A System Dynamics Approach to Simulating the South African Forestry & Logging Sector's Electricity Demand

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Abstract –The focus of this paper is the development of a simulation model to engage with and interrogate the key driving forces affecting the electricity requirements of South Africa's forestry and logging sector, using a system dynamics approach. The objective of the model is to project the sector's electricity demand from 1992-2040 to facilitate dynamic sensitivity analysis that will allow for a better understanding of this complex system of many interacting variables and assist a South African electricity utility in planning for future electricity demand. This paper will discuss the development of a model boundary chart, system architecture maps, a causal loop diagram, structural simulation development in iSee STELLA®, and results generated from selected scenarios.

Keywords – Economic sectors, electricity demand, Eskom SOC, forestry & logging

INTRODUCTION

The growth in South Africa's population and economy increases the need to ensure that South Africa's primary power utility, Eskom Holdings State-Owned-Company (SOC) Ltd, and other electricity suppliers can meet the country's electricity demand to plan optimally and avoid future unserved electricity. Eskom currently owns 27 power stations within South Africa with a nominal capacity of 41 995 MW (Eskom Holdings Corporate Plan 2015/16-2019/20, 2015). Effective electricity supply planning is only possible if the various elements that contribute to the economic sectors' demand are understood. Some of the key reasons for planning for the country's demand include the long lead times required for the development of energy infrastructure as it could take in excess of 10 years for construction to be completed, depending on delays and environmental impact analyses that need to be conducted (Nuclear Energy Agency, 2012).

Developing a model using system dynamics simulation techniques is the most sensible method to model the electricity demand of the economic sectors. It is time consuming and impractical to perform experiments in real life and simulators allow users to run various scenarios with different assumptions to see the effect they will have on the system that is being modelled using time compression (Concentric, 2013). This assists the user in making important decisions well within time constraints.

An integrated economic sector simulator was developed that consists of South Africa's economic sectors, namely mining, forestry & logging, agriculture, energy, residential, manufacturing of final goods, services, and other non-intensive sectors. This paper focuses only on the forestry and logging simulation model. The material flow through the different production mills within the sector drives the demand for electricity. The volume of material flowing through these mills is affected by a change in Gross Domestic Product (GDP) since a higher GDP would indicate increased production and services delivered within a country. Production in each economic sector is therefore related to the change in GDP. The simulator has an interface with which the user can engage to perform sensitivity analysis to see the effect of changes in some of the key drivers of the sector on its electricity consumption. Some of these drivers include trends in the implementation of energy efficient technologies and self- or co-generation options.

Table 1 defines some of the basic concepts that are used within the paper. The key formula used within the simulation follows afterwards.

Table 1: Basic definitions for the concepts used in this paper

Economic Sectors	Areas of the economy in which businesses share the same or related products or services.
Gross Domestic Product	The monetary value of all the finished goods and services produced within a country's borders in a specified time period.

The mathematical formulae used within the model are fairly simple. However, the use of logistics curves should be explicitly mentioned as it forms the basis on which all projections are made within the model. These curves allow for the modeling of trends that show a gradual change over a period of time, striving toward a defined limit (Nel, 2015).

The logistics curves applied are based on the assumptions that:

- All patterns of change have limits in a finite world;
- Short-term patterns are disconnected from long-term limits;
- Long-term trends follow an asymptotic convergence pattern.

The logistics curve that is shown in Figure 1 has the following mathematical equation (Equation 1):

$$\boldsymbol{P(t)} = \frac{\boldsymbol{U}}{\mathbf{1+exp}[-\boldsymbol{c}(\boldsymbol{t}-\boldsymbol{t_0})]} \quad [1]$$

Where: *P(t)* is a function of time, t;
U is the upper limit or limiting value for *P*;
c is the growth rate exponent that determines the maximum slope of the s-curve;
t_0 is the time at which the maximum slope is reached (inflection point).

However, in practice it is usually found that the superposition of logistics curves occurs when considering a long time span, as seen in Figure 2. If a simulation time frame only spans a certain window as indicated by the dashed rectangle in Figure 2, it is necessary to accommodate this by using Equation 2 instead.

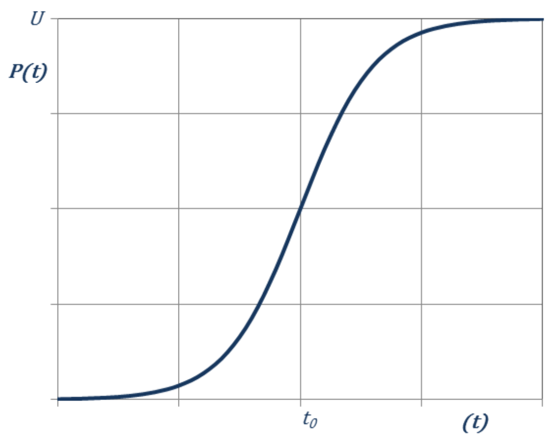

Figure 1: Logistics curve (Nel, 2015)

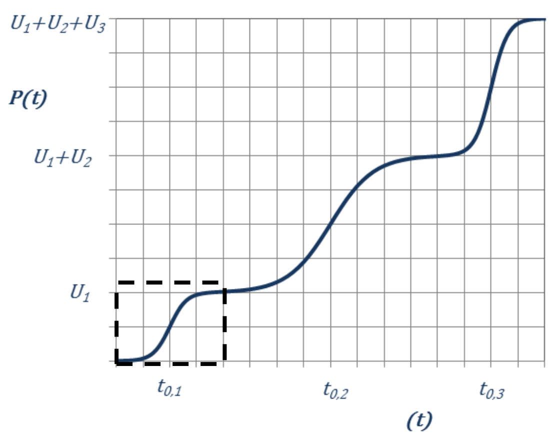

Figure 2: Superposition of three logistic curves (Nel, 2015)

$$\boldsymbol{P(t) = U_0 + \frac{U_1}{1+\exp[-c(t-t_0)]}} \qquad [2]$$

Where: U_0 is the zero offset;
U_1 is the ultimate increase above U_0;
All other variables as defined in Equation [1].

Research Approach

The objective was to project what the total electricity demand for South Africa's forestry & logging sector would be using a system dynamics approach and allow the user to perform scenario analysis. The methodology followed in this research is based on JD Sterman's modelling steps documented in Business Dynamics (Sterman, 2000).

A. *Problem Articulation*

An extensive literature review was performed during which the key variables affecting the system were identified and classified according to a model boundary chart (MBC). The MBC containing the exogenous, endogenous, and excluded variables are shown in Table 2.

Table 2: Model boundary chart for the forestry & logging simulation model

Endogenous	Exogenous	Excluded
Energy intensities	Plantation capacity	Electricity tariff
Energy requirements	Afforestation	Weather
Production demand	Damage to plantations	Fuel cost
Production volumes	Wood processing residues	Soil conditions
Quantity of recycled pulp	Imported products	Water resources
Electricity savings	Exported products	Socio-politics
Carbon emissions	Strike action	
Carbon tax	GDP & GDP growth %	

The start time for the simulator was selected as 1992 based on when the most consistent data could be found. The end date was chosen as 2040 so that the model stretches beyond South Africa's Integrated Resource Plan for Electricity (IRP) (Integrated Resource Plan, 2013). An assumption was made that the South African forests are managed for sustainable growth and therefore the ages of the trees within the plantations are not included in the simulation (Graupner, Dreyer, van Staden, 2014).

B. *Formulation of Dynamic Hypothesis*

The forestry & logging sector comprises of five main product streams which will be incorporated into the simulation model. These product streams are as follow:

- Sawlog manufacturers;
- Paper & pulp industry;
- Mining timber industry;
- Poles & droppers manufacturers; and
- Firewood & other products.

The timber undergoes different production processes within each of the product streams before the final products are ready for consumption. Each product stream's production processes were researched and system architecture maps (SAMs) for each of them were developed, including a more high-level one that outlines the general flow within the sector. The SAM for the sawlogs product stream will be discussed and is shown in Figure 3.

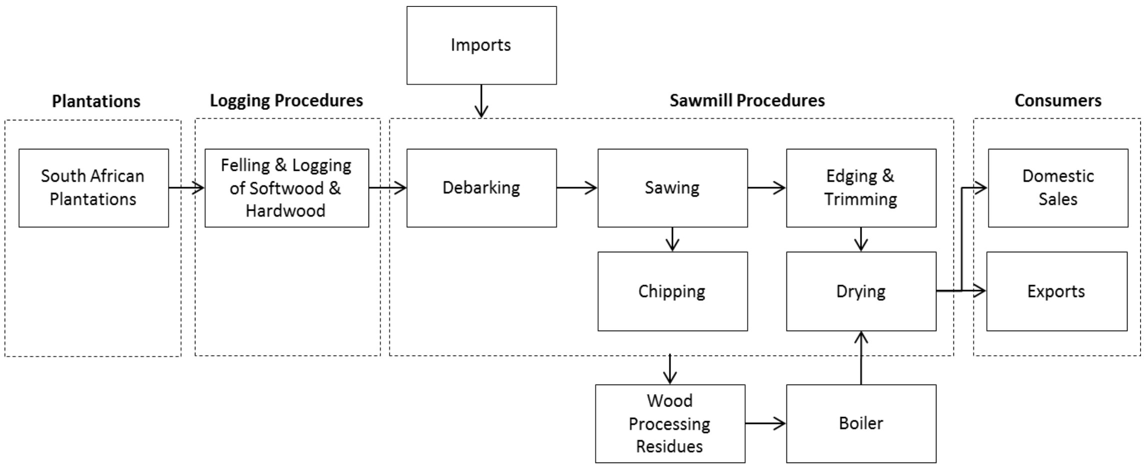

Figure 3: System architecture map for the sawlogs product stream

The SAM in Figure 3 illustrates the high level process whereby raw timber is obtained from the plantations through felling and logging procedures. These procedures include the bucking (cutting into logs) and limbing (removing the branches from the trunk) of the harvested trees. The logs are then transported to the sawmills where they are debarked and sorted by species, size, and use. A head saw is used to break the log into cants (unfinished logs to be further processed) and flitches (unfinished planks). After this the cants could be broken down further by a resaw, or the flitches could be broken down into multiple flitches, depending on the species and quality of the logs. Flitches undergo edging to take off all irregular edges, leaving four sided lumber. The trimming procedure squares the ends at typical lumber lengths. Through the drying process the natural moisture is removed and the lumber then undergoes a final planing process to smooth its surface. After this the lumber is either sold domestically or exported (Allegheny Mountain).

During the processing of the timber in the sawmills, residues such as wood chips, sawdust, bark, and offcuts are collected. These residues have commercial value and can be sold for extra revenue for companies. They can also be used as biomass fuel to generate electricity and heat energy with the use of a boiler (Li, McCurdy, Pang).

The cause-effect relationships between the key variables were explored and a causal loop diagram (CLD) was developed. The CLD is shown in Figure 4, after which an explanation will follow.

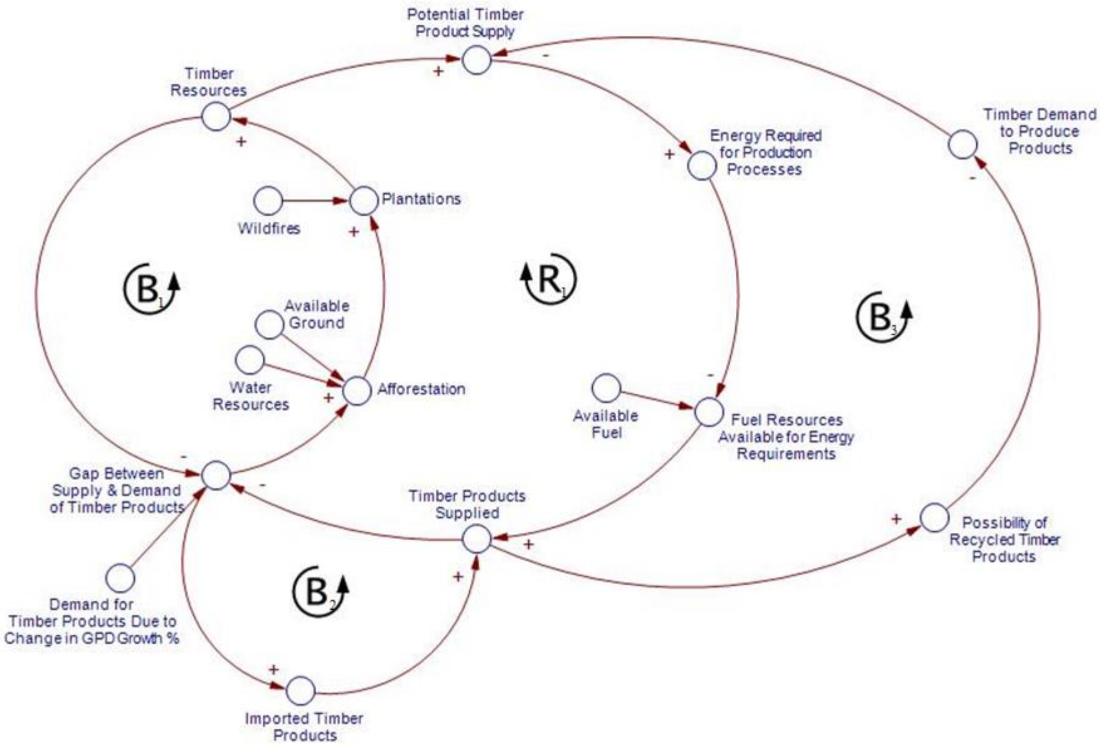

Figure 4: Causal loop diagram for the forestry & logging sector

The *Demand for Timber Products Due to a Change in GDP Growth %* is a limiting factor to the system, as the sector is driven by demand for the different products and would not produce in excess of this demand. As indicated by the name, the demand is influenced by a change in the GDP growth percentage which was defined as an exogenous variable. The demand for products will affect the gap that exists between this demand and the amount of timber products that are supplied to the consumers. If this *Gap Between Supply & Demand of Timber Products* increases, a need arises for *Afforestation* to take place to ensure that there are enough trees that can be harvested to meet the demand. The extent to which Afforestation can take place is limited by the amount of *Available Ground* for new plantations and the availability of *Water Resources.*

The size of the *Plantations* will increase when more *Afforestation* takes place, with limits on the size of the *Plantations* due to the degree of *Wildfires* and other damage that could occur. With an increase in *Plantations* the amount of *Timber Resources* will increase, which will cause a decrease in the *Gap Between Supply & Demand of Timber Products.* This forms the first balancing loop of the system, B_1.

The increased amount of *Timber Resources* will increase the *Potential Timber Product Supply*, which essentially means that more production can be undertaken. This increased *Potential Timber Product Supply* will increase the amount of *Energy Required for Production Processes*. If more energy is required the amount of *Fuel Resources Available for Energy Requirements* will decrease. The *Fuel Resources Available for Energy Requirements* is limited by the amount of *Available Fuel* resources that can be used. If there is not enough fuel available to generate the energy required for production, less production will take place and cause a decreased amount of *Timber Products Supplied* to the consumers. This will cause the *Gap Between Supply & Demand of Timber Products* to increase again. This forms the reinforcing loop, R_1.

If the *Gap Between Supply & Demand of Timber Products* keeps on increasing, a choice could be made to import more products to help meet the country's demand. An increased amount of *Imported Timber Products* will increase the amount of *Timber Products Supplied* to consumers, reducing the *Gap Between Supply & Demand of Timber Products* once more. This forms the second balancing loop of the system, B_2.

An increased volume of *Timber Products Supplied* will increase the *Possibility of Recycled Timber Products*. If there is a higher *Possibility of Recycled Timber Products* it will decrease the *Timber Demand to Produce Timber Products* for future production. If there is a lower demand for raw timber, the total amount of *Potential Timber Product Supply* will increase. This forms the third balancing loop of the system, B_3.

C. Formulation of a Simulation Model

The CLD was translated into a stock and flow diagram through the use of iSee STELLA® software. The software can be configured to use either the Euler or Runge-Kutta method of numeric integration. This simulator's run specifications are set to use the Euler method and the time unit is in years. The Euler method is preferred since even though the Runge-Kutta method is more accurate, it is unsuitable for use if IF-statement logic is used within the simulation.

The model is structured to calculate the production volumes (ton) of all the product streams in relation to changes in the projected GDP. The change in energy intensities (GWh/ton) for the different production processes are calculated and then multiplied with the production volumes so that the electricity consumption (GWh) for each of the product streams as well as the sector as a whole can be determined.

Self- and co-generation that takes place within the sector will affect the amount of electricity that needs to be supplied by Eskom. These savings are calculated by the model and then subtracted from the total electricity requirements. Some environmental impacts and legislature is also covered by the model, e.g. calculations of the volume of carbon emissions by the sector and the possibility of including strike action.

D. Testing

With the use of the iSee STELLA® software, a user friendly interface was developed for the model, providing a platform where the user can easily run different scenarios by making changes to certain variables and observe the resulting effects on the system. A few of these interface pages are documented in the Appendix and used to test the simulation model by running various scenarios.

Listed below are the types of scenarios that can be run using the developed interface. The resulting effect on the electricity demand can be seen when changes are made to:

i. Availability of South African plantations;
ii. Volume of products being exported and imported;
iii. Fractional change of products being recycled;
iv. Implementation of new technologies (type of technology and date of implementation);
v. Ratio of mechanical vs. chemical pulping and possible production line changes;
vi. Amount of self- and co-generation by industries within the sector;
vii. Implementation of carbon tax; and the
viii. Inclusion of strike action within the sector.

Three scenarios were selected for discussion in this paper and the results obtained are discussed in the next section.

RESULTS AND DISCUSSION

After the simulation was run and sensitivity analysis was performed on some of the variables in the system, the following results were obtained.

A. Implementation of new technology

There has been increasing awareness in most industries regarding their carbon footprint and energy savings (Fawkes, 2005). The implementation of more energy efficient technologies becomes more important as industries seek to minimize their carbon emissions and maintain their economic competitiveness. The impact on the Forestry & Logging sector’s electricity demand due to the implementation of two specific technologies is investigated in this scenario.

The first technology, a more energy efficient vacuum system for dewatering, is implemented in both the sawlogs and paper & pulp (P&P) product streams in the simulation. These are the two most energy intensive product streams within the sector and therefore changes within them would bring about a larger impact on the electricity consumption of the sector. Energy efficient vacuum systems can achieve electrical power savings of approximately 20 to 45%. These modern speed-controlled vacuum blowers provide more vacuum flexibility at e.g. the paper machine (Institute for Prospective Technological Studies, 2013).

The second technology is only applied to the pulping processes within the P&P product stream in the model. It is the addition of variable speed drives. In general the flow of the pumps within the paper mills is controlled by a valve, while the pump is running at constant speed. If the speed of the pump can be adjusted to accommodate only the flow required for the current demand, the energy requirements from the motor will be reduced. The resulting energy savings are typically 15 to 25% for each application (Institute for Prospective Technological Studies, 2013).

The results are compared by first running a baseline (thin line) scenario where no new technologies are implemented, after which the improved vacuum systems are added in Scenario 1 (dashed line) and the variable speed drives in Scenario 2 (thick line). The graph in Figure 5 shows the resulting impact on the electricity requirements of the sector.

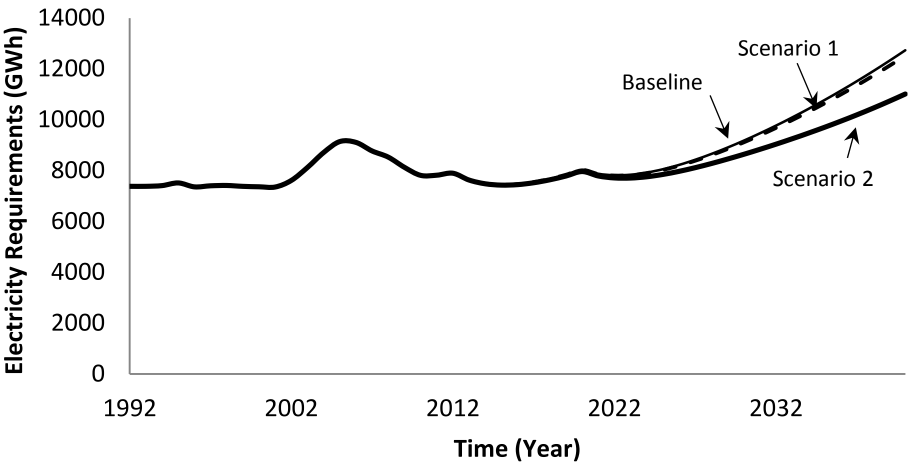

Figure 5: Electricity requirements for the forestry and logging sector

Scenario 1 indicates savings that only amount to approximately 1.7% when considering the impact made on the whole sector. When Scenario 2 is run where the variable speed drive is implemented instead of the improved vacuum systems, it can be observed that the impact is much more significant. The electricity consumption is now reduced by approximately 13.5%.

B. Implementation of carbon tax

Carbon tax is defined as a tax that companies/industrial sectors have to pay for the greenhouse gas (GHG) emissions they emit from burning fuels (Ministry of Finance). A monetary value (in South Africa's case a Rand value) is placed on each tonne of GHG that is emitted. Since some of the sectors are unable to cut down completely on their emissions, the South African Carbon Tax Policy outlines proposed tax-free thresholds for them (Carbon Tax Policy Paper, 2013).

Every sector has a basic tax-free threshold that will be revised in 5 years' time after implementation. This basic tax-free threshold indicates what percentage of the sector's total emissions for the year will be tax-free. Each sector also has additional allowances for trade exposure and process emissions which are added to the basic tax-free threshold to give a total percentage for which they do not have to pay carbon tax.

The additional allowance for trade exposed industries are given to accommodate those who are affected by their suppliers that have to pay carbon tax and thus increasing their price, but they are unable to pass the costs downstream due to the strong competition between companies (Earth Systems). The additional allowance for process emissions are given to those sectors for which the reduction of emissions is limited, e.g. the nature of their production processes do not have great potential for emissions reduction.

Currently the forestry and logging sector falls within the sectors that do not require any carbon tax to be paid, but since this will be revised in the future, it has been included in the simulator. The importance of including carbon tax within this simulator lies in the fact that if industries become more concerned with reducing their carbon emissions in an attempt to curb their expenses, it would also decrease their electricity consumption.

The scenarios used to illustrate the impact of implementing carbon tax in the forestry and logging sector will build on the previous scenario analysis regarding the implementation of new technologies. Table 3 contains the values for the basic tax free threshold, additional allowance for trade exposure, and additional allowance for process emissions that was used in each of the three simulation runs. The baseline values are set according to the Carbon Tax Policy's initial values.

Table 3: Values used in carbon tax scenario analysis

	Basic tax free threshold [%]	Additional allowance for trade exposure [%]	Additional allowance for process emissions [%]
Baseline	60	0	40
Scenario 1 & 2	60	0	30

The baseline scenario was run where no new technologies were implemented and the tax free threshold and additional allowances are set as outlined in Table 3 (Baseline, thin line). It should be noted that for the baseline case no carbon tax will be paid since the total percentage that the sector will not be taxed on equals 100%. If the additional allowance for process emissions is decreased by 10% (Scenario 1, thick line) with the starting date to pay carbon tax as 2015, the total percentage will only amount to 90% and the sector would have to start paying. In this case the industries might opt to implement more energy efficient technologies to reduce the amount of CO_2 they emit, since decreased energy consumption will result in decreased carbon emissions. Scenario 2 (dashed line) is run after the implementation of variable speed drives in the P&P industry. The resulting amount of carbon emissions in ton for each of these scenarios can be seen in Figure 6 and the amount of carbon tax to be paid is shown in Figure 7.

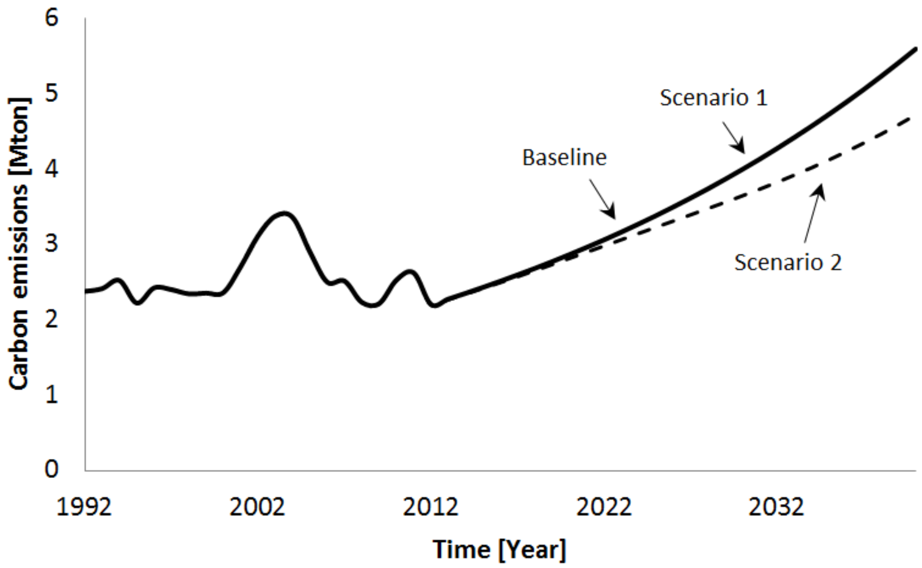

Figure 6: Resulting amount of carbon emissions emitted

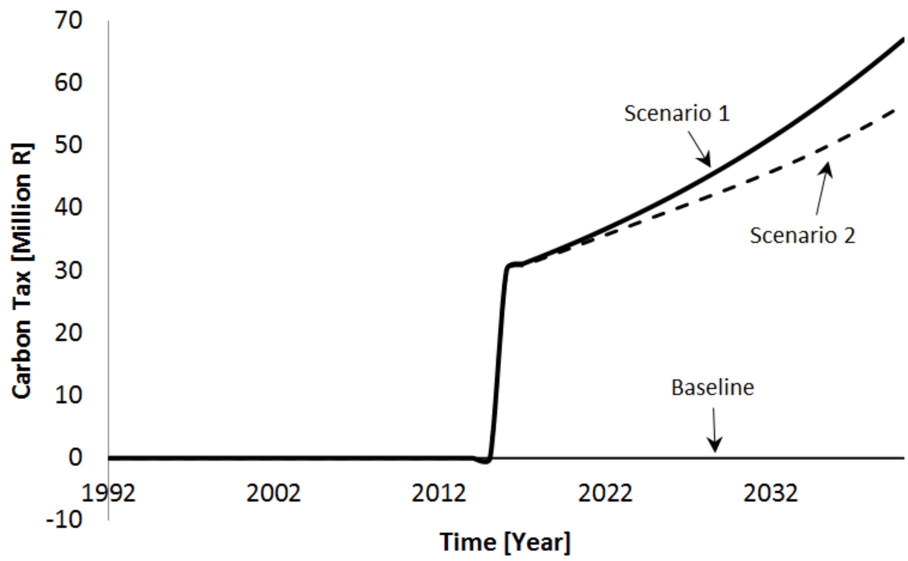

Figure 7: Amount of carbon tax to be paid

C. Production line changes in paper and pulp

The simulation accounts for the production of mechanical, chemical, and dissolving wood pulp in the P&P product stream. This scenario analysis will look at the mechanical and chemical pulp production lines. The paper that is produced from mechanical pulp typically includes newsprint, whereas paper produced from chemical pulp typically includes printing and writing paper, as well as packaging (Bajpai). A line change between the two types at the P&P mills could occur in response to changes in product demand. A decrease in the demand for newsprint has been recorded, mostly due to the increased popularity of e-books (Li, 2013).

Within the simulator, the user can make changes to the production lines to reflect the change in product demand. As a typical line change takes 2 to 3 years to implement the simulator accounts for this through a time delay (Graupner, 2014). The importance of including line changes within the simulator lies in the fact that the mechanical pulping process is much more energy intensive and therefore the sector's electricity consumption will be affected (Jacobs, 2006). Scenario analysis was performed to determine the impact of a change in production lines. The results are shown in Figure 8.

A Baseline (thin line) scenario was run with the percentage of mechanical pulp set at 20% of total pulp production (FAOSTAT). If the amount of mechanical pulp production lines is decreased by 10%, the resulting effect on the electricity requirements can be observed as Scenario 1 (thick line).

A decrease in demand for mechanical pulp would affect the industry positively seeing as the chemical pulp production line is less energy intensive. Another significant factor is that the chemical pulping process also produces a by-product called black liquor which can be used as a fuel in electricity generation (Paper Online). The increased amount of chemical pulp therefore produces more black liquor, effectively decreasing the electricity requirements from Eskom.

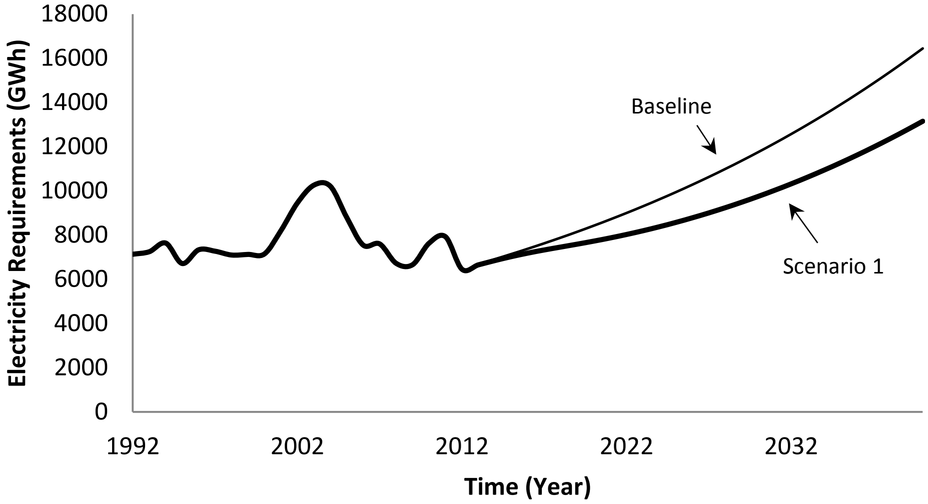

Figure 8: Electricity requirements for paper and pulp industry

Conclusion and Recommendations

This simulation model projects the future electricity demand of South Africa's forestry and logging sector, allowing sensitivity analysis to be performed to determine how certain changes to system variables will impact the electricity requirements of the industries within the sector and consequently the sector as a whole. The model forms part of the larger integrated economic sector model which consists of all South Africa's economic sectors. This integrated model will aid Eskom SOC to plan more effectively for the country's future electricity demand.

Future research may include changes (due to socio, economic, political and/or environmental influences) which could occur within the economic sectors which might require an expansion of the current Stella structure, making this project an iterative process. The forestry and logging sector is no different, and it is therefore recommended that both structure and data be revisited in 3 years to assess whether the model still accurately simulates the electricity demand for the sector.

Acknowledgments

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APPENDIX

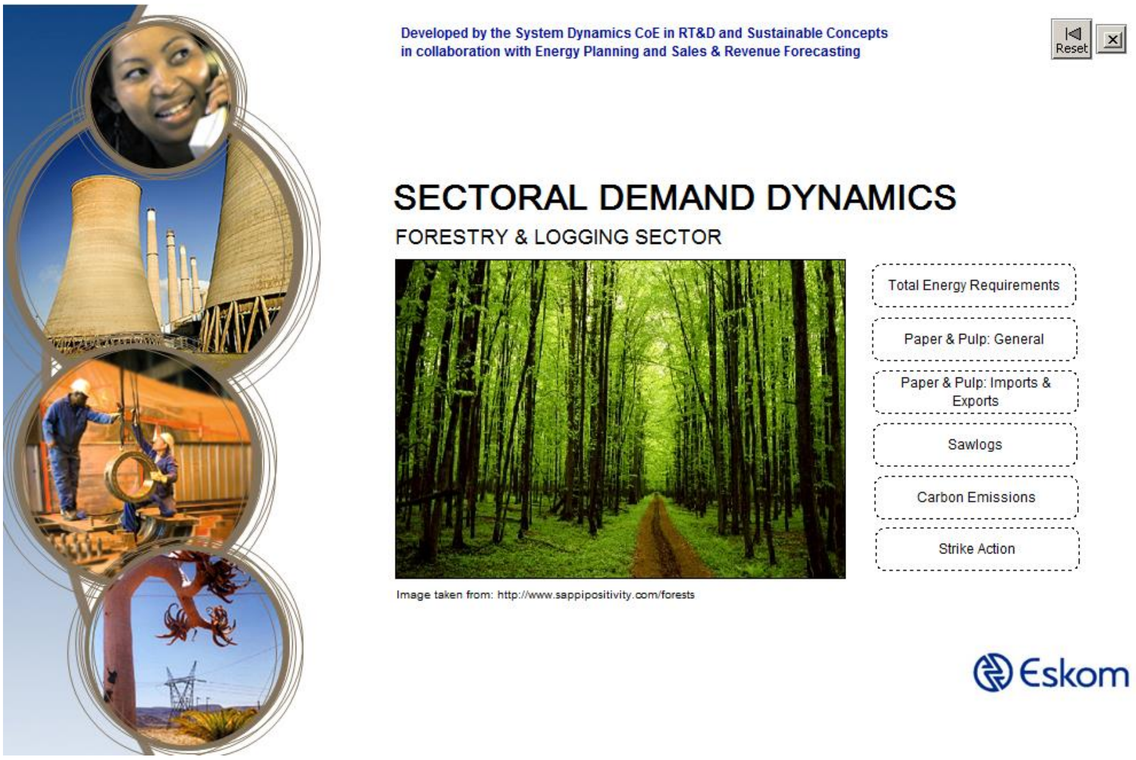

Figure 9: Interface for the forestry & logging sector model (home page)

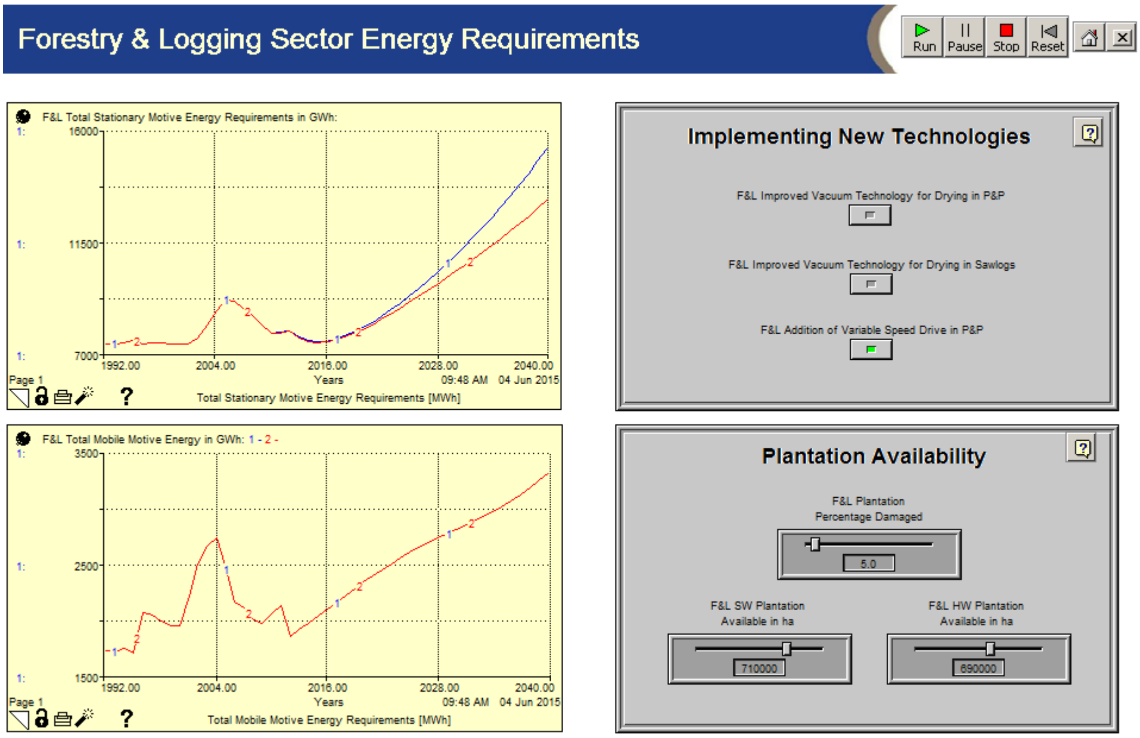

Figure 10: Interface for the forestry & logging sector model (total energy requirements)

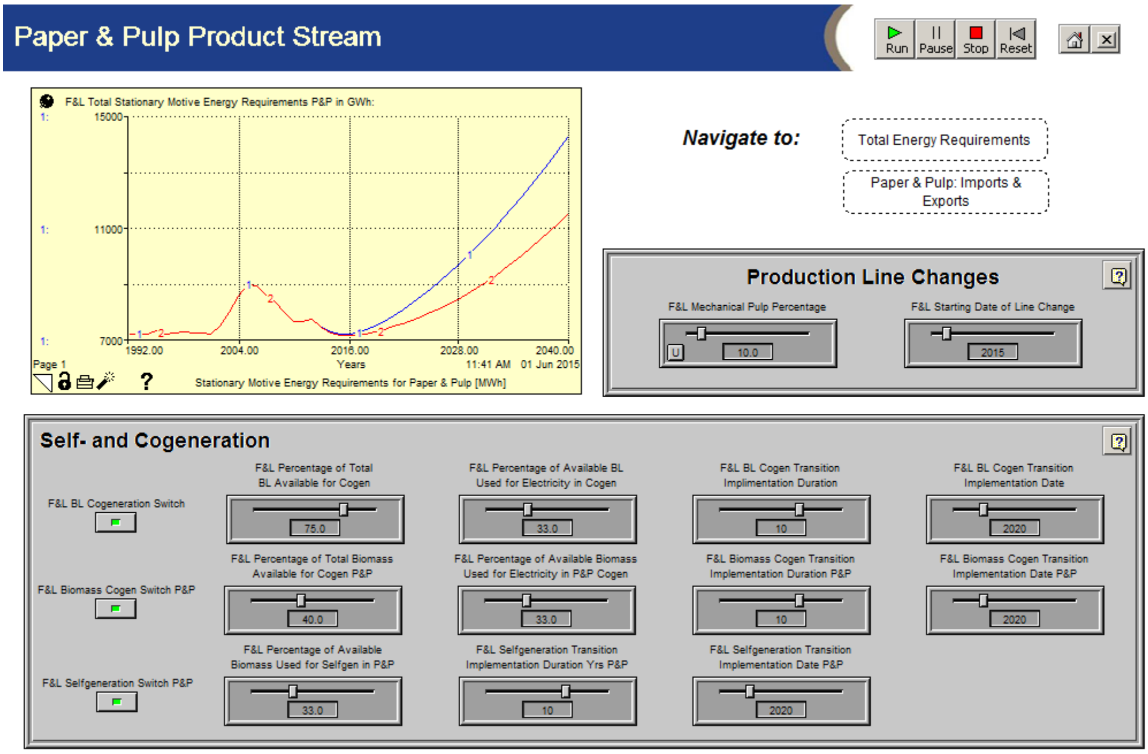

Figure 11: Interface for the forestry & logging sector model (general paper & pulp page)

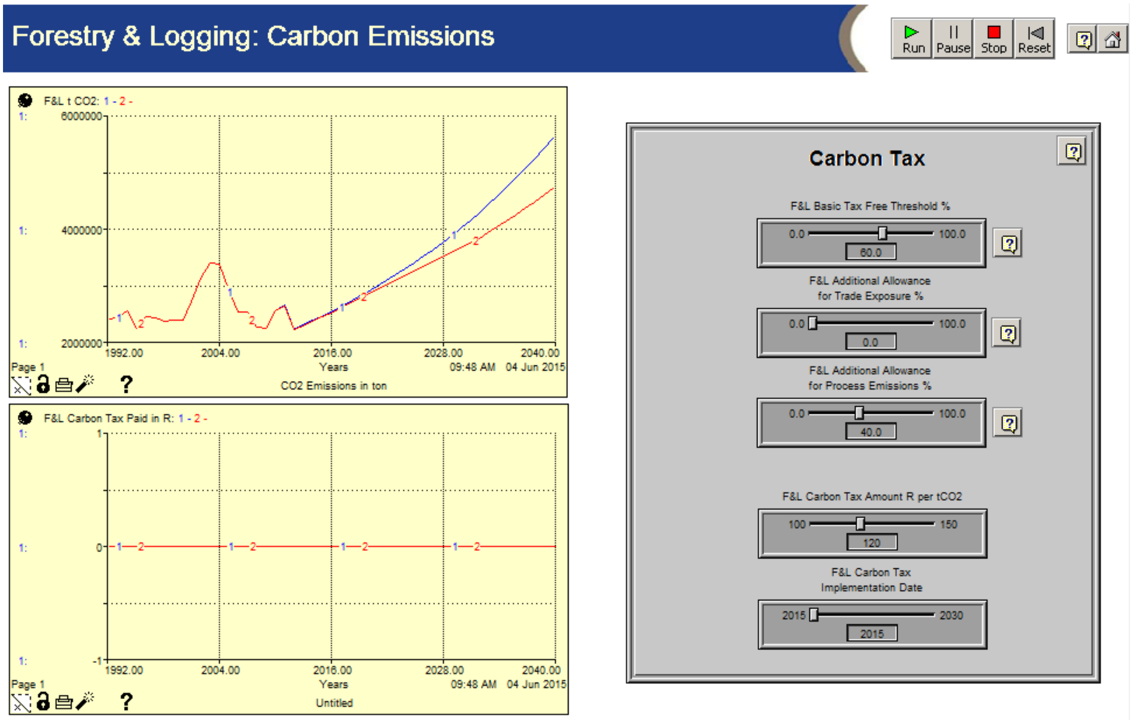

Figure 12: Interface for the forestry & logging sector model (carbon emissions)