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Scenario Analysis for Supply Chain Management of Milled Grain Products in South Africa: A System Dynamics Approach

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ABSTRACT

This study aimed to identify the interactions between the sub-systems of the supply chain system of milled grain products, in South Africa, namely: (1) farming (agricultural); (2) transport (transportation); (3) manufacturing (milling); and (4) trade (retail). Furthermore, this paper investigated how these sub-systems are affected by economic and natural external factors namely: (1) the exchange rate between ZAR and USD; (2) the price of international crude oil; and (3) climate change and/or droughts. For this purpose, system dynamics (SD) model was developed and used, which enabled to accommodate the system components and factors influencing the performance of the supply chain system of milled grain products. The SD model runs demonstrated the interdependent relationships among the four sub-systems of the supply chain of milled grain products. Furthermore, the simulation results and scenario analysis showed the impact of the three external factors on the overall performance of the milled grain supply chain and its four sub-systems in terms of the availability and utilization of farming land, grain yield, transportation costs, milling costs, retail costs and farming profits.

Keywords: *crude oil price, distribution, drought, exchange rate, farming, grain products, manufacturing, milling, retailing, simulation, supply chain, system dynamics*

1. INTRODUCTION

The most consumed milled grain products in South Africa and in most Africa are maize, wheat, rice, and stamp. These four products are consumed by the most population of South Africa and Africa as major staple foods (Macauley and Ramadjita, 2015). Maize, also called corn, is a major staple food crop and one of the most malleable crops in the world, especially in underprivileged countries in Africa (Bibiana *et al*., 2014). Internationally, 60% to 70% of maize production is used to feed livestock, and the remaining 30% to 40% is used to produce items for human consumption such as maize meal, mealie rice and stamped maize (called Samp) (Gwirtz and Garcia, 2014). Wheat is the primary component of bread (Bibiana *et al*., 2014). The consumption of bread in South Africa is steadily increasing because it can be an easily prepared and instantly consumable (Bibiana *et al*., 2014). Composite flour technology (which mixes wheat with other cereals and legumes) has many benefits, including the creation of higher quality food products. Over the past 20 years, wheat consumption has been progressively increasing in all African countries. Rice has become a highly strategic and priority commodity for food security in Africa. Consumption is growing faster than that of any other major staple on the continent because of high population growth, rapid urbanization and changes in eating habits (Diagne *et al*., 2013). Although local efforts to expand rice production, a key problem facing the rice sector in Africa in general is that local production has never caught up with demand. The continent, therefore, continues to rely on import to meet its increasing demand for rice (Macauley and Ramadjita, 2015).

The continuous increase in population raises a need for expanding the production of milled grains. For example, the population of South Africa is doubled over the last thirty years from 30 million in 1990 to approaching 60 million nowadays (Stats SA, 2021). However, the expansion of crops production is not following the same increasing profile. For example, maize production tended to increase through the last thirty years, which doubled during the 1990 - 2020 period ending at 17,000 thousand tons in 2020 compared with 8,600 thousand tons in 1990 (Agricultural Statistics, 2021 and Agri SA, 2021). However, South African maize production fluctuated substantially over the last decade. **Figure 1** illustrates the gradual increase in the population of South Africa in comparison to the fluctuated profile of the maize production in South Africa. This finding raises an urgent need for not only to expand the maize production, but also for perfect management of the supply chain of milled grain products.

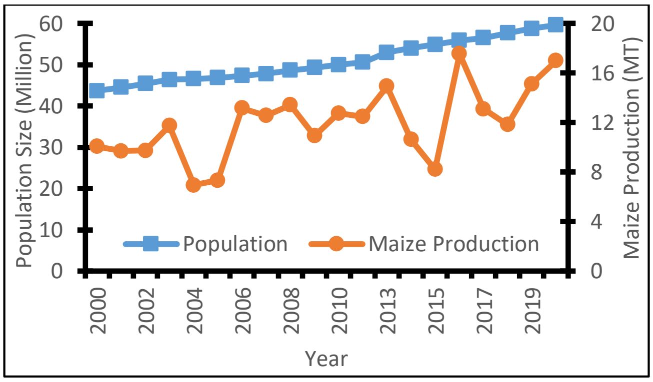

Figure 1 Mize production vs population size in South Africa 2000–2020

The supply chain of milled grain products is a complicated system. It compromises of four sub-systems, namely: Farming, Transportation, Milling/Manufacturing and Retail. A system dynamics (SD) model for the whole system was developed with a set of four sub-models, where a sub-model is developed for each corresponding sub-system in the whole supply chain of milled grain products. First, the farming sub-model estimates yield (tons of crop produced per hectare per year), farmland availability (hectare per year), and farming profitability (cash inflows and outflows). Furthermore, it investigates and traces the interrelationships and any correlations between yield, farming profitability and land availability. Second, the transportation sub-model estimates all transport costs – from the farmers to manufacturing facilities, from manufacturing to retail, import transportation costs, etc. Third, the manufacturing sub-model includes two sources of grain namely, grain produced by local farming and grain imports. Thus, the manufacturing sub-model considers transforming both locally produced and imported grain to manufacturing plants, adds other manufacturing costs, and estimates an average manufacturing cost. Fourth, the retail sub-model processes the manufacturing inputs together with transportation and retail-related cost factors to estimate retail cost per ton.

Beyond the critical need for improved maize production efficiency and milled grain supply chain management in South Africa, the literature identifies additional academic challenges of equal importance demanding our attention. The following key factors underscore the necessity and motivation for this present study.

First, current Supply Chain Management research often lacks a strong regional focus, particularly in developing countries (Adhim and Mulyono, 2023). Second, research specifically addressing Supply Chain Management challenges in the Middle East and Africa regions remains scarce (Gurrala and Hariga, 2022).

Third, a review of existing literature reveals a prevalence of research on generic food chains, highlighting a significant gap in research focused specifically on agri-food chains (Gurrala and Hariga, 2022). This emphasizes the critical need for future studies to conduct in-depth investigations aimed at improving the quality and safety of agri-products, like milled grain products.

Fourth, the majority of existing milled grain supply chain management research focuses on individual tiers or, at most, two tiers within the chain (Mansur *et al.*, 2023; Mukhtar and Azhar, 2020). This necessitates a shift towards an integrated approach encompassing all tiers. Such an integrative approach would foster collaboration, coordination, and synergy across the entire supply chain, ultimately leading to the co-creation of unique and inimitable value (Mansur *et al.*, 2023).

Fifth, unlike the majority of existing literature that predominantly focuses on financial aspects and factors, a strong need exists to consider and analyze the supply chain from various perspectives. This extends beyond solely considering financial factors but also encompasses environmental and natural elements that may impact the performance of the entire supply chain system or individual sub-systems (Carvalho *et al.*, 2021; Suryani *et al.*, 2022; Siddh *et al.*, 2017).

The objectives of this study are fourfold: first, to analyze and improve the operational performance of the entire supply chain of milled grain products. This is to be achieved by analyzing the four sub-systems of the supply chain of milled grain products. Second, this study aims to investigate the interrelationships between those four sub-systems in the context of South Africa. Third, this research discovers the impact of the economic and environmental/natural factors that might have an impact on the performance of the entire supply chain system and/or on an individual sub-system. The system behavior was tested against three disturbances or external factors: (1) Drought or variations in climate (natural factor); (2) Rand/Dollar Exchange Rate (economic factor); and (3) International crude Oil Prices (economic factors). Fourth, SD modelling (Forrester, 1994) was utilized to provide a framework in developing supply chain sub-systems and scenarios to improve the system performance. SD simulation model is utilized to simulate and envisage the behavior of the system under a given set of conditions, options and scenarios to establish grounds for decision-making.

The rest of this paper is organized as follows. Section 2 contains a literature review comprising the role of SD modelling in analyzing the milled grain supply chain. Section 3 describes the development of the base model, which consists of the problem formulation, Stock and Flow Diagram (SFD) development, and model formulation. Section 4 describes the development of the scenarios that were simulated, results of the simulation, sensitivity analysis, and discussion. Finally, in Section 5, the conclusion and future research are presented.

2. LITERATURE REVIEW

This section explores the existing applications of SD for supply chain management in milled grain products. First, the previous studies are to be critically discussed. Second, a summary, research gaps and paper contributions are to be presented.

Shegelman *et al*. (2020) categorized the research on supply chain management in any food processing industry into five classes: (1) food plantation, (2) cutting, (3) food transportation to industry, (4) industry for processing, and (5) market. They stated that the supply chain of food processing industry is highly integrated among these five components. In this study, the supply chain system of milled grain products is considered as four macro environments/sectors/sub-systems. The conceptual framework of the system is separated into four sub-systems: farming, milling (manufacturing), transportation and retail (trade), as shown in **Figure 2**. In South Africa, the milled grain products supply chain starts with farming (seeding, followed by planting and finally harvesting). The harvested crop will then be stored and transported for milling (manufacturing) and packaging. After going through the milling process, and through logistics and transportation process, the milled grain products are ready for distribution to wholesalers, retailers and consequently end consumers.

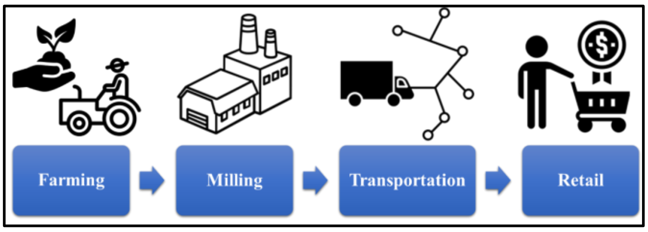

Figure 2 Conceptual network flow of milled grain products supply chain system

On one hand, many studies focused on a(an) single(isolated) sub-system out of the four ones in the milled grain products supply chain system. Fried *et al*. (2018) studied supply chain and local freight flows in USA with specific focus on geographic information system analysis of Minnesota cereal grain movement. They focused on grain products route to market, while highlighting road infrastructure and congested freight corridors as the main challenges. Thus, they tested a policy which aims to study evolving analysis of the geographic information system of industry supply chain actors and local freight flows of Minnesota cereal grain movement. However, their framework focused only on the transportation sub-system.

Hossain and Jahan (2018) investigated the potential causes of poor integration of the rice supply chain in Bangladesh. For that purpose, they conducted both structured and semi-structured questionnaire survey to know the characteristics and the main issues of that system. They explored the potential benefits of reorientation of the informal rice industry into integrated rice and paddy/rice through clustering and grouping into specialised rice industry zone(s). It could be seen that they focused on the milling/manufacturing sub-system. However, they omitted at least the farming, transportation and on-shelf trade sub-systems that make up the entire supply chain.

Chopra *et al*. (2017) investigated the role and relationship among the participating stakeholders in rice supply chain in Chhattisgarh, India. Once they identified stakeholders, they focused on developing relevant performance indicators for each. They studied the supply chain system with a different perspective and focused on stakeholders rather than the sub-systems nor sectors. They didn't develop any model; however they concluded a huge recommendation for model development in the supply chain management in order to examine the implications of economic and environmental factors.

Ambekar *et al*. (2015) developed a two-stage multi-agent-based mapping model for the distribution subsystem for the Indian public distribution system of food grain products from procurement to transportation and distribution process. The paper assessed the entire supply chain, showed the complexity of the system, supported the policy and decision makers with the shortfalls in the system, and suggested strategies for improving the performance of the system. The authors recommended for extending the conceptual mapping model by developing optimization and simulation models that might be helpful in improving the overall performance of the entire system. However, they focused mainly on the distribution/transportation subsystem and completely omitted the farming, milling and retail sub-systems that make up the entire supply chain.

On the other hand, many studies considered two or more sub-systems (out of four) in the milled grain products' supply chain system. Jamaludin *et al*. (2021) developed a SD model for in-depth study of the supply chain system of rice industry in Indonesia. They considered the rice industry supply chain system as a set of actors: (1) farmers who process rice; (2) grain traders; (3) rice traders; (4) rice traders in production areas; and (5) rice traders in urban markets, where each of them has own goal of maximizing solo profits. They tested a policy aimed at maximizing incentives for all the supply chain actors of the rice industry. However, they studied the supply chain system with a different perspective and focused on the farming and milling/manufacturing sub-systems omitting the transportation and on-shelf trade sub-systems that make up the entire supply chain.

Similarly, Suryani *et al*. (2022) developed an SD model aiming to increase farmers' profit and improve the value of the rice supply chain under environmental dynamics. They concluded that the value of the rice supply chain in Indonesia could be increased by implementing a set of strategies such as: (1) increasing the quantity and quality of the crop yield through the use of production, harvesting, and post-harvesting technologies; (2) implementing the Bio-Industry programme through determining the age of the rice crop, milling machine reconfiguration, and the implementation of a softening technology; and (3) supporting farmer empowerment through the development of farmer groups and information sharing. However, they did not consider any environmental/natural factors and aspects that could disrupt the entire supply chain.

Cheraghalipour *et al*. (2019) developed a bi-level mathematical optimization model to minimize total cost for rice supply chain in Iran, which is NP-hard problem. They utilized two-hybrid and modified algorithms based in two well-known meta-heuristic algorithms: Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). They focused only on the farming and transportation sub-systems and omitted the milling and on-shelf trade sub-systems. They highlighted the need for integrating agriculture supply chain with sustainability aspects as a future research direction.

Bala *et al*. (2017) investigated supply chain of rice in Bangladesh starting from the farmers to the consumers. They developed a SD model to analyze the impacts of productivity changes of the seasonal production of rice, lead time and demand variability on the supply chain performance. They mainly aimed for more efficient and sustainable supply chain and to guarantee the availability of rice in an economic manner under uncertainty. They considered the farming, milling and retail sectors; however, they omitted at least the transportation sector which plays a significant role in the entire supply chain. Similarly, Chung (2015) developed a SD model to study the rice industry supply chain in Malaysia. In particular, he utilized the SD model to examine the impacts of removing price controls and the subsidies from the rice milling sector and rice industry in Malaysia. Thus, the model simulated the removal of price controls and subsidies and examined their impacts on rice prices, production, consumption, import, capacity utilization, capital investments, the head rice recovery ratio and the rice self-sufficiency level in Malaysia. However, the model omitted at least the transportation sub-systems.

Jensen *et al*. (2013) adopted an explorative, a single-embedded case study and semi-structured interviews research design of a food supply chain in USA. They mainly were concerned with the implementation of green supply chain innovation aspects. They considered four actors in the food supply chain: a retailer, an industrial bakery, a mill, and a farmer. They highlighted the crucial need to consider different supply chain actors in order to obtain valid and realistic research outcomes. Furthermore, a chain perspective, rather than isolation of one company's perspective, could support green supply chain as a waste can be transformed to a value in another stage of the chain. Similarly, Mena *et al*. (2013) investigated multi-tier supply chain management based on a multiple case study design consisting of: a buyer, supplier and supplier's supplier. They aimed to explore the relationships among the multi-tiers of the supply chain in the UK's food sector.

The most relevant literature is summarised in **Table 1** as shown below. **Table 1** classifies each of those previous studies based on: (1) the sub-systems included; (2) the research method; (3) the modelling approach; (4) the crops considered; (5) the country of the case study; and (6) the main concern of the study. The table highlights that, to the best of our knowledge, the four sub-systems of the supply chain have not been addressed simultaneously together in a single study before. This finding matches the recommendations of Carvalho *et al*. (2021) that a more holistic approach considering all sub-systems of the supply chain needs more interest. Considering all the sub-systems could be beneficial for overcoming the local optimal decision making and overcoming any disruptions and misalignments of the supply chain.

Furthermore, it is worth highlighting that all the SD models were developed for the rice supply chain. Those limitations motivate for developing of SD model for supply chain management in milled grain products. A last important limitation was highlighted by many previous studies, such as, Carvalho *et al*. (2021), Suryani *et al*. (2022) and Siddh *et al*. (2017), that the impact of economic and environmental factors in milled grain supply chain performance should be comprehensively investigated. For example, Carvalho *et al*. (2021) highlighted the need for addressing exceptional weather brought by climate change. Suryani *et al*. (2022) called for building a sustainable supply chain by considering the economic, social, and environmental aspects. Siddh *et al*. (2017) concluded that economic and environment sustainability of the supply chain is a crucial aspect and economic and environmental factors have a major effect on sustainable performance along the entire length of supply chain.

Table 1 Summary of litrature review

Authors	**Supply Chain Subsystems**				**Research Methods**			**Modelling Approach**	**Crops**	**Country**	**Main concern**
	Farming	Milling	Transportation	Retail	Quantitative	Qualitative	Mixed	• System Dynamics (SD) • Mathematical (M) • Conceptual (C) • N.A.			
Jamaludin *et al*. (2021)	✓	✓					✓	SD	Rice	Indonesia	Production & profitability
Suryani *et al*. (2022)	✓	✓		✓			✓	SD	Rice	Indonesia	Production & profitability
Cheraghalipour *et al*. (2019)	✓		✓		✓			M	Rice	USA	Operations & production

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Authors	Supply Chain Subsystems				Research Methods			Modelling Approach	Crops	Country	Main concern
	Farming	Milling	Transportation	Retail	Quantitative	Qualitative	Mixed	• System Dynamics (SD) • Mathematical (M) • Conceptual (C) • N.A.			
Fried *et al*. (2018)			✓			✓		N.A.	All	USA	Transportation costs
Hossain & Jahan (2018)		✓				✓		N.A.	Rice	Bangladesh	Food impact & costs
Bala *et al*. (2017)	✓	✓		✓	✓			SD	Rice	Bangladesh	Food impact
Chopra *et al*. (2017)	✓					✓		N.A.	Rice	India	Food impact
Ambekar *et al*. (2015)			✓				✓	C	All	India	Distribution cost
Chung (2015)	✓	✓		✓	✓			SD	Rice	Malaysia	Price control & subsidy impact
Mena *et al*. (2013)	✓	✓		✓		✓		N.A.	All	UK	Food supply chain
Jensen *et al*. (2013)	✓	✓		✓		✓		N.A.	All	USA	Green supply chain

This paper contributes to the supply chain literature by developing a comprehensive and holistic SD model for the milled grain supply chain. This study considers the four sub-systems of the supply chain of milled grain products and investigates the interrelationships between those four sub-systems in the context of South Africa. The developed SD model enabled to accommodate internal and external factors that influence the milled grain supply chain. The study further discovers the impact of three economic and environmental/natural factors that might have an impact on the performance of the entire supply chain system and/or on an individual sub-system.

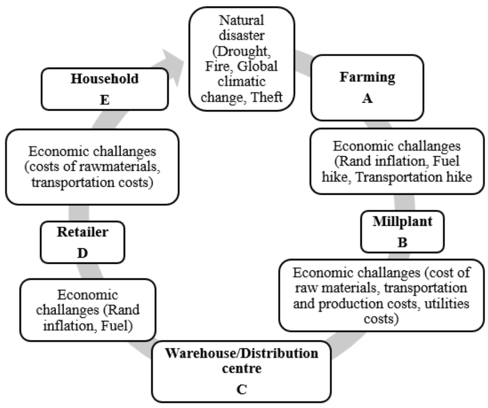

Figure 3 The proposed framework

3. FRAMEWORK AND MODEL DEVELOPMENT

This section demonstrates the development of the proposed SD model including the development of stock and flow diagrams (SFD). SD is an approach to understand the complex and mutual relation between the system components and sub-systems over time using stocks, flows, internal feedback loops, table functions and time delays (Sterman, 2000). Recently, Handaya *et al.* (2022) presented an example for the implementation of System Dynamics simulation approach in Supply Chain Management. In our study, SD was used to simulate and investigate the interrelationships between the sub-systems of milled grain supply chain. The study considered four sub-systems: farming; transportation; milling (manufacturing); and retail (trade), in a computer-based simulation environment using Anylogic® simulation software. This paper adopted four SD sub-models to describe of those four sub-systems in detail. **Figure 3** illustrates the proposed framework with elements and the investigated factors**.**

SFD describes in detail the structure of a system and distinguishes the flows of information and material. This would enable for clear understanding of system behaviour and the parameters that might affect the performance which is vital to an entire supply chain management of milled grain products (Berends and Romme, 2001). Furthermore, a simulation reveals and clarifies factors such as hikes in sub-systems costs (farming cost, transportation cost, manufacturing/milling cost, and retailing cost).

Five SFDs for the milled grain supply chain were developed. First, an SFD was developed and introduced to forecast the value of a main driver variable, i.e., diesel price. Second, four SFDs were developed and introduced for the four sub-systems of the milled grain supply chain considered in this study: farming, transportation, manufacturing and retail.

The model runs in a time unit of a year over 50 years. Therefore, all variables in the model are ***per year*** (*note the time unit is not exclusively stated in the description below, it* *is understood the reader is aware that all variables are per year*). Furthermore, it is important to know that the model does not model any specific crop, for example, corn or wheat. Instead, this is a weighted average of all grain produced. Thus, variables such as seeds used, fertilizer, yield, grain prices, etc., are all weighted average over all grains produced. The parameters and variables used in this paper are summarized in **Table 2**.

Table 2 Notation summary

Notation	Description and or units
fuel_price	The fuel price (units: R/l)
oil_price	The US$-based Brent Crude Oil price (units: $/bbl*)
zar_$	The Rand/US$ exchange rate (ZAR/$) (units: R/$)
oilmax_R	Constant represents the Maximum Brent Crude Oil price in Rand (optional default value: R1100)
oilmin_R	Constant represents the Minimum Brent Crude Oil price in Rand (optional default value: R250)
diesel_max	Constant represents the Maximum Diesel price in Rand (optional default value: R17)
diesel_min	Constant represents the Minimum Diesel price in Rand (optional default value: R11)
fertilizer	Fertilizer used in kg/ha (optional default value: 58.51 kg/ha)
herbicides and pesticides	Herbicides and Pesticides used in kg/ha (optional default value: 4.125 kg/ha)
seeds	Seeds used in kg/ha (optional default value: 12 kg/ha)
climate	An index represents rainfall, where a value of "1" is optimal (the default), less than one is dry (representing drought of varying severity), and larger than 1 are wet conditions.
yield rate	The normal optimal grain yield in ton/ha/crop cycle. If everything (fertilizer, herbicides and pesticides, seeds and climate) is set to their optimal values, this will be the grain produced in a ton, per hectare of land, per crop cycle.
crop cycles per year	The number of crop cycles in a year. If a farmer plants a crop that will be harvested within a few months, the farmer might plant a second crop within the same year.
Seed cost	Cost of seeds in U.S. $/kg.
Fertilizer cost	Cost of fertilizer in $/kg.
Herbicides pesticide cost	Cost of herbicides and pesticides in $/kg.
Crop_labour_ha	The number of workers (labour) employed/used per ha of land in manpower/ha.
Crop_labour_cost	The wages paid per labourer in R/manpower.
Crop fuel consumption	The amount of diesel-fuel used per hectare of land for the crop production cycle, unit's l/ha (litre of fuel per hectare, note annual fuel consumption).
Change_in_land use	This variable could be positive (increase) or negative (decrease) and impacts the farmland "land" variable in ha/time.
Land	The amount of farmland available for grain production in ha.
Farmer_enter_exit rate	This index (in ha/time) depends on "farming_margin" and follows a delay of one year.
Land_exit_sensitivity	This is a tuning parameter for the "farmer_enter_exit rate" variable. It controls the acceleration of farmers exiting farming relative to the anticipated/default rate., i.e., default value of 1, faster (> 1) or slower (< 1).
Max_land	The maximum amount of land available, the default value is 3,400,000 ha (for Gauteng province).
Round trip	Average roundtrip distance, i.e., the truck runs loaded to the plant and empty back. (Default for Manufacturing is 360 km/trip)
Truck efficiency	The number of kilometres the truck gets per litre of fuel. (Default 2.8 km/l)
Tons_per_trip	Number of tons of grain that a truckload will transport. (Default for Manufacturing is 32 tons/trip)
Transportation labour rate	The average rate for transportation worker. (Default R175/h)
Transportation working hours	The number of hours a day that a transportation worker usually works. (Default 9 h/day)
Number of trips	The number of trips per day in trip/day.
Tyres	Averaged cost for tires. (Default R0.33/km)
R & M	Averaged cost for repair, maintenance and insurance. (Default R1.9/km)
Milling cost	This is the total manufacturing cost, in R/ton, including procuring the grain, transport, and non-food input costs.
Average transportation cost	Weighted average transportation cost, in R/ton, for grain including local production as well as imports.
Average crop cost	Weighted average cost for grain (local production and imports) in R/ton.
Import price	The weighted average price for imported grain, in $/ton (note in US $). It is exchanged to Rand using an Exchange Rate of (ZAR/$).
Crop imports	Difference between crop demand and local production amount, in ton/annum. Where Crop demand in ton/year is an input variable to the model that represents the total grain demand for the country's population.
Crop sales price	Price in R/ton, see farming income claculation in section 3.2.2.
Non-food inputs	Non-food inputs costs, in R/ton.

3.1 SFD of Fuel Price Forecasting

Fuel price is a key factor in transportation sub-system and consequently transportation cost. However, fuel cost is a critical factor for other sub-systems as well. Thus, the SFD of fuel price forecasting was developed and presented first.

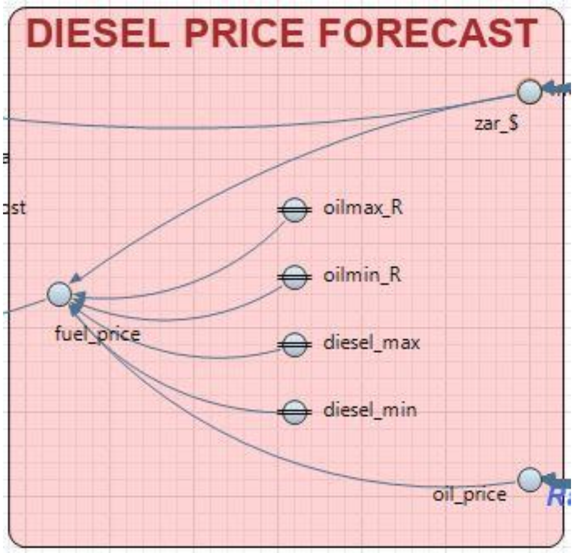

Figure 4 SFD of fuel price forecast

South African fuel prices are a complex combination of an international basket of crudes, the Rand-Dollar exchange rate, and various levies and taxes. As shown in **Figure 4,** for this simulation, the main contributors and drivers of fuel price are the exchange rate and the US$-based Brent Crude Oil price. Based on the developed model, a simplified algorithm was derived to forecast the SA Fuel Price as a function of the exchange rate and oil price, as shown in equation 1. The equation gives a fair estimation of the South African diesel-fuel price in Rand per litre based on the Exchange Rate and Dollar-Oil Price. Generally, an increase in unrefined petroleum value prompts a decline in sales/demand of food; however, not all explanations and result connections happen instantaneous (Williams *et al*., 2015).

$$Feul\ price\ (R/\ell) = \left[\left[\frac{(Oil\ Price\ (\$) \times Exchange\ Rate\ (ZAR/\$)) - OilMIN(ZAR)}{OilMAX(ZAR) - OilMIN(ZAR)}\right] \times [DieselMAX(ZAR) - DieselMIN(ZAR)]\right] + DieselMIN(ZAR) \quad (2)$$

3.2 SFD of Farming

As presented in **Figure 5,** farming sub-model function can be described by understanding the dynamics of three main variables: *Grain Yield* or *Crop Production*, *Income* or *Margin*, and the *Lands* available for farming. Those three variables affect each other in one way or another. The dynamics and the mutual effects of the three variables and the farming sub-system are described in more details in the following three subsections.

3.2.1 Yield – Production of Grain

There are many contributing and driving variables and parameters affecting crop yield, as shown in **Figure 5** (the upper part). Those factors are listed in the nomenclature table above and described using the following equations.

The yield factor is a function in four variables as a multiplication factor using equation 2, where "1" is optimal; any variation from "1" will reduce the yield factor below "1" and therefore reduce the overall Yield. The model looks at the value of *seeds*, *herbicides-and-pesticides*, *fertilizer*, and *climate* individually and determines a yield factor as indicated in the following four **Figures 6-9.** After then, the yield of grain in ton/ha can be estimated based on equation 3. The end grain produced in a ton (per year) can be estimated based on the land available for grain production in ha (hectare) using equation 4.

$$Yield\ factor = Seeds \times Herb\ and\ pesticides \times Fertilizer \times Climate \quad (2)$$

$$Yield = yield\ rate \times yield\ factor \times crop\_cycles\_yr \quad (3)$$

$$Producation = Yield \times land \quad (4)$$

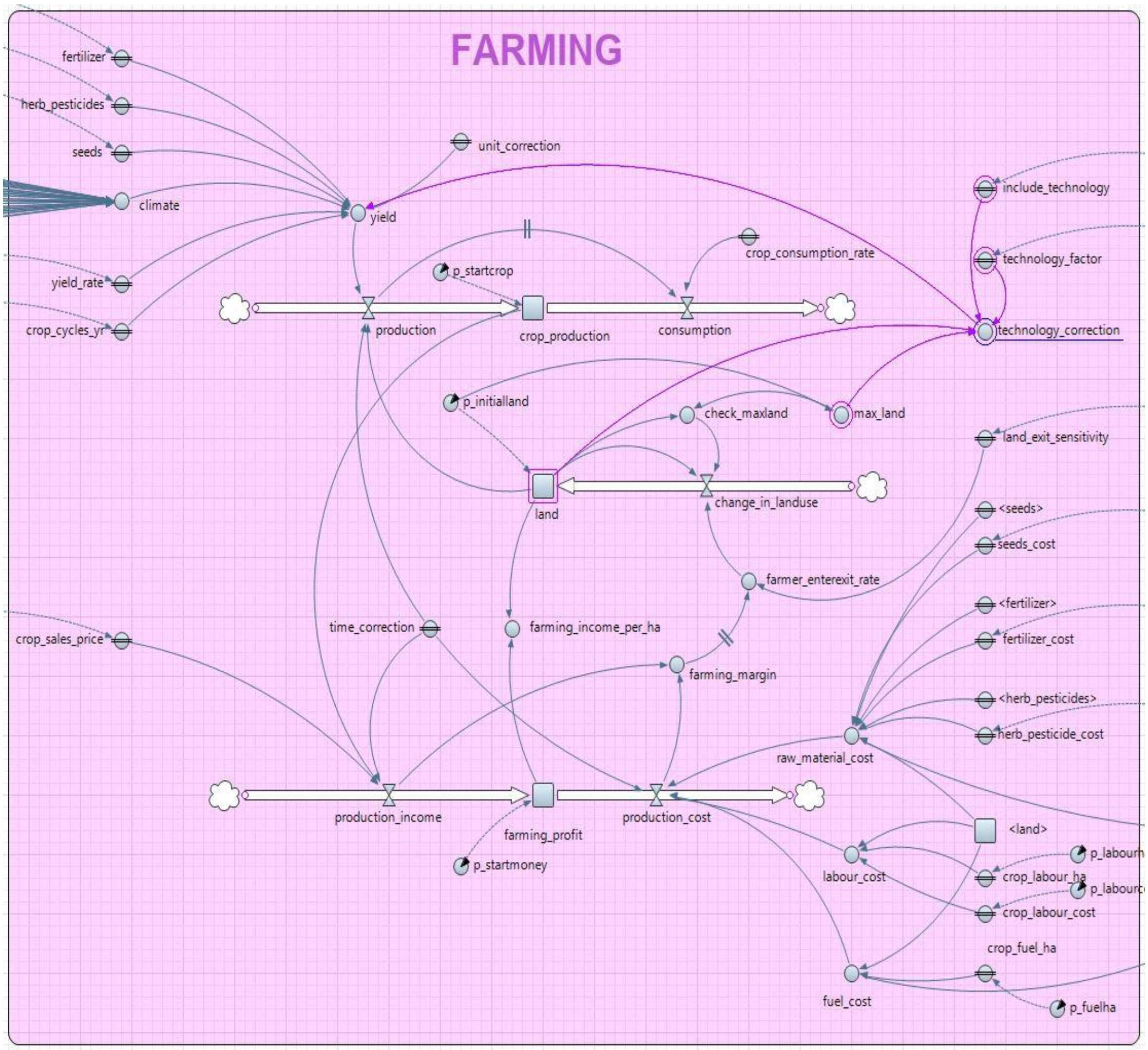

Figure 5 SFD of farming sub-system
(Please ignore lines running into the model across the model boundaries – those are simulation variables added to aid the online model game-mode)

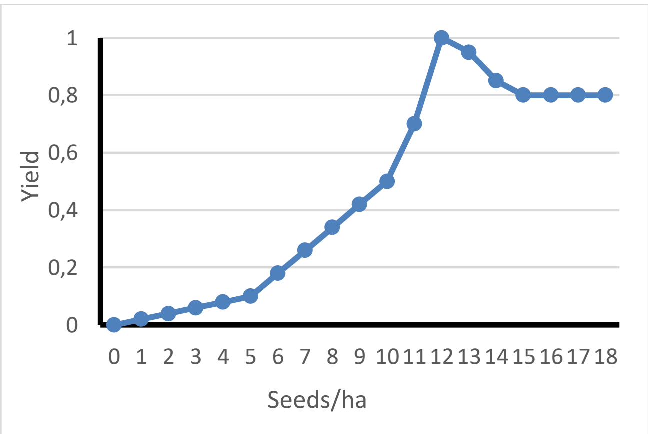

Figure 6 Seed's effect on yield

Technology brings a second potential effect on Yield. Generally, scientific methods and high-tech farmers could harvest more comparing to the low-tech subsistence farmers. When farming margin/profits decline, farmers may exit the business. However, low-tech with low yield farmers struggle and exit earlier. But as they leave, the average farming demand share for farmers that remains in business will increase.

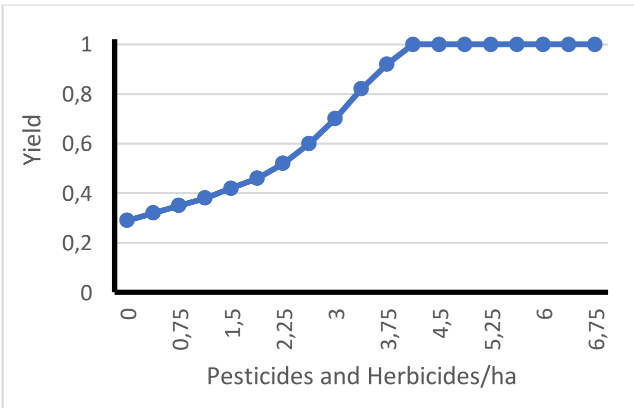

Figure 7 Pesticides' and herbicides' effect on yield

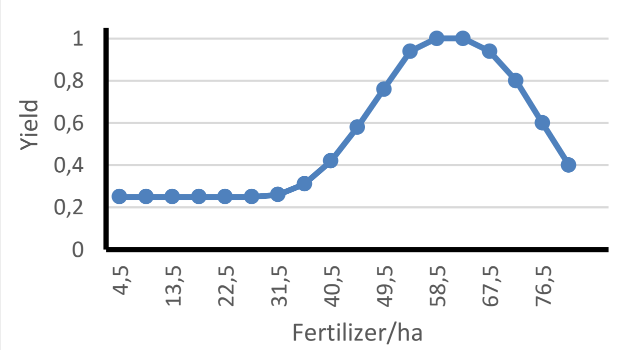

Figure 8 Fertilizer's effect on yield

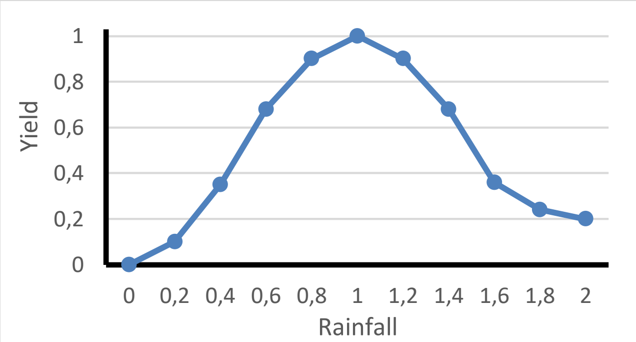

Figure 9 Climate's effect on yield

Through high-tech farming methods used, they might achieve much higher grain yields. Consequently, the remaining farmers make more money per ha, which increases farming profit and balances the farmers abandonment of the farming business.

For example, high-tech farmers use a GIS system to track and analyze the yield per square meter during harvest time. The information is saved according to geological coordinates and during soil preparation for the next cycle the fertilizer addition is automatically adjusted for underperforming areas. The farmer can achieve yields in the range of 16 ton/ha (corn) or more. This high yield/ha comes at high cost and requires large areas of farmland. On the other end of the scale, the subsistence farmer uses virtually no technology and obsolete farming methods to achieve less than 3 ton/ha yield on the same farmland.

Generally, the more the technology penetration in farming, the higher the yield. "technology factor" is used to represent the effect of the entrance of high technology farmers on the yield. In other words, *technology factor* measures the "strength" of the technology correction and the duration it takes for the yield change as the "low-tech" farmers exit the business. When including high technology farmers, *Technology correction* variable can be estimated accordingly as follows:

$$Technology\ correction = \left[\left[\left(\frac{max\_land}{land}\right) - 1\right] \times technology\_factor\right] + 1 \quad (5)$$

Definitely, if there is no change or no high technology included, *technology correction* is considered constant with value of one. Based on the value of *technology correction*, the Yield value is updated as follows:

$$Yield = Previous\ yield \times technology\_correction \quad (6)$$

3.2.2 Farming Cost and Margin

As shown in **Figure 5** (the bottom part), there are many variables that determine and impact farming margin and cost, and consequently farming profits. Farming profit and margin in Rand/annum (R per annum) is a function in the net cash-flow a farmer makes annually (income) and farming sub-system cost. Farming profit and margin can be formulated as follow:

$$Farming\_profit = production\_income - production\_cost \quad (7)$$

$$Farming\_margin = (production\_income) / (production\_cost) \quad (8)$$

Cost items and income terms are described in the following points. Farming income depends on two main variables - the crop production that is defined earlier in the previous subsection and the crop selling price. Crop_sales_price is measured in R/ton. This is the grain selling price in the open market and a farmer has no control over this value. It is determined by supply and demand factors in the market, price speculation, etc. This is the final price the farmer will receive for the grain produced. Production_income measured in Rand/annum (R per annum). This is the income for the farmer from grain production - the grain produced multiplied by the sales price.

$$Production\ Income = crop\ production \times crop\ sales\ price) \quad (9)$$

On another hand, farming cost consists of many cost items that can be summarized in three categories - raw material cost, labour cost and fuel cost. Production_cost is Rand/annum (R per annum) and can be estimated by summing all the cost items. It is important to highlight that it is an estimation of the farmers' running costs only, ignoring assets (farming equipment, maintenance, fixed costs, etc.).

$$Production\ Cost = raw\ material\ cost + labour\ cost + fuel\ cost \quad (10)$$

Where raw material, labour and fuel cost terms can be estimated based on equations (11), (12) and (13), respectively.

$$raw\_material\_cost = [(seeds \times land \times seeds\_cost) + (fertilizer \times land \times fertilizer\ cost) + (herbicides\ and\ pesticides \times land \times herbicides\ and\ pesticides\ cost] \times ZAR/\$ \quad (11)$$

$$labour\_cost = crop\_labour\_ha \times crop\_labour\_cost \quad (12)$$

$$fue\ cost = crop\ fuel\ consumption\ (fuel\ /ha\ ) \times fuel\ price \quad (13)$$

To estimate the profitability of farming, farming_income_per_ha in R/ha was calculated. This shows the net profit per hectare of farmland. This is used to calculate whether farming will be sustainable or not and it impacts the increase/decrease in the farming land discussed in the following subsection.

$$Farming\_income\_per\_ha = farming\_profit/land \quad (14)$$

3.2.3 Land

This part of the model calculates the amount of land that is available for farming and consequently for grain production (the middle part of **Figure 5**). There is an absolute maximum land availability (max_land) representing the upper threshold for the farming land. Where the actual land availability will decrease/increase as the profitability of farming decreases/increases, respectively. When farming margin falls, a reduction of available farmland will occur that causes less production and requires an immense import of grain, reflecting on retail prices. As farming margin increases, the opposite happens. When more farmers enter the farming business, there is an increase in farmland, up to the maximum, and consequently an increase in production. However, it might not be a linear proportional increase, due to the penetration of low-tech farmers to the farming sector with low yield. The change (increase/decrease) in farmland profile is shown in **Figure 10** and can be estimated using the following equation:

$$change\ in\ land\ use = land\ \times farmer\_enter\_exit\_rate \times land\_exit\_sensitivity) \quad (15)$$

Where "Land" cannot exceed the "max_land" amount and to be estimated based on the following equation.

$$land = minimum\ [(previous\ value\ for\ land \times change\ in\ land\ use); max\ land] \quad (16)$$

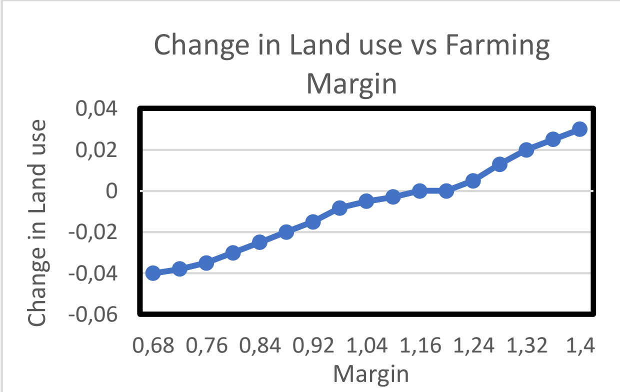

Figure 10 Change in land use versus farming margin

3.3 SFD of Transportation

As presented in **Figure 11**, transportation sub-model considers logistics in three different transactions: from *farmers* to *manufacturing*; from *imports* to *manufacturing* and from *manufacturing* to *retail*. The dynamics and calculations are the same for the three areas; except, the different magnitude of some parameters. For example, average distances for imports to manufacturing plant may be much longer than from farmer to manufacturing plant. Transportation cost for the transaction from *farmers* to *manufacturing* is explained next, where the same can be applied to the other two transportation areas. Transportation cost consists of three cost terms: fuel cost, labour costs and other cost items.

$$Transportation\ cost = fuel\ cost + labour\ cost + other\ cost\ items \quad (17)$$

Fuel cost, per ton, (R/ton) term was calculated based on the following equation where fuel cost is driven from the "Diesel Price Forecast" sub-module, using the Rand/Dollar exchange rate and Brent Crude Oil price.

$$Fuel\ cost = (round\ tip\ /truck\ efficienty) \times (fuel\ price\ /tons\ per\ trip) \quad (18)$$

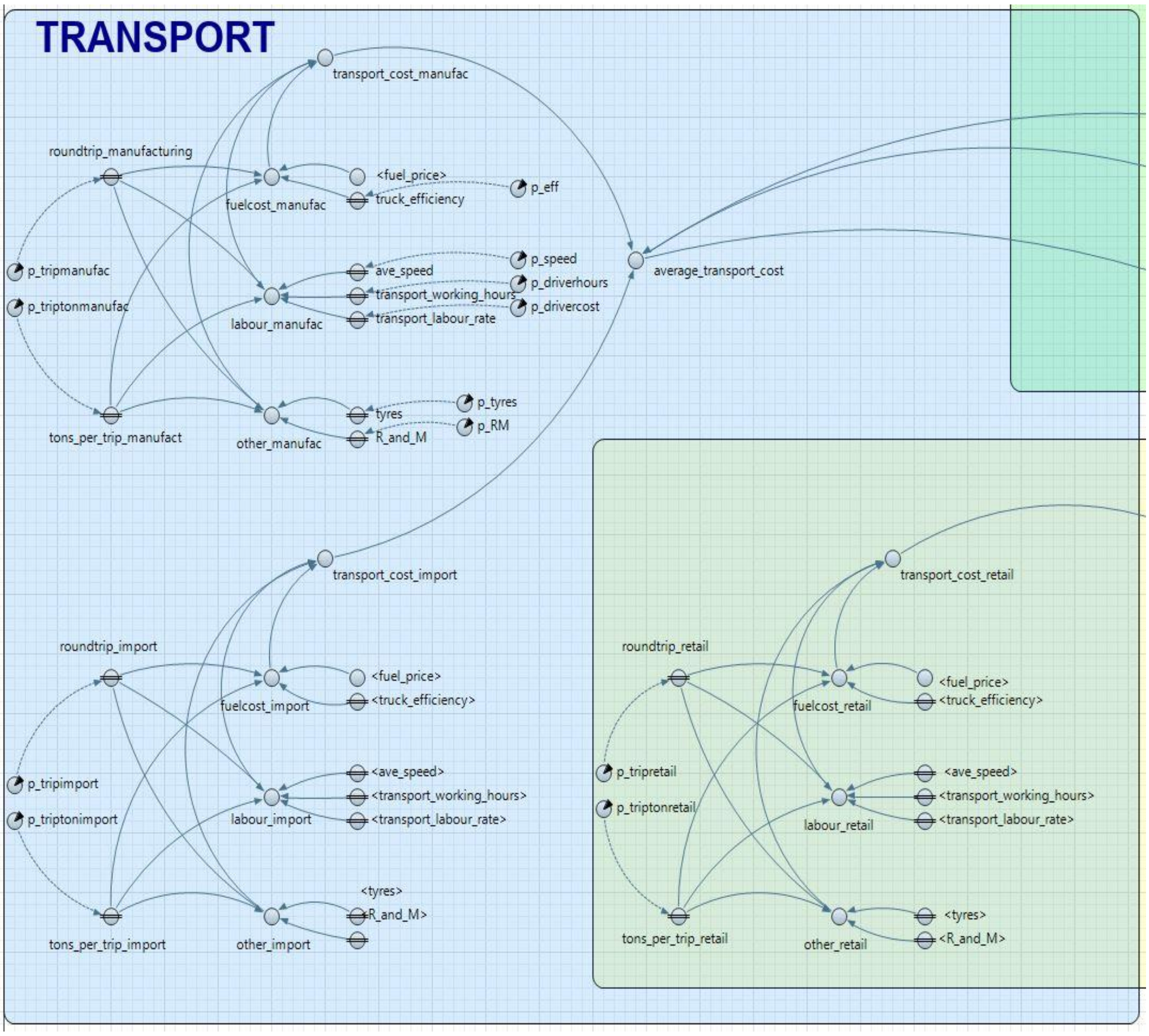

Figure 11 SFD of Transportation sub-system
(Please ignore lines running into the model across the model boundaries – those are simulation variables added to aid the online model game-mode)

Labour cost, per ton, (R/ton) term was calculated based on: (1) the number of trips per day – which is rounded down, needs to compensate for loading time, off-loading time, etc., and (2) the labour cost.

$$Labour\ cost = (transportation\ labour\ rate \times transportation\ working\ hours)/(tons\ per\ trip \times number\ of\ trips) \quad (19)$$

Where *Number of trips* can be estimated by dividing the *Transportation working hours* by the average *trip duration* [(km/trip)/(km/h) = h/trip]. The *trip duration* is calculated by dividing the *Round trip* by the average *truck speed*. Where the *truck speed* in km/h is the average speed the truck travels at (*Default 48 km/h*). The *Number of trips* resulted value is rounded down to an integer (extra time is for loading/unloading between trips) and the value is then corrected to at least "1".

$$Number\ of\ trips = Max[1; RoundDown[(transportation\ workinghour\ Round\ trip)/truk\ speed]] \quad (20)$$

Other transportation cost (R/ton) term considers tires, repair & maintenance (R & M), insurance, etc.

$$Other\ cost = (tyres + R\&M) \times Round\ trip\ /Tons\_per\_trip \quad (21)$$

3.4 SFD of Manufacturing

Grain manufacturing/milling is the main way for fulfilling the country's needs of grain. Any shortage (the difference between locally produced and demand) is to be compensated via grain importing. Total manufacturing cost (R/ton) is calculated by adding the following cost items together: locally produced grains procured at the grain price (income for the farmer, the cost for manufacturing), imported grain costs, transportation costs and other manufacturing costs. **Figure 12** illustrates manufacturing/milling sub-model and the associated dynamics. Milling/manufacturing cost can be formulated as follows:

$$Milling\ cost = Average\ transportation\ cost + Average\ crop\ cost + Non\ food\ inputs \quad (22)$$

Where *Milling cost* is the total manufacturing cost including: procuring the grain, transport, and non-food input costs; and *Average transportation cost* is a weighted average transportation cost for grain including local production as well as imports that was estimated based on the transportation cost items addressed in section 3.3. *Average transportation cost* and *Average crop cost* are calculated using equations 23 and 24, respectively.

$$\begin{aligned} &Average\ transportation\ cost \\ &= (transportation\ cost\ for\ manufacturing \\ &\times crop\ production \\ &+ transportation\ cost\ for\ importing \\ &\times crop\ imports)/(crop\ production \\ &+ crop\ imports\ ) \end{aligned} \quad (23)$$

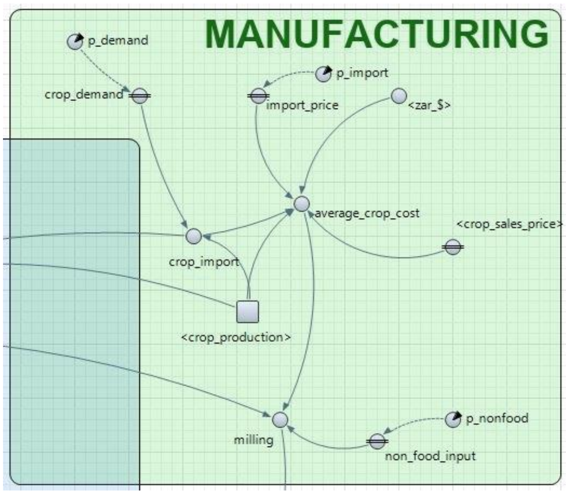

Figure 12 SFD of Manufacturing sub-system (Please ignore lines running into the model across the model boundaries – those are simulation variables added to aid the online model game-mode)

$$\begin{aligned} &Average\ crop\ cost \\ &\qquad = import\ price \times ZAR_{\$} \\ &\qquad \times crop\ imports \\ &\qquad + crop\ sales\ price \\ &\qquad \times crop\ production \\ &\qquad /(crop\ imports \\ &\qquad + crop\ prodcution) \end{aligned} \quad (24)$$

3.5 SFD of Retail

Figure 13 illustrates that the final Retail price for grain products in R/ton is calculated by adding costs of the grain from manufacturing, transportation cost to market, rebranding expenses (R/ton), and then applies a retailing mark-up (percentage) as shown in the following equation.

$$\begin{aligned} &Retail\ price \\ &= (price\ from\ milling \\ &+ rebranding\ cost \\ &+ transport\ cost\ for\ retail)/(1 \\ &- retail\ mark\ up) \end{aligned} \quad (25)$$

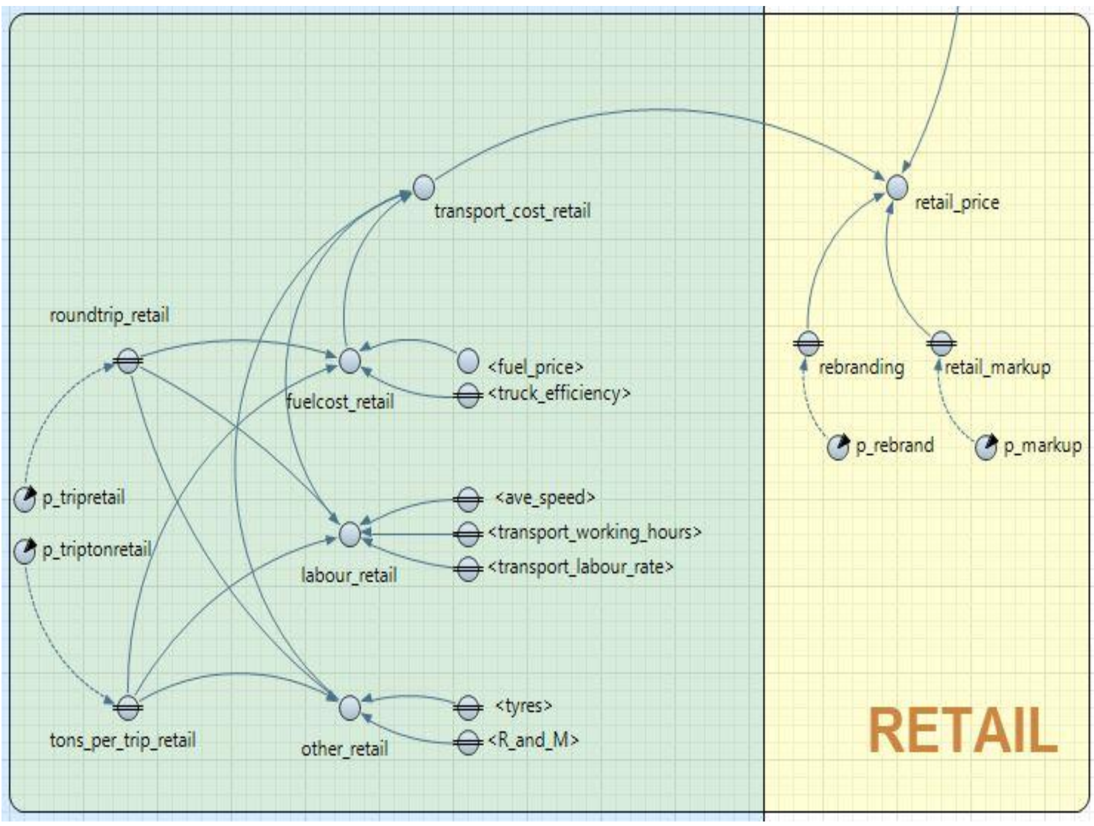

Figure 13 SFD of retail sub-system (Please ignore lines running into the model across the model boundaries – those are simulation variables added to aid the online model game-mode)

4. RESULT AND SENSITIVITY ANALYSIS

The developed SD model was first verified and validated to ensure the model's accuracy. Verification and validation were conducted using two error indicators: The error rate and error variance. The computation of the error rate and error variance were done based on real data in the period of 2015–2018. Three performance measures and model variables were used for this purpose: land use (hectare), Grain Yield (ton/hectare/year) and Retail Price (Rand/ton). Analysis showed that the error rate and error variance are within the acceptable ranges 5% and 30%, respectively (Suryani *et al*., 2022). The developed Anylogic SD model is available and runnable on the cloud *. **Figure 14** shows the SD parameters values and scenarios control screen.

The SD model was used to test the impact of the following three disturbances or external factors: Drought, or variations in climate; Rand/Dollar Exchange Rate; and changes in International Oil Prices. Each factor will be discussed individually in short, then a comprehensive analysis is to be conducted.

4.1 Factors analysis

In this study, the impact of three disturbances or external factors was investigated: Drought, or variations in climate; Rand/Dollar Exchange Rate; and changes in International Oil Prices. An overview about the effect of each of those factors will be discussed. **Figure 14** shows the values and ranges of the three disturbances/external factors.

4.1.1 Climate Change-Drought

In this study, CLIMATE does not represent rainfall and/or drought only. However, "rainfall" and/or "drought" weather conditions are the most important parameter as they might exist for long periods, the wet monsoon (season) the dry monsoon (season). However, the climate could consider any other parameters like temperature and humidity. The unique point about drought is that it is not usual to find a humidity problem or abnormal hot/cold weather lasting that long for years, a drought condition can be found lasting that long. CLIMATE is considered as a unitless value, with the optimal value being "1", representing "optimal climate or the most preferable weather conditions". Climate with a value above or below "1" is used to represent a nonpreferable weather condition in one way or another. In this sense for humidity, anything above "1" is "more humid than optimal" while anything below "1" is "less humid than optimal". For temperature, anything above "1" is "hotter than optimal", and anything below "1" is "colder than optimal". For rainfall, anything above "1" is "wetter than optimal", anything below "1" is "drier than optimal". Thus, 0.9 is a minor deviation from optimal, whereas 0.5 is a significant deviation from optimal. In terms of precipitation, 0.9 is slightly less than normal. 0.5 is fairly dry, and 0.2 is extremely dry. While 1.2 is slightly wetter than normal.

Climate changes and drought impact negatively on the locally produced grain yield. A decrease in Yield reduces the grain production, which will result in the following two chains of impact. First, farmers will have less crop production for the same input cost, therefore less income, which will have the ripple effect of lowering income that impacts the farmer's profit margin and consequently the farmer's profit/hectare.

* Investigating The Impact Of Economic And Natural Parameters In The Supply Chain Management Of Milled Grain Products - Simulation Models In Anylogic Cloud (https://cloud.anylogic.com/model/d21d955a-4ec7-42a7-9204-0d11946a51f4?mode=SETTINGS)

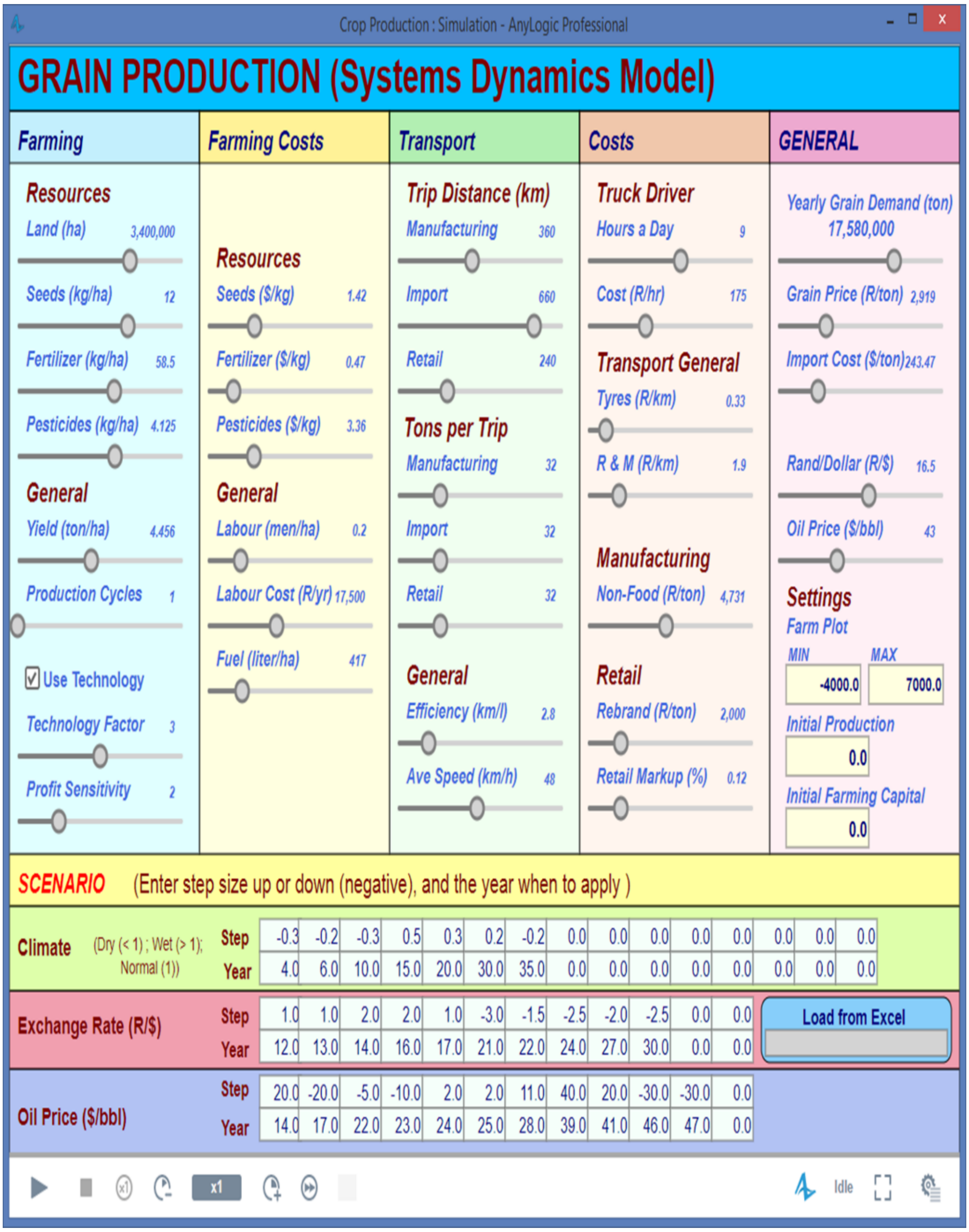

Figure 14 The SD control screen with parameters' value and the three disturbance external factors ranges

4.1.2 Exchange Rate

An increase or worsening of the exchange rate (opposite to a strengthening of the Rand to the Dollar) will have two impacts. Firstly, weaker Rand will result in increase in the fuel price and cost of raw material, which will increase the farming input costs and reduces the farmer's profit margin. After a delay, it might cause some farmers to exit the sector, making less land available for farming. This will affect locally produced grain, and increase import costs, manufacturing, and retail prices. Less farmland also increases the yield for the remaining farmers and the land equation will autocorrect. An increase in fuel costs also impacts transport costs, increasing the manufacturing and retail prices. The relative strength of these impacts depends on the percentage contribution of transport to the overall cost equation. Secondly, it will increase the import cost of grain which will increase the manufacturing and retail prices as well.

4.1.3 Oil Price

An increase in oil prices will have the following impact. Firstly, it will cause an increase in fuel prices, which will have chain reaction. Farmer's input cost increases, which will reduce the farming margin, depending on how significant the fuel cost contribution is relative to the total farming costs. Subsistence farmers might exit after a delay. Farmers exiting will cause a decrease in land availability for production, local production and an increase in imports and retail prices. The use of technology will however cause a rise in yields to counter the decrease in land availability. Secondly, there will be an increase in transportation costs (manufacturing, imports, and retail), which will cause an overall increase in manufacturing and retail prices.

4.2 Analysis and Discussion

The basic "crop demand" is the aggregated country needs of multiple grains such as corn, wheat, and rice, all of which are staple foods for the population. Demand could be fulfilled by two ways of supply: local production and imports. Of these, imports are expensive since it comes at a higher price, higher transport cost, and longer process from farmer to retail. A similar finding was recently reported by Adams (2022).

Local production is complex, stemming from the country's political and historical backgrounds. On the one hand, there is a well-educated, high technological commercial farmers with a strong balance sheet. On the other hand, there are poor, uneducated, almost subsistence farmer who uses the land to produce for the survival of the local community. Lai *et al.* (2023) and Zhou and Liu (2022) have also confirmed and extended upon the phenomenon of the two farmer clusters. There exists a highly politicised land problem where people want access to land, based on the understanding that land equates to wealth. However, land alone is not enough. There is a need for meaningful production for one to get the real value of land. In the model, such political concerns are modelled in terms of a "technology factor" which is a function of the availability of land and its impact on the yield. In times of difficulty, low yield farmers will exit the farming business and they will survive by sub-leasing the land. The lessee (high-tech farmers) may be able to achieve a higher yield on the same farmland. The model shows that to a certain extent, the farmland availability decreases which increases the technology factor, which in turn increases the yield to a level that over-compensates for the loss in land availability. If the economic hardship continues, land availability will drop faster than the technology factor is able to increase the yield and overall crop production will be affected.

The purpose of this scenario-based analysis is to investigate the impact of the three driving factors on the four sub-systems of the milled grain supply chain. The implications of disruptions on any of those three driving factors are to be traced based on the model performance indicators for each sub-system such as: Land Use (hectare), Grain Yield (ton/hectare/year), Net Farming Income (Rand/hectare), Transportation Cost (Rand/ton), Milling Cost (Rand/ton), and Retail Price (Rand/ton), as shown in **Figure 15**.

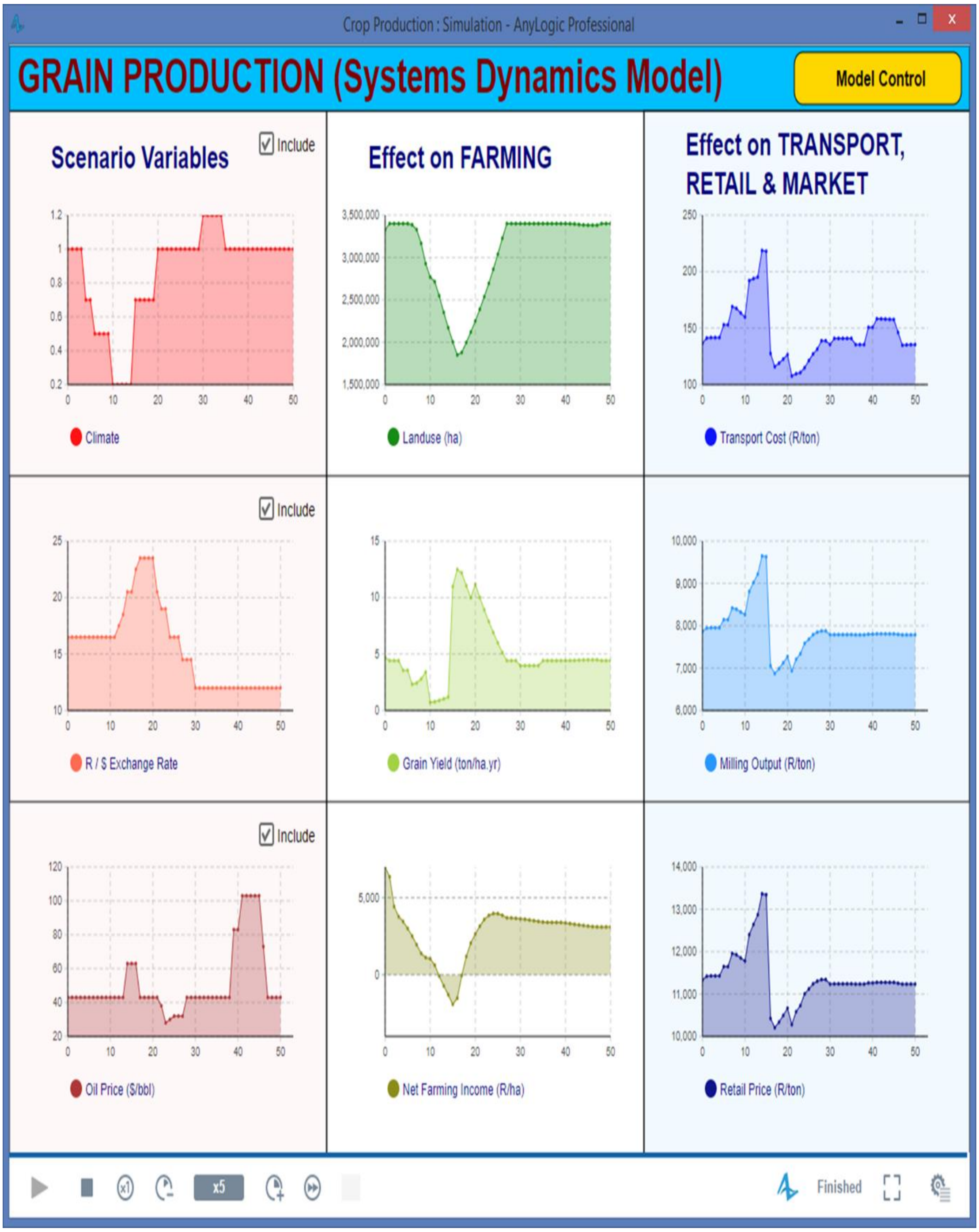

Figure 15 The disruption factors against the system performance measures over time

Elasticity of those measures are traced over time along with disruption on the driving factors. This would enable predicting the future behaviour and dynamics of the milled grain supply chain system against the external factors that might disrupt the system. First, the impact of the environmental/natural factor (Climate Change and Drought) were analyzed. Second, the economic factors (Exchange Rate and Oil Price) were investigated.

4.2.1 Impact of the Environmental/Natural Factor (Climate Change and/or Drought)

Figure 16 depicts a simulation run with a severe drought affecting the farming sector. The impact of climate change on the farming context was also recently investigated by Hansen (2022). Initially, the farming sector absorbed the drought's impact in years 4-6. The Grain Yield is slightly decreased; however, no Land is lost (farmers are still surviving). When the drought started to worsen in years 7-9, farmers began to leave the business, but the large commercial farmer tries to balance the system. Those large commercial and high-technology farmers usually utilize high technology which makes the average Grain Yield slightly increase. The first escape of farmers (small scale and low-technology farmers) occurred in Year 8. When the drought became much more severe in years 10-14, serious implications are experienced with a rapid farmers exit and a sharp lack of farmland. Furthermore, yield tanks (silos) experience acute shortages of grains, and only large commercial farmers and high-tech farmers could survive. Zhou and Liu (2022) also reported on the technology gap in the agricultural industry and its consequences for fairness and sustainability. This gap is shifting, even as it partially compensates for the decline in available farming acreage.

By year 15 and when the rain started to fall, only the large commercial farmers with high-tech production and high yield are still surviving in the farming business. This could explain the sudden and sharp skyrocketing of Grain Yield in year 15, even without any considerable increase in the farmland.

The impact of drought on the number of hectares (negative impact) is little bit straight forward and easy to be captured from **Figure 16**. However, the impact of drought on transportation cost, manufacturing cost and retail price is an indirect effect. The model justifies that the peak in transportation costs occurs during droughts and the sharp decrease in transportation costs occurs during rainy seasons. To explain this, it is important to note that the total transportation cost consists of two components: local manufacturing transportation costs and imports transportation costs. The model data shown in **Figure 14** shows that the average distance for local manufacturing (from farmer to local manufacturing facility) is 360 km roundtrip, while the average distance for imports (port of entry to local manufacturing facility) is 660 km roundtrip, both delivering 32 tons that is the capacity in tons per trip. The transportation labor is the same, but the "Fuel" and "Maintenance" cost components for the imports component is significantly higher than those for the local manufacturing component. For example, the model shows that during the worst drought, Manufacturing transport (Fuel, Labor and R&M) is 131.535 Rand/ton in total (57.228, 49.219 and 25.087, respectively). Whereas imports came with 200.131 Rand/ton in total (104.919, 49.219 and 45.994, respectively). For more explanation and for verification purposes, the fuel cost share was calculated, at a certain instance with the fuel price of R14.2435/l, using equation 18.

$$Fuel\ cost\ for\ local\ manufacturing = \frac{360\ km}{2.8\ km/l} \times \frac{R14.2435\ /l}{32\ ton/trip} = R57.21\ /ton$$

$$Fuel\ cost\ for\ imports = \frac{660\ km}{2.8\ km/l} \times \frac{R14.2435\ /l}{32\ ton/trip} = R104.919\ /ton$$

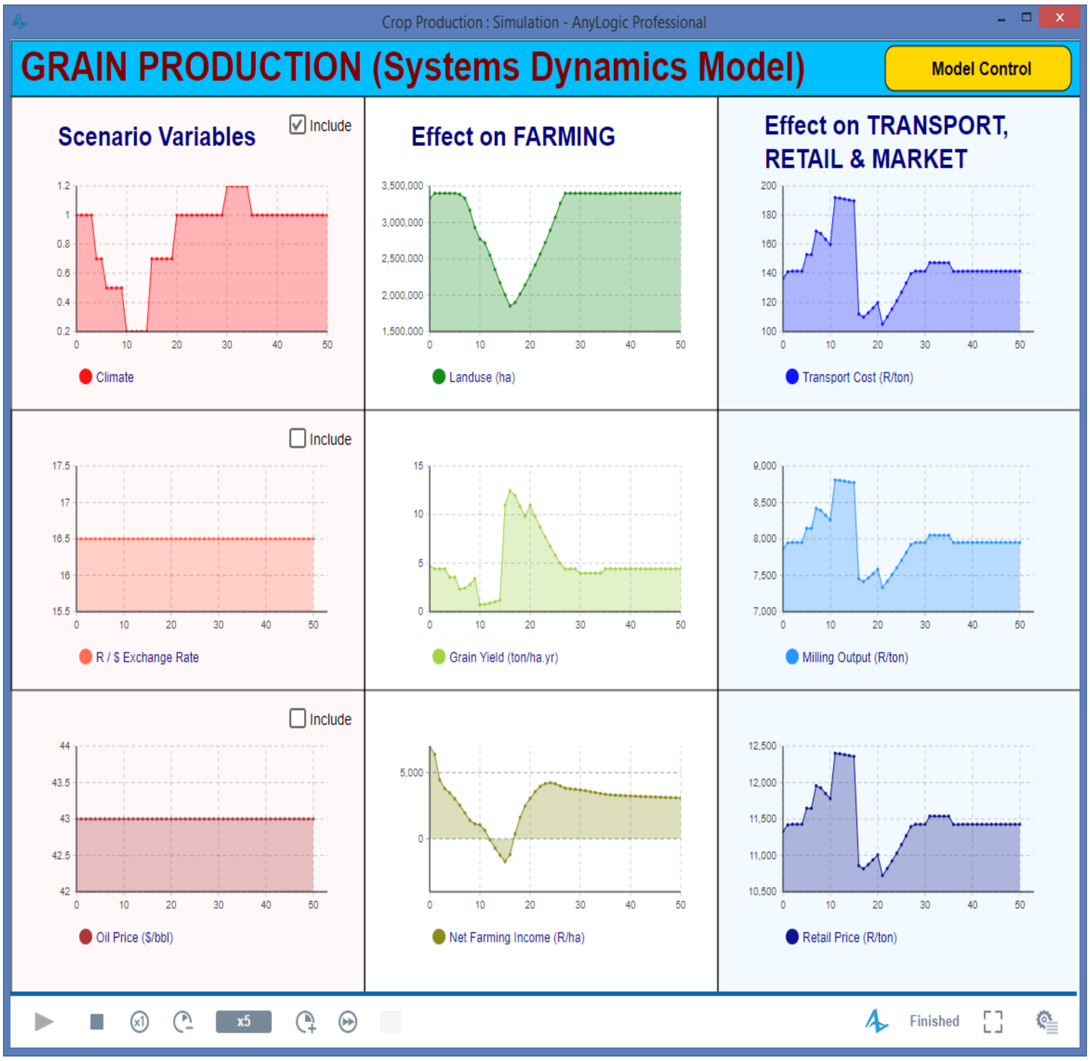

Figure 16 The impact of climate change on the four sub-systems of the milled grain supply chain over time

So, demand is fixed (crop is a basic need-food for people); what could not be fulfilled from local manufacturing must be imported. When extreme CLIMATE strikes, crop yields fall, and local production suffers. The demand shortfall must be imported, but as seen above, the average transport cost for imported grains is much higher than that for local production—the production facilities are close to the farmers, but far from ports of entry (more grain is produced inland than at the coast). As a result, as the drought worsens, the average cost of transportation (both domestic and imported) rises. Simultaneously, small-scale and low-tech farmers leave the game, leaving only large commercial farmers with deep pockets and highly scientific farming techniques—high-yield farmers—in the game.

To explain the phenomena of small-scale and low-tech farmers abandonment further, the "Net Farming Income (R/ha)" is to be traced as well. The main characteristics of small-scale and low-tech farmers, or the subsistence farmers, are the farmers who have, in somehow, acquired land but are struggling with: lack of education; lack of knowledge, understanding, and experience with these highly scientific farming methods; and lack of capital or economies of scale to implement such. Under those circumstances, the subsistence farmers struggle with either an increase in cost for the same yield or a decrease in yield for the same cost. That is actually the case when the drought became much more severe in years 10-14. Thus, with a negative average "Net Farming Income (R/ha)", farmers start to suffer. The low capital, low yield farmer exits the game because they can no longer afford it, and they do not have the ability to absorb capital upsets.

When the drought condition shifts, the yield shifts because the low yield subsistence farmers are no longer in the farming game, only high-tech commercial farmers are, and the system suddenly has a record crop yield, very high local production, very low need for imports, and a very sharp drop in transportation costs (the high transportation costs for imports disappeared almost immediately). Farmers have returned to the game, the average yield has stabilized, and transport levels have returned to "normal levels". In short, as the yield falls (due to climate), there is less production, which must be compensated for with imports. Because imports have a high transport cost, the average cost rises until the condition shifts, at that point the system has a record yield, imports disappear almost instantly, and transport costs fall significantly.

In year 20 and with time, there is a gradual return of farmers—more land available—but the average yield falls, lending credence to the idea that the big commercial, high yield farmers survived the drought. Farmers who use less technology and produce less produce are more vulnerable to economic shock returns to the farming business. Average yield falls, available farmland expands, and the system stabilizes. The pulse in the weather in year 30 doesn't impact the system significantly, and the farming business could easily absorb it.

4.2.2 Impact of the economic factors (Exchange Rate and Oil Price)

According to the model, "Exchange rate" and "Oil Price" have the same effect on "Transportation Cost". To justify this observation for South Africa, and whether it might be the same in other countries, the correlation and interrelation between "Exchange rate" and "Oil Price" is essential to be analyzed. Diesel prices in South Africa are determined by the ZAR-oil price. Although SASOL* (South African Coal, a global chemicals and energy Corporation) may be converting fuel from coal, the Department of Energy pricing formula still uses an oil-priced fuel pricing mechanism. This explains why SASOL shares price increases when oil prices increase, even when they use Coal as raw material, not oil. Because the Rand-based Oil Price is a combination of the US$-based Oil Price and the ZAR/USD exchange rate, either will have the same effect. Oil prices can remain stable, but if the Rand weakens against the Dollar (ZAR/$ rises), the Rand-based oil price rises, and transportation costs rise. If the exchange rate remains constant but the oil price rises, then the Rand-based oil price rises, as do diesel prices and transportation costs. Both have the same effect; they increase the farmer's input cost. For most low-yield farmers, the business is barely profitable. Any slightest increase in costs and they will exit the business (probably leasing their land to the bigger commercial high-tech farmers). The technology factor kicks in (low yield farmer exiting means higher-yield farmer entering) resulting in a slight increase in the average yield.

As discussed earlier, subsistence farmers cannot survive during unpreferable climate conditions. Similarly, the model shows that an increase in cost items (i.e., fuel price) makes farming uneconomic for the small subsistence farmer. They "exit" the farming business, and this of course causes dropping the available farmland. This finding was further corroborated by Singh and Kumari (2023). The "technology factor" compensates that abandonment by abruptly increasing of the yield with only the high-tech large-scale commercial farmers. This could justify the increase of "Grain-Yield" with the increase of Exchange rate and Oil Price, as shown in **Figure 17**. However, it is important to highlight the insignificance of that increase. The vertical scale magnifies the yield increase; however it is insignificant as the yield increased with around 17% for a 150% increase in oil price in year 45 as shown in **Figure 17.** The small variations in oil price such as from $40 to $60 in year 14 – 16 (this is a 50% increase in oil price) and from $40 to $25 in year 21 – 28 (this is a 38% decrease in oil price) were absorbed by the farmer without having any noticeable effect as shown in **Figure 17.** Similarly, the yield increased with around 2% for a 42% increase in Exchange rate. Thus, it requires a very significant increase in either exchange Rate or Oil Price before a noticeable change could reflect in the yield. Furthermore, if the technology factor is excluded while running the model, this will take away the ability of the large commercial farmers to survive economic hardships.

* https://www.sasol.com/who-we-are/about-us

This will neutralize the impact of either Exchange Rate or Oil Price in the yield. Thus, neither of these have any impact whatsoever on the yield, this is purely a function of the technology factor which compensates for the low-yield farmer exiting by entering a higher yield farmer in his place, which increases the average yield.

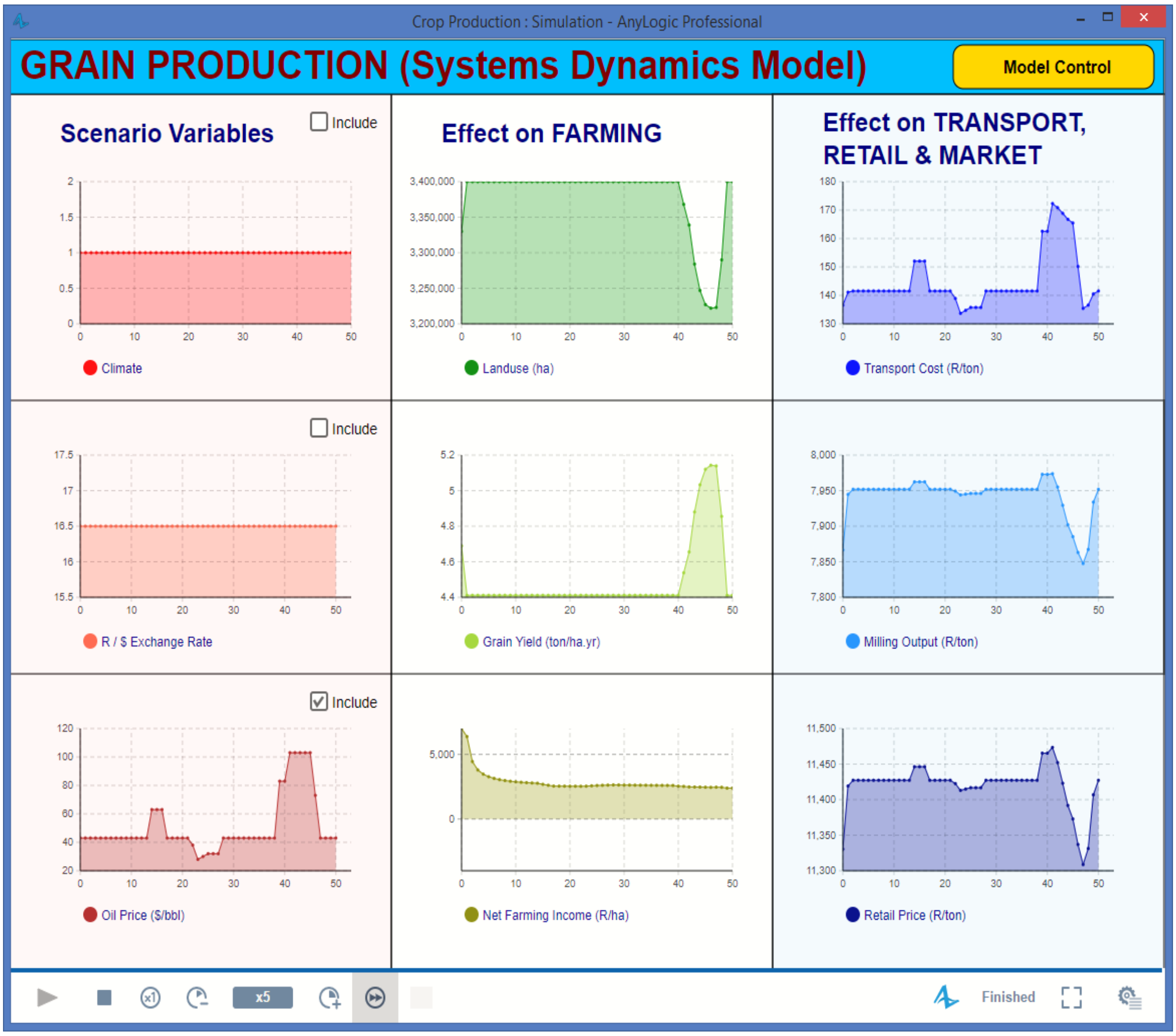

Figure 17 The impact of oil price change on the four sub-systems of the milled grain supply chain over time

As yield increases, local production increases and therefore quantity of imports decreases. Imports are associated with larger distances travelled and higher import transportation cost. However, with lower imports, the import transportation cost declines and overall transport costs in the model shows a decrease **(Figure 17).** Accordingly, the same effect is reflected on milling and retail price as well. However, it is important to highlight the insignificance of that effect. The vertical scale magnifies the cost items increase; however, it is not that significant. For example, **Figure 17** shows that the retail price increased from 11,427 to 11,473 (a 0.4% increase) as a response to the 150% increase in oil price in years 38-40. For the Transportation cost, it increased by around 24% (from 140 to 173) as a response to the 150% increase in oil price in years 38-40 as shown in **Figure 17.**

Based on the developed model results and the study findings, the study insights and recommendations could be summarized as follows. First, this study highlights the need for applying safety yield tanks (silos) to guarantee, in somehow, that a subsystem with a struggle (i.e., no rain, drought, fire, strikes, or theft) does not affect immediately all other dependent subsystems of the milled grain supply chain. Thus, farmers should produce more than needed so that surplus grain products can be used as security during difficult times. Second, farming technology must be implemented at all levels of agriculture and should be facilitated especially for the small-scale subsistence farmers. Furthermore, there is a need for more reliable and robust win-win agreement between the large-scale high-tech farmers and small-scale subsistence farmers. This agreement should address how to improve the learning curve, technology penetration, land utilization and margin profits for all stakeholders. This could maximize the overall land yield and utilization. Third, the crude oil production and storage facilities must be expanded to compensate any oil shortages and be able to sustain the country and avoid international economic shock.

5. CONCLUSION

This study makes significant contributions to understanding the complexities of the milled grain supply chain (MGSC) under the influence of environmental and economic disruptions. By employing a novel system dynamics (SD) approach, the research offers valuable insights for stakeholders looking to navigate these challenges and enhance overall performance.

This study makes key contributions in three areas. First, it presents a holistic SD model encompassing the entire MGSC. This model empowers stakeholders by enabling them to analyze and improve operational performance across the entire chain, facilitating informed decision-making. Second, by modeling the MGSC as four interconnected sub-systems – farming, transportation, milling (manufacturing), and retail (trade) – the study reveals intricate relationships within the chain. This knowledge equips stakeholders to identify potential bottlenecks, inefficiencies, and opportunities for collaboration across the different segments. Third, the study analyzes the impact of three critical factors on the MGSC: drought or climate variations, Rand/Dollar exchange rate, and international crude oil prices. This analysis provides valuable information for developing strategies to mitigate these disruptions and build resilience within the supply chain.

The developed SD model transcends its role as a mere analytical tool. By utilizing Anylogic® simulation software, the model allows for the evaluation of the MGSC performance in terms of crucial metrics like available farming land, grain yield, and various cost factors. Additionally, the model's versatility allows for scenario simulations through parameter adjustments, facilitating its potential application and replication in diverse contexts.

The simulations conducted using the model yielded valuable insights. These include: (1) Differential drought impact: The study reveals the varying vulnerabilities of different farming sectors to drought severity. (2) Environmental influence on transportation: A correlation between environmental conditions and transportation costs is established, highlighting the impact of droughts on logistics. (3) Economic vulnerability of small-scale farmers: The research underscores the heightened susceptibility of smaller-scale farmers to economic fluctuations. (4) Specific impacts of exchange rate and oil prices: While not significantly affecting the entire system, these factors can influence transportation, milling, and retail costs.

The insights derived from the study, coupled with the comprehensive SD model, offer valuable tools for stakeholders within the MGSC. These tools could enable them to enhance decision-making by understanding the intricate dynamics of the MGSC and the impact of various factors, stakeholders can make more informed and strategic decisions. Moreover, the knowledge gained from the study equips stakeholders to proactively mitigate the impact of environmental and economic disruptions. Furthermore, by leveraging the insights and the model's capabilities, stakeholders can identify opportunities to improve efficiency and overall performance within the MGSC. This study, through its innovative approach and insightful findings, offers a significant contribution to understanding and managing the complexities of the milled grain supply chain. By empowering stakeholders with knowledge and tools, the research paves the way for a more resilient and efficient MGSC, ensuring the sustained availability and affordability of milled grain products.

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