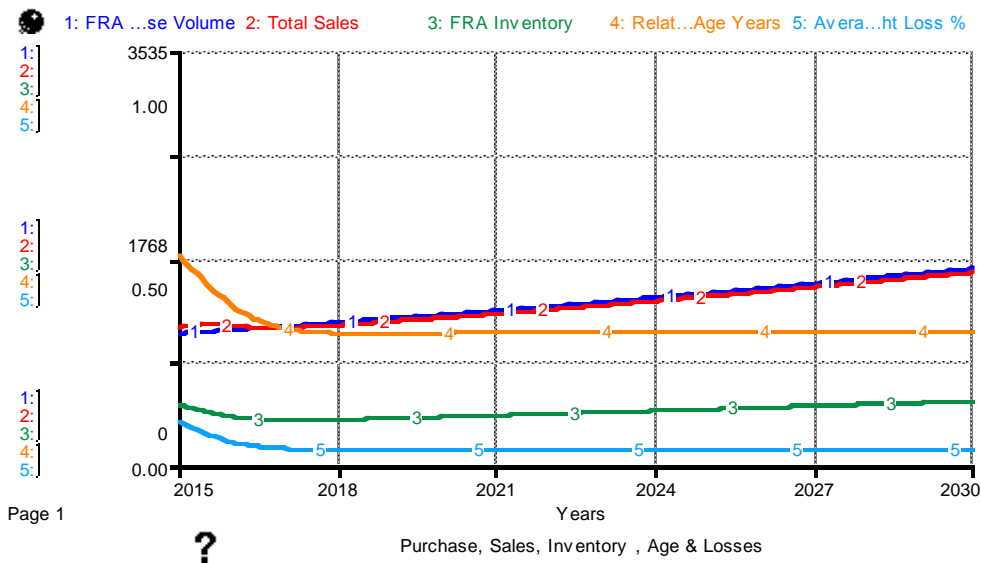


**Figure 32: Purchases, Sales, Inventory, Age and Losses (2.7% Scenario)**

Since the total sales allowed by the market closely match the FRA purchase volume and grow at the same rate over time, the FRA inventory stabilizes. This specific level of average inventory (set by the reserve size) and total sales, cause the relative age of the inventory to also stabilize. As seen in figure 31 relative age stabilization causes the level of weight losses to also stabilize at a 9% value.

As a possible policy option for this specific scenario, a first idea would be to test the possible impact of reducing the desired reserve size. The idea this test is to close the apparent small gap between purchases and sales since closing the gap between these curves would increase inventory rotation, and as such reduce inventory age and weight losses in general.

Figure 33 shows the results of reducing the reserve size from the normal three months to two months.



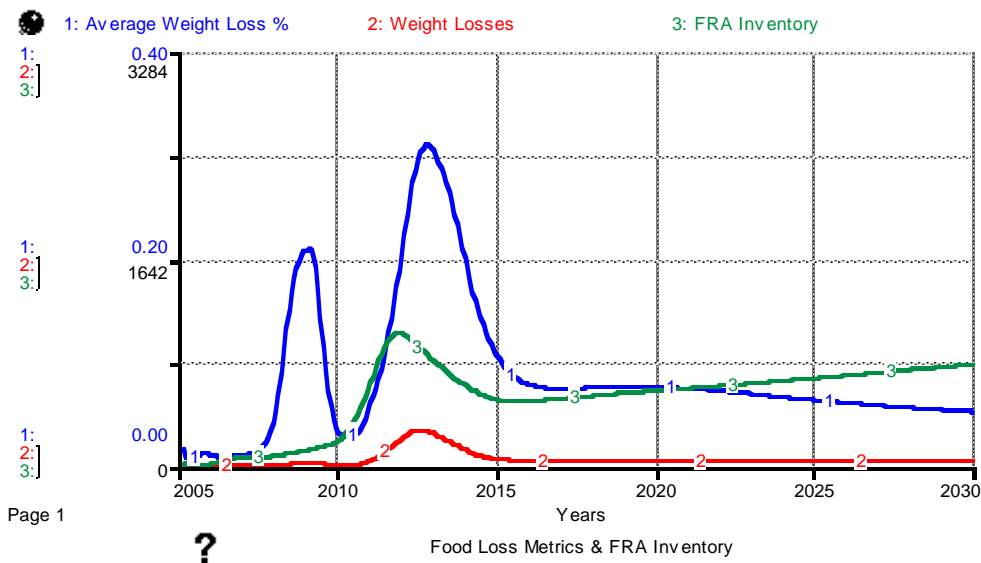
**Figure 33: Purchases, Sales, Inventory, Age and Losses (2.7% Scenario Policy 1)**

By closing the gap between purchases and total sales, inventory rotation is maximized and inventory age stabilizes at a new level which is defined by the new desired reserve size; this leads to lower levels of weight losses of about 4%.

What this implies in terms of implementation might strike as unrealistic; it implies that purchases can be done all throughout the year and that sales can be done in the same fashion; this two conditions would stand as prerequisites in order to achieve an inventory rotation of two months. Achieving such a high level of inventory rotation is both unfeasible, when considering the seasonal nature of maize focused agriculture in Zambia, and inconvenient, as it would not permit control over prices by managing seasonal inventory releases. Even if such a policy wouldn't result in the simulated benefits, it still provides a valuable conceptual lesson behind: reducing the size of the reserves would make possible higher inventory rotation, which would cause average inventory age to be diminished and as consequently achieve lowers weight loss levels. As a side note, by the way the reserve size is modelled it can be reinterpreted as the desired average inventory over a year, not as a purchase target per se.

This first tested policy option addressed one of the main components of weight losses: inventory age. Now the specific capacity investment decision will be changed in order to address the other factor affecting weight losses: storage method. This specific policy option will simulate a shift in the attribution of investments from sheds to silos. The current assumption is that 91% of investments go to shed capacity buildup and 9% to silos. The current policy change will invert the investment choice, attributing 90% of

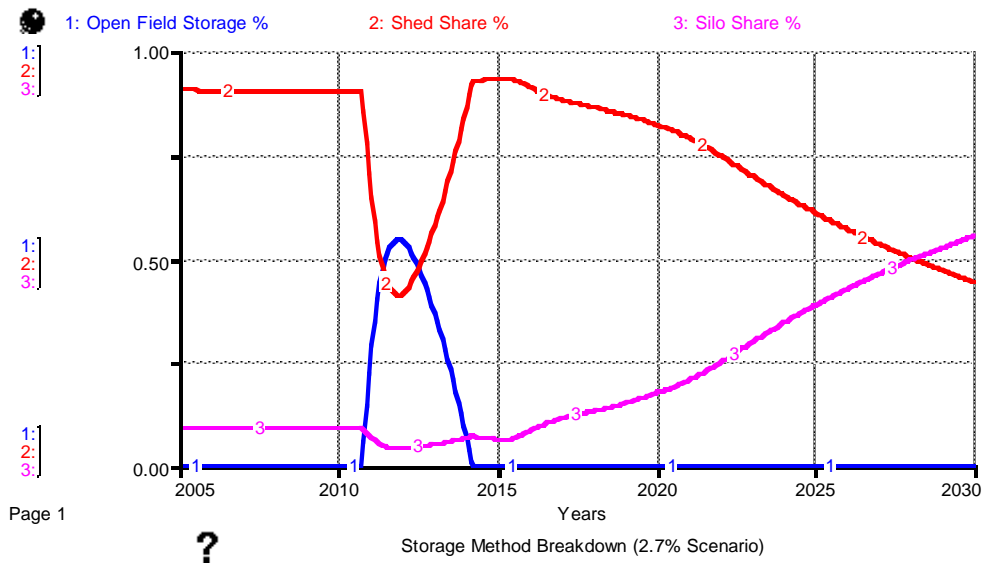
capacity investments to silos and 10% to sheds. The simulation results of this policy change can be seen in figure 34.



**Figure 34: Food Loss Metrics & FRA Inventory (2.7% Scenario Policy 1)**

What this policy causes is to set weight losses to a lower average level by enabling more silo capacity. Silo storage weight losses are assumed be close to constant over time (about 2%). This constant and low expected losses in silos are evidently a superior alternative when comparing them to the alternative exponentially rising over time losses in polypropylene bags treated with Actellic Super (up to 80% maximum losses). This policy change causes weight losses to slowly decrease, reaching a value of 5% in year 2030. This decrease should continue until capacity reaches its steady state of 90% of overall capacity (set by a 90% to silo investment policy).

This policy change has a strong long term focus since the assumed lifetime of storage capacity is set to 20 years. Even if today’s investments focus is drastically switched to silos, shed capacity wouldn’t be discarded until its lifetime expires. Even with such an aggressive shift in investment preference the bettering of storage technology materializes 6 years after the implementation of the policy. Figure 35 shows the share of the different possible storage methods development over time. The benefits of the policy start when the silo share of total capacity reaches 21% in year 2021.



**Figure 35: Storage Method Breakdown (2.7% Scenario Policy 2)**

When comparing this policy to the previously designed one, advantages are evident. Storage method choice is independent of seasonality and does not imply constant sales or purchases. One possible challenge when facing implementation resides in the fact that the necessary switch from bag storage to bulk storage might face smallholder resistance since they would have to adapt to bulk storage and transportation, and challenges for the FRA in terms of inventory management and control as polypropylene bags permit easier handling, counting and transportation.

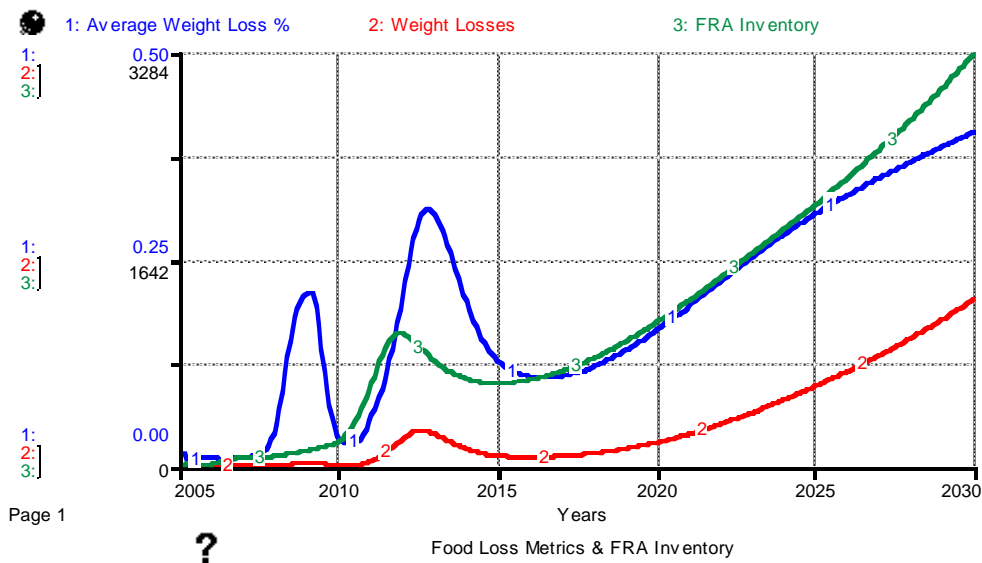
Another possible source of implementation resistance might be that in the short run silo capacity requires higher initial financial disbursements. This resistance could be reduced by performing a cost benefit analysis such as the one carried out by De Groote and Kimenju (2010). This cost benefit analysis proved the long run economic benefits of silo storage over other storage methods.

Again, regardless of specific challenges in implementation the conceptual lesson from testing this policy is valuable: improving storage technology by investing in silos will, in the long run, result in lower weight losses.

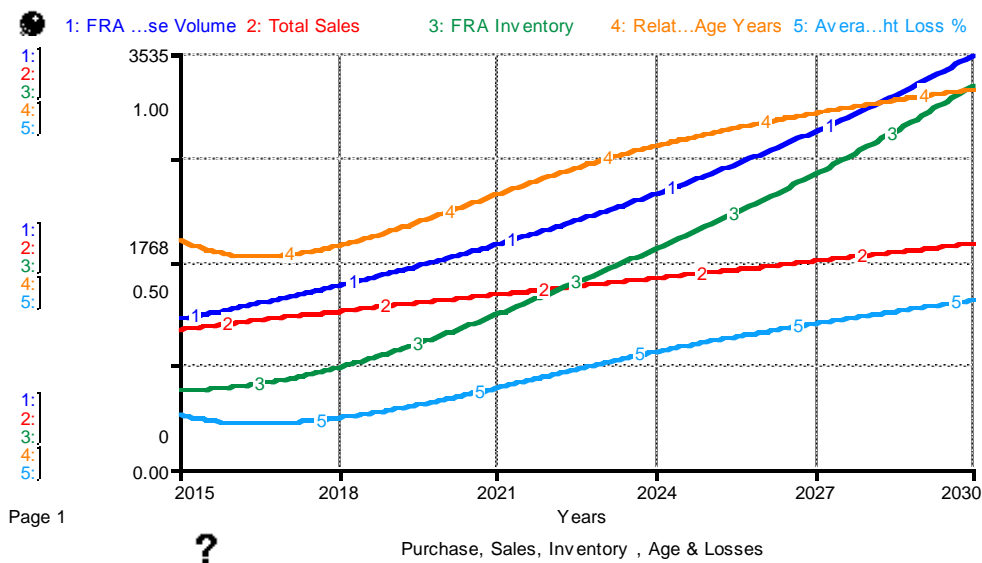
### 6.3 Desired economic growth scenario (7% growth Scenario)

This scenario portrays the decision of mimicking the Agricultural sector's expected growth as a strategy in terms of growth management within the FRA. This scenario implies that the agricultural sector in Zambia would grow mainly through increases in

production volumes of maize at a 7% per year rate. As a reaction to this growth the FRA would opt for trying maintaining its dominant position in the maize market by also increasing its purchases by 7% each year. This scenario depicts a situation in which the agricultural sector expansion happens at a faster rate than domestic and foreign consumption patterns (2.7% assumed growth rate). As can be seen in figure 36 and figure 37 this situation results in increasing stocks of maize, increasing the average age in the inventory (from .55 to .92 years) and overall increases in weight losses during storage (from 13% to 41%) since the product since markets get saturated.



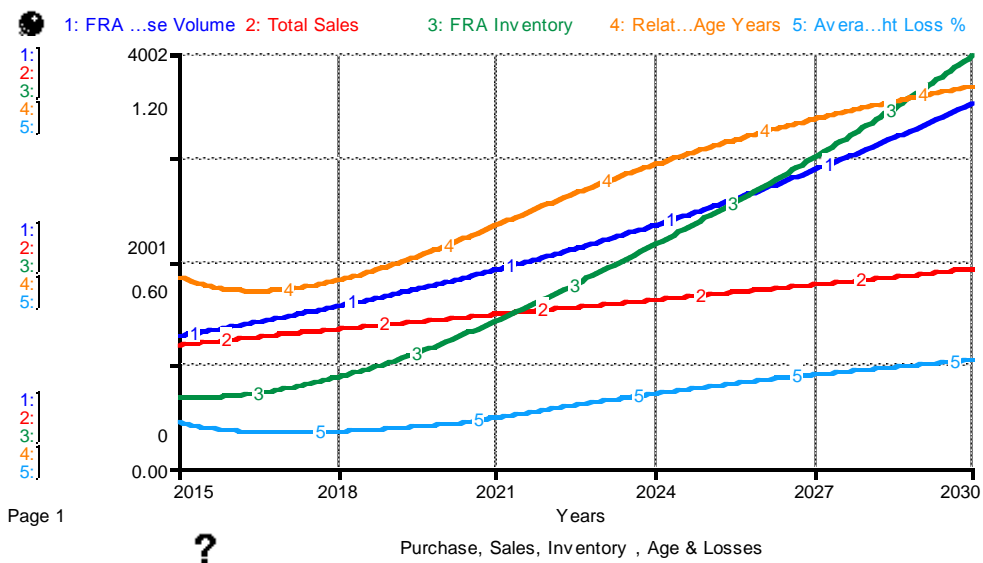
**Figure 36: Figure 37: Food Loss Metrics & FRA Inventory (7% Scenario)**



**Figure 38: Purchases, Sales, Inventory, Age and Losses (7% Scenario)**

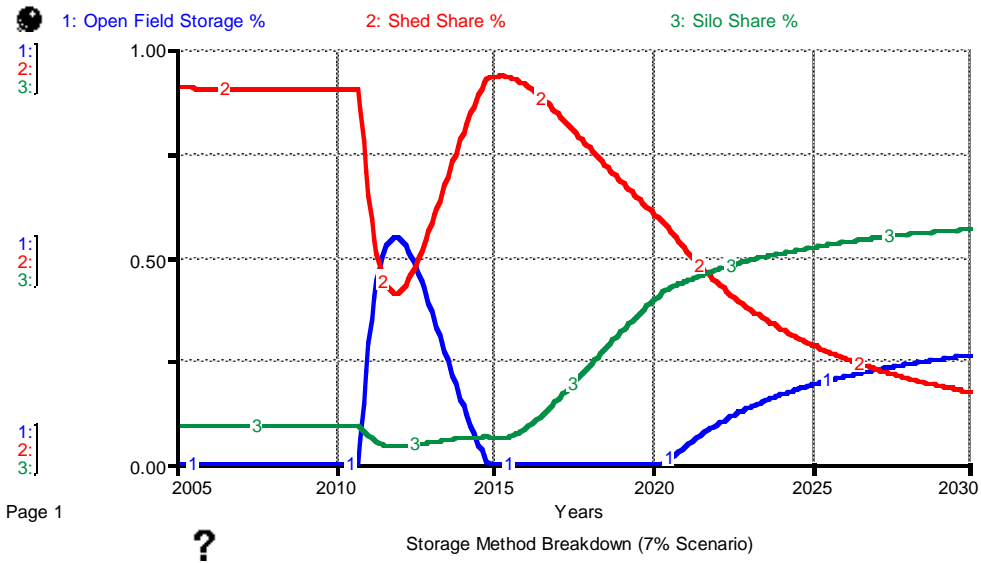
In this specific case reducing the reserve size is not a very useful option since the reason behind the accumulation of inventory comes from the limited availability in markets (both domestic as foreign) compared to the purchases volumes and hence the inventory. The results of reducing the reserves size to one month worth of national consumption (as an attempt to enable higher rotation) were tested, resulting in almost identical results to the base run and hence will not be discussed.

The idea of switching storage technologies from a shed majority to a silo majority was also tested and the simulation results can be seen in figure 38.

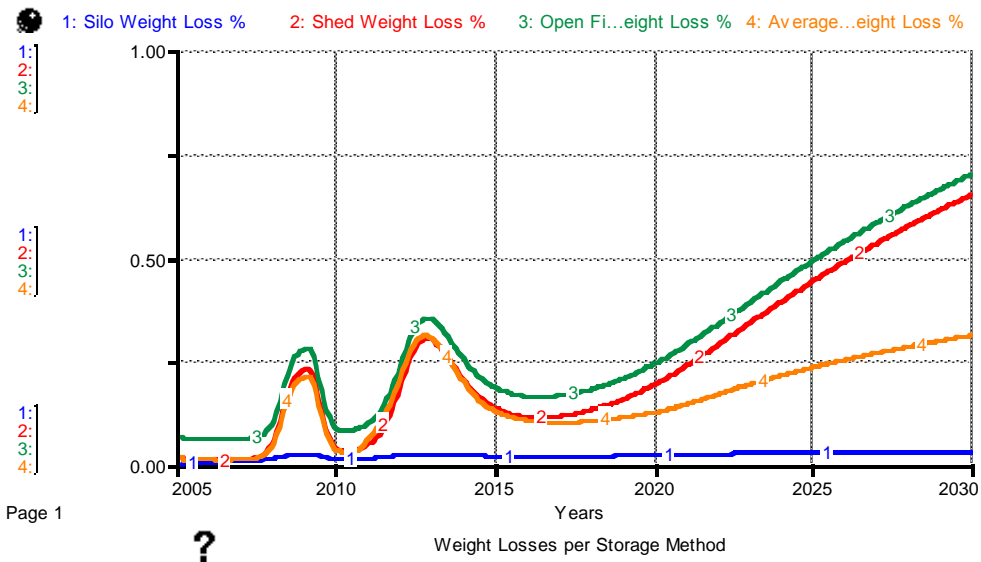


**Figure 39: Purchases, Sales, Inventory, Age and Losses (7% Scenario Policy 1)**

Again the investment in silo storage proved valuable in terms of average weight losses reduction, but to a lesser extent than in the previous scenario (2.7% scenario). The reason for this difference is quite simple: the great increase in inventory levels causes the reemergence of open field storage since the assumed budget increases are insufficient to provide enough storage capacity at a fast enough pace. The share of capacity share between the different storage methods can be seen in figure 39 and the specific weight losses per storage method in figure 40.



**Figure 40: Storage Method Breakdown (7% Scenario Policy 1)**

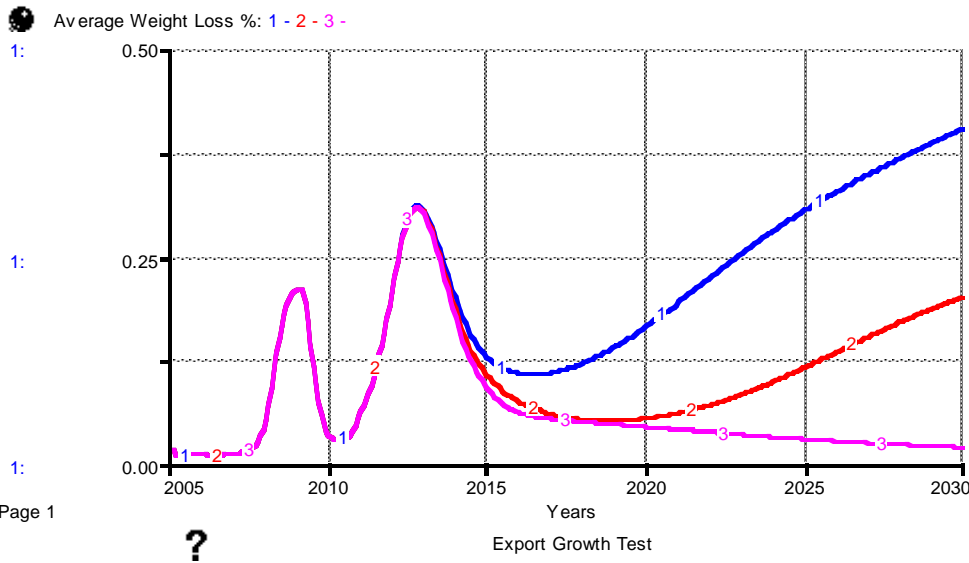


**Figure 41: Weight Losses per Storage Method (7% Scenario)**

This scenario, with its current core assumptions on budget growth as well as in foreign market growth leaves very small room for action. What must be understood though, is firstly that the assumption of a 2.7% growth in foreign markets is highly uncertain and secondly that in such a scenario of limited export markets follow, an increase in purchases will certainly result in high levels of maize losses.

In order to overcome the uncertainty around growth in export markets this assumption will be modified so as to test different export market growth rates. Figure 41 shows the simulation results of three new assumed growths rates for the export markets available to the FRA.

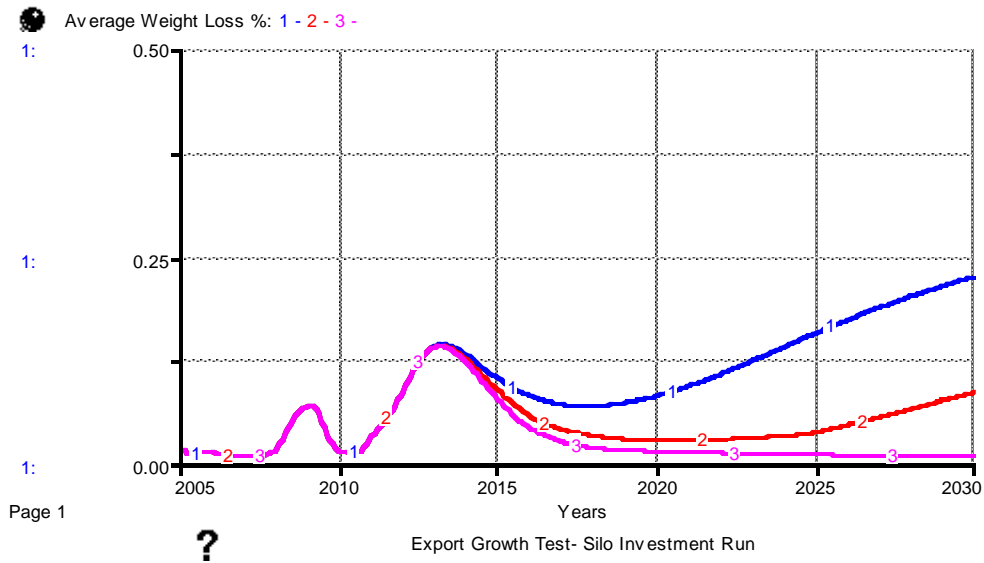




**Figure 42: Export Growth Test (2.7%, 7% and 10% Scenarios)**

Simulation run 1 assumes a 2.7% growth rate in exports and results in a final 41% weight loss rate, run 2 assumes a 7% growth rate in exports and results in a final 21% weight loss rate and run 3 assumes a 10% growth rate in exports and results in a 2% weight loss rate. This change in the scenario implies that the FRA would be in a sufficiently good position to take advantage of those spaces in the market. Being able to seize this kind of opportunities in a globalized market with high levels of competition in the international agricultural environment would not be easy. It is known that crop yields in Zambia are rising, but are still far below the international benchmarks and still below those of regional competitors such as South Africa. Even if space is available in future export markets the question is, can Zambia become a regionally competitive in order to meet these markets? This practical limitation though, does not change the fact that weight losses are mostly driven by inventory rotation, a factor that must be cautiously considered if the national agricultural strategy is to foster production growth, a situation that will lead to excessive maize surplus, since the only source of maintaining healthy rotation levels would be through exports.

Finally a switch from shed to silo investment will be tested as a possible policy option in order to test its result in these three different export market growth scenarios. In figure 43 we can see the results of such simulation runs.



**Figure 43: Export Growth Test- Silo Investment Run**

The first run assuming a 2.7% growth on export markets results on a 23% average weight loss of maize, the second run assuming 7% growth on export markets results on a 9% average weight loss of maize and the third run assuming a 10% growth rate on export markets results in a 1% average weight loss of maize. The benefit of switching storage technologies is evident as it nearly halves the expected average losses in all of the scenarios.

After analyzing a situation that reflects the achievement of the currently plotted national strategy on agricultural development, a strategy that aims at increasing production levels (by an assumed 7%) of maize on an already saturated domestic market, the lesson this policy test leaves is as simple as it is powerful: on a domestic saturated market, the only option to avoid storage losses is exporting the maize to where it can be consumed. Another interesting finding is that there are great benefits in switching storage technologies from sheds to silos in such a saturated market, since average losses are almost halved.

On final word that cannot be stressed enough regarding policy design/analysis through the use of the current model: the simulation results of this model must be taken with great caution since the practical implications of policy change are vast and its consequences cannot be fully reflected by it, and as such, further and detailed research and analysis should be carried out before taking them into action.

## **Chapter 7: Conclusions**

### **7.1 Answer to Research Questions**

Chapter 1 served as an introduction to the Food Reserve Agency (FRA) case in Zambia, motivated its importance and served as means to focus on one of its major pressing issues, storage losses of maize. This chapter also introduced the research objective and research questions that would be addressed by this thesis. To summarize, the objective of this thesis project was to provide a tool that could describe the causal mechanisms driving the maize loss phenomena in the FRA and that could also be used to identify and assess possible policy leverage points in order to mitigate the effects and risks inherent in such mechanisms.

Chapter 2 focused on describing the existing literature and was focused on providing an answer to the first research question (What causal mechanisms/theories are described in the existing maize loss during storage literature?). This chapter provided a detailed explanation of the current status of both the sub-Saharan cereal postharvest loss literature and the FRA case specific literature. It was through the work that led to the writing of this chapter that the biological mechanisms resulting in weight losses of maize during storage were understood and later translated into a stock and flow diagram. As a concrete answer to research question one: the mechanisms causing weight losses of maize during storage described in literature can be integrated as a function of storage method (risk dimension) and storage time (risk exposure dimension). It was through the work portrayed in this chapter that the specific case of the FRA was also summarized in terms that could appropriately represent those two previously mentioned driving factors (storage method and storage time/inventory age). As these two mechanisms were integrated in a causal loop diagram (CLD) described in Chapter 3, several macro mechanisms (feedback loops) were found, most of them describing goal seeking behavior. Through a re-interpretation of these macro mechanisms (feedback loops) from a benchmarking perspective, possible policy leverage points were identified. Such leverage points included: in the idea of redirecting investments to silo capacity buildup (reducing storage risk), changing the reserve size and fostering export markets (both reducing risk exposure).

As the causal mechanisms/theories driving maize losses during storage were identified and understood, and a clear picture of the FRA situation was generated, these two components were integrated into a system dynamics simulation model. Chapter 3 also explained in detail how these mechanisms interact with each other, as well as explicitly stated the assumptions supporting the model. This chapter provided an answer to the second and third research questions: 2. - How can these mechanisms be integrated into a coherent and consistent framework? And 3. - How can these mechanisms be quantified for the specific case of the FRA in Zambia? To summarize the answer in a very broad sense, it is proposed that these mechanisms can be appropriately integrated and quantified for the Zambian case, in a coherent and consistent framework, through a system dynamics simulation model.

Once a system dynamics simulation model was built, Chapter 4 and 5 established its validity and provided strengthened confidence both in its qualitative and quantitative results. This strengthened confidence was supported by the coherent and consistent manner in which the key variables of the model such as maize losses, inventory levels, storage capacity, sales and inventory age were related to each other and the simulation of these key components resulted in adequate behavior (both in scale and pattern) when compared that available for comparison in the real system. These two chapters also served as validation to the answer of research questions 2 and 3, as they evidenced the appropriateness of using a system dynamics model to integrate and quantify the causal mechanisms relating maize losses during storage and the specific characteristics of FRA case.

Finally, Chapter 6 through the delimitation of two different possible scenarios evaluated possible policy options that could reduce or mitigate the risk of high maize losses for the FRA in the future. These policies were evaluated in terms of their resulting maize loss outcomes and briefly discussed the possible implications of the implementation of such policies. This chapter aimed at answering the fourth research question addressed by this thesis: What alternative strategies or management practices can contribute to mitigating future maize losses during storage given the specific case of the FRA? In this regard the answer can be given along the line of the two main fundamental causal mechanisms leading of maize losses during storage: inventory age and storage method. As such, a viable option under a scenario of non-saturated markets (domestic or foreign); the FRA could opt for reducing its reserve size (or the average inventory under

a reserve status) and hence increase their inventory rotation through increased average releases and hence reduce the average storage losses. Under both a non-saturated and a saturated local market scenario, one effective line of action was identified in the shifting of storage technologies from sheds to silos. This option nearly halved the expected average losses by year 2030 in the saturated market scenario by reducing the total risk factor to which maize is exposed by placing it on silos instead of sheds (silos present constant losses over time, sheds exponentially rising). This policy option is a safe and sound step the FRA could take in the direction financial sustainability, as silo storage has proven economically beneficial in the longer run (De Groote & Kimenju, 2010). As mentioned in chapter 6 the main concern regarding the implementation of such a policy would be the initial disbursements required to build up silo capacity and the required operational challenges for smallholder farmer of abandoning the relatively convenient propylene bag; this analysis stands as possible future work. Another viable (although relatively trivial) option under such a scenario and the only fundamental solution towards achieving competitive levels of maize loss during storage was found to be achieving sufficient exports growth.

## **7.2 Limitations and Further Work**

The limitations of the current research effort as well as the suggested future work in the topic are:

1. The utilized curves relating maize weight losses during storage and storage time are neither Zambia nor FRA specific. Measurements over time of the specific weight losses of maize within the different storage methods available to the FRA would further refine the model and provide it with enhanced specificity since they would capture the specific risk factors under which maize is stored in the FRA.
2. While purchase volumes strongly influence the behavior of the system, they were not endogenously modelled. Expanding the boundaries of the model so as to include the purchasing decisions in the FRA and its effects on the maize market and production, would prove of great value in further identifying and assessing leverage points leading the FRA to a more sustainable path.
3. The current research effort based the unknown decision rules within the FRA on robust assumptions or best available data. All data sources regarding FRA

related variables were distilled from literature, newspapers or magazine articles. Inside access to the FRA, their records and mental models would prove invaluable in terms of validating these assumptions and the results of their simulation.

4. The current level of aggregation of the simulation model is adequate for pinpointing structural or fundamental leverage points (at a conceptual level); it does not permit for precise estimates that could lead to the design of policies that could be carried into action. Disaggregating and detailing this model by adding seasonality and/or spatial considerations would be a necessary step to follow in this regard.
5. As further work, a cost benefit analysis of the proposed policies could be carried out. The idea of such an analysis would be on determining the possible financial and food security benefits and costs associated to the identified potential policies.
6. Along the lines of a scenario portraying surplus production of maize, storage losses (and their cost) would represent a key component in the cost feedback mechanisms influencing pricing and hence influencing possible exports. Uncovering and analyzing the causal mechanism relating storage losses costs, their relationship to exports pricing and hence export viability is another possible line of future work that could help better understand the prerequisites to the achievement of the so longed goal of becoming the regions breadbasket.

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# Appendix A: Stock and Flow Diagram (Complete View)

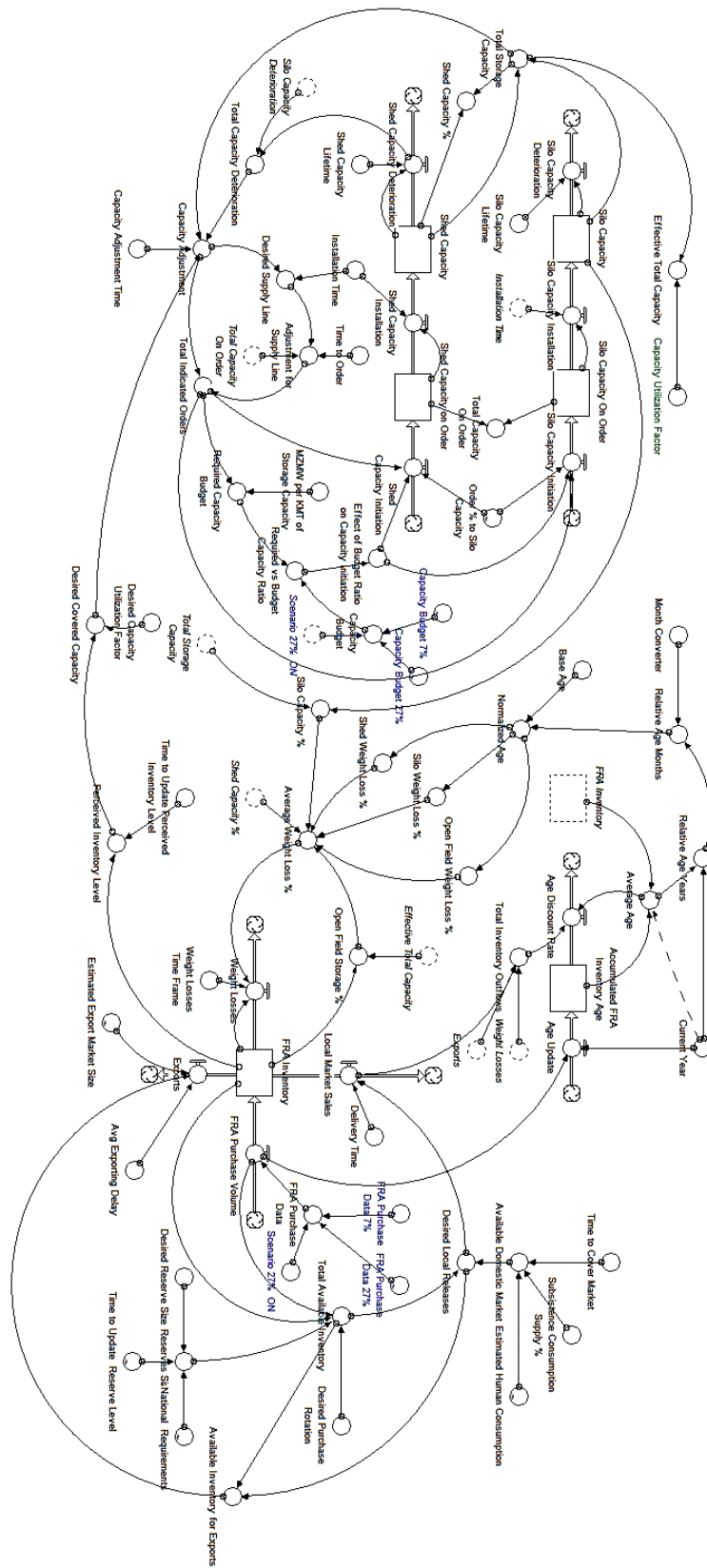


Figure 44: Stock and Flow Diagram (Complete View)

## Appendix B: Calculation of Analytic Functions for Weight Losses Estimation

Reference	A	B	Average (A, B): Shed Losses	C : Silo Losses
Month	Weight loss as % of total stored	Weight loss in sample, %	Weight loss in sample, %	Weight loss in sample, %
1	1.00%	0.43%	0.72%	0% **
2	2.00%	1.22%	1.61%	0.28%
3	3.00%	0.65%	1.83%	0.81%
4	5.00%	3.93%	4.47%	0.82%
5	8.00%	5.00%	6.50%	0.83%
6	12.00%	8.24%	10.12%	1.36%
7	18.00%	11.93%*	14.97%	1.66%*
8	25.00%	16.21%*	20.61%	1.86%*
9	32.54%*	21.17%*	26.86%	2.04%*
10	41.37%*	26.81%*	34.09%	2.20%*
11	51.30%*	33.13%*	42.22%	2.34%*
12	62.33%*	40.13%*	51.23%	2.46%*
13	74.46%*	47.81%*	61.14%	2.56%*
14	87.69%*	56.17%*	71.93%	2.64%*
15	102.02%*	65.21%*	83.62%	2.70%*
16	117.45%*	74.93%*	96.19%	2.74%*
17	133.98%*	85.33%*	109.66%	2.76%*
18	151.61%*	96.41%*	124.01%	2.76%*

\* Regression Calculated Value

\*\* Modified value

**Figure 45: Weight Losses over Time (Analytic Functions Calculation)**

### Sources:

**A:** Harris & Lindblad (1976, Ch. VIII, Table VI, p 137) – example figures

**B:** De Groote et al (2013, table 2) – Polypropylene and Actellic Super treatment

**C:** De Groote et al (2013, table 2) – Metal Silo and No treatment

### Regression equations and R-squared:

**A:**  $0.0055x^2 - 0.0162x + 0.0257$ , R-squared: .9979

**B:**  $0.0034x^2 - 0.0082x + 0.0101$ , R-squared: .9599

**Average (A, B):**  $0.0045x^2 - 0.0122x + 0.0177$ , R-squared: 1

**C:**  $-.0001x^2 + .0035x - 0.003$ , R-squared: 0.9011

### Calculation process:

As a first step to arrive to the specific shed and silo weight loss analytic functions, quantified results of weight loss over time were searched in the available literature. These estimates were then subjected to a second order polynomial regression, since it provided the best r-square match. The results of this regression provided specific analytic functions depicting the relationship between time and weight losses. These equations were extrapolated to calculate further values. For the case of shed losses, new weight losses were calculated through the average of the two curves that could be appropriately related to the Zambian case. For the case of silos, the relationship found in De Groote et al (2013) was the only appropriate available curve. This curve's first value was modified so as to eliminate the artificial infestation effect on the calculation of the regression curve. In the final version of the model the constant value of the regression is omitted as part of the calibration process (it does not make conceptual sense to have negative losses when product lifetime is too low). Although being the result of an artificially infested experiment, the curves found in De Groote et al (2013) were deemed as appropriate, since the three sites in which these tests were carried out, presented very different levels of infestation. These levels of infestation can be seen figure 3 of such paper (De Groote et al, 2013). As to why the values used for calculating the shed analytics were averaged with those numbers found in Harris & Lindblad (1976), the major reason was simply to consider other estimates of food loss over time. This stands as an opportunity area since both curves are neither Zambia nor FRA specific. The scope of the current project and the available resources couldn't justify obtaining these estimates from any other source than literature.

The lower and upper limits found in Affgonon et al (2015, table 5) served as reference points in order to qualitatively asses the resulting behavior of the model.

## Appendix C: List of Equations

Accumulated\_FRA\_\_Inventory\_Age(t)=Accumulated\_FRA\_\_Inventory\_Age(t-dt)+Age\_Update - Age\_Discount\_Rate) \* dt

INIT Accumulated\_FRA\_\_Inventory\_Age = init(FRA\_Inventory)\*init(Current\_Year)

### INFLOWS:

Age\_Update = FRA\_Purchase\_Volume\*Current\_Year

### OUTFLOWS:

Age\_Discount\_Rate = Total\_Inventory\_Outflows\*Average\_Age

FRA\_Inventory(t) = FRA\_Inventory(t - dt) + (FRA\_Purchase\_Volume - Local\_Market\_Sales - Weight\_Losses - Exports) \* dt

INIT FRA\_Inventory = 10  
**INFLOWS:**  
FRA\_Purchase\_Volume = FRA\_Purchase\_Data  
**OUTFLOWS:**  
Local\_Market\_Sales = Desired\_Local\_Releases/Delivery\_Time  
Weight\_Losses=FRA\_Inventory\*Average\_Weight\_Loss\_%/Weight\_Losses\_\_Time\_Frame  
Exports=min(Available\_Inventory\_for\_Exports/Avg\_Exporting\_Delay,Estimated\_Export\_Market\_Size/Avg\_Exporting\_Delay)  
Shed\_Capacity(t)=Shed\_Capacity(t-dt)+(Shed\_Capacity\_Installation-Shed\_Capacity\_Deterioration) \* dt  
INIT Shed\_Capacity = 623.7\*.91  
**INFLOWS:**  
Shed\_Capacity\_Installation = Shed\_Capacity\_on\_Order/Installation\_Time  
**OUTFLOWS:**  
Shed\_Capacity\_Deterioration = Shed\_Capacity/Shed\_Capacity\_\_Lifetime  
Shed\_Capacity\_on\_Order(t)=Shed\_Capacity\_on\_Order(t-dt)+ (Shed\_\_Capacity\_Initiation - Shed\_Capacity\_Installation) \* dt  
INIT Shed\_Capacity\_on\_Order = 64.37\*.91  
**INFLOWS:**  
Shed\_\_Capacity\_Initiation = If time<2015 then  
Total\_Indicated\_Orders/Effect\_of\_Budget\_Ratio\_on\_Capacity\_Initiation -2.81 else  
Total\_Indicated\_Orders\*(1-  
Order\_%\_to\_Silo\_\_Capacity)/Effect\_of\_Budget\_Ratio\_on\_Capacity\_Initiation  
**OUTFLOWS:**  
Shed\_Capacity\_Installation = Shed\_Capacity\_on\_Order/Installation\_Time  
Silo\_Capacity(t)=Silo\_Capacity(t-dt)+(Silo\_Capacity\_Installation-Silo\_Capacity\_\_Deterioration) \* dt  
INIT Silo\_Capacity = 623.7\*.09  
**INFLOWS:**  
Silo\_Capacity\_Installation = Silo\_Capacity\_On\_Order/Installation\_Time  
**OUTFLOWS:**  
Silo\_Capacity\_\_Deterioration = Silo\_Capacity/Silo\_Capacity\_\_Lifetime  
Silo\_Capacity\_On\_Order(t) = Silo\_Capacity\_On\_Order(t - dt) + (Silo\_Capacity\_Initiation - Silo\_Capacity\_Installation) \* dt  
INIT Silo\_Capacity\_On\_Order = 64.37\*.09  
**INFLOWS:**  
Silo\_Capacity\_Initiation=If time<2015 then 2.81 else  
Order\_%\_to\_Silo\_\_Capacity\*Total\_Indicated\_Orders/Effect\_of\_Budget\_Ratio\_on\_Capacity\_Initiation  
**OUTFLOWS:**  
Silo\_Capacity\_Installation = Silo\_Capacity\_On\_Order/Installation\_Time

#### **AUXILIARY VARIABLES AND EXTERNAL PARAMATERS**

Adjustment\_for\_Supply\_Line=(Desired\_Supply\_Line-  
Total\_Capacity\_\_On\_Order)/Time\_to\_Order  
Available\_Domestic\_Market = Smth1(Estimated\_Human\_Consumption\*(1-  
Subsistence\_Consumption\_\_Supply\_%),Time\_to\_Cover\_Market,0)  
Available\_Inventory\_for\_Exports = if(Desired\_Local\_Releases<=0) then 0 else  
Total\_Available\_Inventory-Desired\_Local\_Releases  
Average\_Age=IF FRA\_Inventory<=0.00 THEN Current\_year ELSE  
Accumulated\_FRA\_\_Inventory\_Age/FRA\_Inventory  
Average\_Weight\_Loss\_% = Open\_Field\_Storage\_%\*Open\_Field\_Weight\_Loss\_%+(1-  
Open\_Field\_Storage\_%)\*(Silo\_Capacity\_%\*Silo\_Weight\_Loss\_%)+(1-  
Open\_Field\_Storage\_%)\*(Shed\_Capacity\_%\*Shed\_Weight\_Loss\_%)

Avg\_Exporting\_Delay = 1  
 Base\_Age = 1  
 Capacity\_Adjustment = max((Desired\_Covered\_Capacity - Total\_Storage\_\_Capacity) / Capacity\_Adjustment\_Time + Total\_Capacity\_Deterioration, Total\_Capacity\_Deterioration)  
 Capacity\_Adjustment\_Time = 1  
 Capacity\_Budget\_27% = GRAPH(TIME)(2005, 21.0), (2006, 28.0), (2007, 47.0), (2008, 70.0), (2009, 99.0), (2010, 130), (2011, 139), (2012, 145), (2013, 149), (2014, 153), (2015, 157), (2016, 161), (2017, 166), (2018, 170), (2019, 175), (2020, 179), (2021, 184), (2022, 189), (2023, 194), (2024, 200), (2025, 205), (2026, 211), (2027, 216), (2028, 222), (2029, 228), (2030, 234)  
 Capacity\_Budget\_7% = GRAPH(TIME)(2005, 21.0), (2006, 28.0), (2007, 47.0), (2008, 70.0), (2009, 99.0), (2010, 130), (2011, 139), (2012, 145), (2013, 155), (2014, 166), (2015, 178), (2016, 190), (2017, 203), (2018, 218), (2019, 233), (2020, 249), (2021, 267), (2022, 285), (2023, 305), (2024, 327), (2025, 349), (2026, 374), (2027, 400), (2028, 428), (2029, 458), (2030, 490)  
 Capacity\_Utilization\_Factor = 0.75  
 Capacity\_\_Budget = if time > 2013 then (if Scenario\_27%\_\_ON=1 then Capacity\_Budget\_27% else Capacity\_Budget\_7%) else Capacity\_Budget\_7%  
 Current\_Year = GRAPH(TIME)(2005, 2005), (2030, 2030)  
 Delayed\_Delivery\_Time = delay1(FRA\_Inventory/Total\_Inventory\_Outflows, 1, 0)  
 Delivery\_Delay = FRA\_Inventory/Total\_Inventory\_Outflows  
 Delivery\_Time = 1  
 Desired\_Capacity\_Utilization\_Factor = 0.52  
 Desired\_Covered\_Capacity = Perceived\_Inventory\_Level/Desired\_Capacity\_Utilization\_Factor  
 Desired\_Local\_Releases = Min(Available\_Domestic\_Market, Total\_Available\_Inventory)  
 Desired\_Purchase\_\_Rotation = 1  
 Desired\_Reserve\_Size = 3/12  
 Desired\_Supply\_Line = Capacity\_Adjustment\*Installation\_Time  
 Effective\_Total\_Capacity = Capacity\_Utilization\_Factor\*Total\_Storage\_\_Capacity  
 Effect\_of\_Budget\_Ratio\_on\_Capacity\_Initiation = If Required\_vs\_Budget\_Capacity\_Ratio <= 1 then 1 else Required\_vs\_Budget\_Capacity\_Ratio  
 Estimated\_Export\_Market\_Size = GRAPH(TIME)  
 (2005, 200), (2006, 200), (2007, 200), (2008, 200), (2009, 200), (2010, 229), (2011, 500), (2012, 500), (2013, 514), (2014, 527), (2015, 542), (2016, 556), (2017, 571), (2018, 587), (2019, 603), (2020, 619), (2021, 635), (2022, 653), (2023, 670), (2024, 688), (2025, 707), (2026, 726), (2027, 746), (2028, 766), (2029, 786), (2030, 808)  
 Estimated\_Human\_Consumption = GRAPH(time)  
 (2005, 1283), (2006, 1290), (2007, 1319), (2008, 1370), (2009, 1442), (2010, 1536), (2011, 1652), (2012, 1791), (2013, 1839), (2014, 1889), (2015, 1940), (2016, 1992), (2017, 2046), (2018, 2101), (2019, 2158), (2020, 2216), (2021, 2276), (2022, 2338), (2023, 2401), (2024, 2466), (2025, 2532), (2026, 2601), (2027, 2671), (2028, 2743), (2029, 2817), (2030, 2893)  
 FRA\_Inventory\_Data = GRAPH(TIME)  
 (2011, 630), (2012, 917), (2013, 597)  
 FRA\_Purchase\_Data = if time > 2013 then (if Scenario\_27%\_\_ON=1 then FRA\_Purchase\_Data\_27% else FRA\_Purchase\_Data\_7%) else FRA\_Purchase\_Data\_7%  
 FRA\_Purchase\_Data\_27% = GRAPH(TIME)  
 (2005, 79.0), (2006, 390), (2007, 396), (2008, 74.0), (2009, 199), (2010, 879), (2011, 1752), (2012, 1046), (2013, 1074), (2014, 1103), (2015, 1133), (2016, 1164), (2017, 1195), (2018, 1227), (2019, 1260), (2020, 1294), (2021, 1329), (2022, 1365), (2023, 1402), (2024, 1440), (2025, 1479), (2026, 1519), (2027, 1560), (2028, 1602), (2029, 1645), (2030, 1689)  
 FRA\_Purchase\_Data\_7% = GRAPH(TIME)  
 (2005, 79.0), (2006, 390), (2007, 396), (2008, 74.0), (2009, 199), (2010, 879), (2011, 1752), (2012, 1046), (2013, 1119), (2014, 1197), (2015, 1281), (2016, 1371), (2017, 1467), (2018,



1570), (2019, 1679), (2020, 1797), (2021, 1923), (2022, 2057), (2023, 2201), (2024, 2356),  
 (2025, 2520), (2026, 2697), (2027, 2886), (2028, 3088), (2029, 3304), (2030, 3535)  
 Installation\_Time = 2  
 Inventory\_Allocation\_Policy\_Validation = (Total\_Availabe\_\_Inventory\_Val-Reserves\_Size)-  
 Desired\_Local\_Releases-Available\_Inventory\_for\_Exports  
 Inventory\_Net\_Flow = FRA\_Purchase\_Volume-Total\_Inventory\_Outflows  
 Month\_Converter = 12  
 MZMW\_per\_KMT\_of\_\_Storage\_Capacity = 0.864  
 National\_Requirements = GRAPH(TIME)  
 (2005, 1906), (2006, 1936), (2007, 2028), (2008, 2005), (2009, 2101), (2010, 2254), (2011,  
 2414), (2012, 2474), (2013, 2541), (2014, 2609), (2015, 2680), (2016, 2752), (2017, 2827),  
 (2018, 2903), (2019, 2981), (2020, 3062), (2021, 3144), (2022, 3229), (2023, 3316), (2024,  
 3406), (2025, 3498), (2026, 3592), (2027, 3689), (2028, 3789), (2029, 3891), (2030, 3996)  
 Normalized\_Age = Relative\_Age\_Months/Base\_Age  
 Open\_Field\_Storage\_% = max((FRA\_Inventory-Effective\_Total\_Capacity)/FRA\_Inventory,0)  
 Open\_Field\_Weight\_Loss\_% = 0.0045\*Normalized\_Age\*Normalized\_Age -  
 0.0122\*Normalized\_Age  
 +0.0177 +.05  
 Open\_Field\_\_Share\_% = Open\_Field\_Storage\_%  
 Order\_%\_to\_Silo\_\_Capacity = GRAPH(Time)  
 (2005, 0.00), (2006, 0.09), (2007, 0.09), (2008, 0.09), (2009, 0.09), (2010, 0.09), (2011, 0.09),  
 (2012, 0.09), (2013, 0.09), (2014, 0.09), (2015, 0.09), (2016, 0.09), (2017, 0.09), (2018, 0.09),  
 (2019, 0.09), (2020, 0.09)  
 Perceived\_Inventory\_Level =  
 SMTH1(FRA\_Inventory,Time\_to\_Update\_Perceived\_Inventory\_Level,0)  
 Relative\_Age\_Months = Relative\_Age\_Years\*Month\_Converter  
 Relative\_Age\_Years = Current\_Year-Average\_Age  
 Required\_Capacity\_\_Budget =  
 Total\_Indicated\_Orders\*MZMW\_per\_KMT\_of\_\_Storage\_Capacity  
 Required\_vs\_Budget\_Capacity\_Ratio = Required\_Capacity\_\_Budget/Capacity\_\_Budget  
 Reserves\_Size =  
 smth3(National\_Requirements\*Desired\_Reserve\_Size,Time\_to\_Update\_\_Reserve\_Level,0)  
 Scenario\_27%\_\_ON = 0  
 Shed\_Capacity\_% = Shed\_Capacity/Total\_Storage\_\_Capacity  
 Shed\_Capacity\_\_Lifetime = 20  
 Shed\_Share\_% = (1-Open\_Field\_\_Share\_%)\*Shed\_Capacity\_%  
 Shed\_Weight\_Loss\_% = 0.0045\*Normalized\_Age\*Normalized\_Age -  
 0.0122\*Normalized\_Age+0.0177  
 Silo\_Capacity\_% = Silo\_Capacity/Total\_Storage\_\_Capacity  
 Silo\_Capacity\_\_Lifetime = 20  
 Silo\_Share\_% = (1-Open\_Field\_\_Share\_%)\*Silo\_Capacity\_%  
 Silo\_Weight\_Loss\_% = -0.0001\*Normalized\_Age\*Normalized\_Age+ 0.0035\*Normalized\_Age  
 Storage\_Capacity\_Data = GRAPH(TIME)  
 (2005, 624), (2006, 641), (2007, 658), (2008, 675), (2009, 692), (2010, 709), (2011, 726),  
 (2012, 743), (2013, 784), (2014, 825), (2015, 866)  
 Subsistence\_Consumption\_\_Supply\_% = 0.56  
 Time\_to\_Cover\_Market = 5  
 Time\_to\_Order = 1  
 Time\_to\_Update\_Perceived\_Inventory\_Level = 1  
 Time\_to\_Update\_\_Reserve\_Level = GRAPH(5)  
 (2005, 5.00), (2012, 0.00)  
 Total\_Availabe\_\_Inventory\_Val=  
 FRA\_Inventory+FRA\_Purchase\_Volume\*Desired\_Purchase\_\_Rotation  
 Total\_Available\_Inventory=  
 Max(FRA\_Inventory+FRA\_Purchase\_Volume/Desired\_Purchase\_\_Rotation-Reserves\_Size,0)

Total\_Capacity\_Deterioration = Shed\_Capacity\_Deterioration+Silo\_Capacity\_\_Deterioration  
Total\_Capacity\_\_On\_Order = Silo\_Capacity\_On\_Order+Shed\_Capacity\_on\_Order  
Total\_Indicated\_Orders = Adjustment\_for\_Supply\_Line+Capacity\_Adjustment  
Total\_Inventory\_Outflows = Local\_Market\_Sales+Exports+Weight\_Losses  
Total\_Sales = Exports+Local\_Market\_Sales  
Total\_Storage\_\_Capacity = Silo\_Capacity+Shed\_Capacity  
Total\_\_Estimated\_Market\_Size= Available\_Domestic\_Market+Estimated\_Export\_Market\_Size  
Weight\_Losses\_\_Time\_Frame = 1  
zero\_line = 0

## **Appendix D: Simulation Model**

Please refer to the annexed iThink file.

## **Appendix E: Parameter database**

Please refer to the annexed Excel file.tede