The Application of a Concept Model to Illustrate the Tragedy of the Commons in the Sugar Cane Supply Chain[1]

Shamim Bodhanya

Abstract

The sugar cane supply chain is highly fragmented with large numbers of mutually interacting but independent stakeholders. It is expected that it will be characterised by many examples of the 'tragedy of the commons'. This paper explores the underlying feedback loops in the tragedy of the commons for one small aspect of the supply chain, namely that of transport from growers to the respective mill area. This is by application of the system archetype. Thereafter a system dynamics *concept model* is presented. The purpose of a *concept model* is to explore and understand a phenomenon, and is designed neither for prediction nor optimised decision making. Nevertheless, the model indicates that there are an optimum number of trucks for the system as a whole but this would be invisible to individual growers. The results also indicate that because of the underlying system structure and respective feedback loops the system will be operating sub-optimally. The utility to individual growers drives the system relentlessly towards the tragedy of the commons. Opportunities for extending the work in a number of new directions are identified.

Keywords: tragedy of the commons, systems archetypes, system dynamics model, supply chain, sugar cane

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Introduction

It is anticipated that the sugar cane supply chain is characterised by many examples of the 'tragedy of the commons'. The reason is that it is highly fragmented with large numbers of mutually interacting but independent stakeholders. It is likely that they each act based on their own individual incentives without necessarily taking into account the impact on the collective whole system of which they are part. As a result they tend to optimise their own sub-systems while sub-optimising the whole sugar cane supply chain. In addition, they share common resources often without realising it. These together render the conditions typical of the tragedy of the commons.

In this paper, I explore the application of the tragedy of the commons by, firstly, drawing on the relevant systems archetype and, secondly, by application of a concept system dynamics model to help understand and illustrate the tragedy of the commons.

Although it is likely, given the context of the sugar cane supply chain, that there are many more such examples, in this paper I limit the inquiry to a small aspect of the transport system in the sugar cane supply chain.

What is the Tragedy of the Commons?

The 'tragedy of the commons' is a concept formulated by Hardin (1968) to illustrate how individual incentives may lead to systemic collapse in a commons. He presents an example of herdsmen in common pasture land. Under frontier conditions, each herdsman gets the full benefit of introducing a new head of cattle into the pasture. However, as the total number of cattle introduced into the pasture starts approaching the carrying capacity (Hardin 1996) of the land, each herdsman also experiences a small negative effect, which reduces the overall utility to that herdsman. The full utility of adding a head of cattle by a particular herdsman accrues to that individual, while the negative utility of overgrazing is shared by all herdsmen. It is therefore rational for each herdsman to add an extra head of cattle, and then to continue doing so incrementally. The problem is that at the level of individual rationality it makes sense for all herdsmen to do the same. The systemic effect is collective ruin. As stated by Hardin (1968: 162), '[E]ach man is locked into a *system* that compels him to increase his herd without limit' (e.a.).

Although Hardin used the case of overpopulation to demonstrate the tragedy of the commons, it applies in any situation where there is a commons, without specific mechanisms to prevent the tragedy. Examples of such mechanisms include private ownership, coercive regulation or self-regulation by the community. A commons is any resource that is freely available for shared use (Dietz, Dolsak, Ostorm & Stern 2002). Some examples include land, oceans, other natural resources and air. More abstract examples include the frequency spectrum, human capability and market share of a firm. The recent energy crisis leading to the need for load shedding in South Africa may also be characterised as stemming from the tragedy of the commons.

The comparison of Hardin's example of herdsmen in pastoral land with sugar cane transport between growers and the respective mill area is striking. A direct transposition of a herdsman with a grower and a head of cattle with a truck in the example illustrate the tragedy of the commons in sugar cane transport.

Tragedy of the Commons - Systems Archetype

The systems archetypes are common patterns of behaviour and underlying systems structure that replicate themselves in a variety of natural, physical and social systems (Senge 2006; Senge, Kleiner, Roberts, Ross & Smith 1994; Wolstenholme 2004). One such archetype, unsurprisingly, is that of the tragedy of the commons. The situation is one where there are several stakeholders who use a common but limited resource. They each accrue benefit from using the resource but this benefit is subject to diminishing returns in the longer term. In extreme situations, this is manifested by short terms gains but long term ruin. The systems archetype operationalises Hardin's tragedy of the commons by explicating the underlying feedback loops (Sterman 2000). This archetype is illustrated in the diagram below:

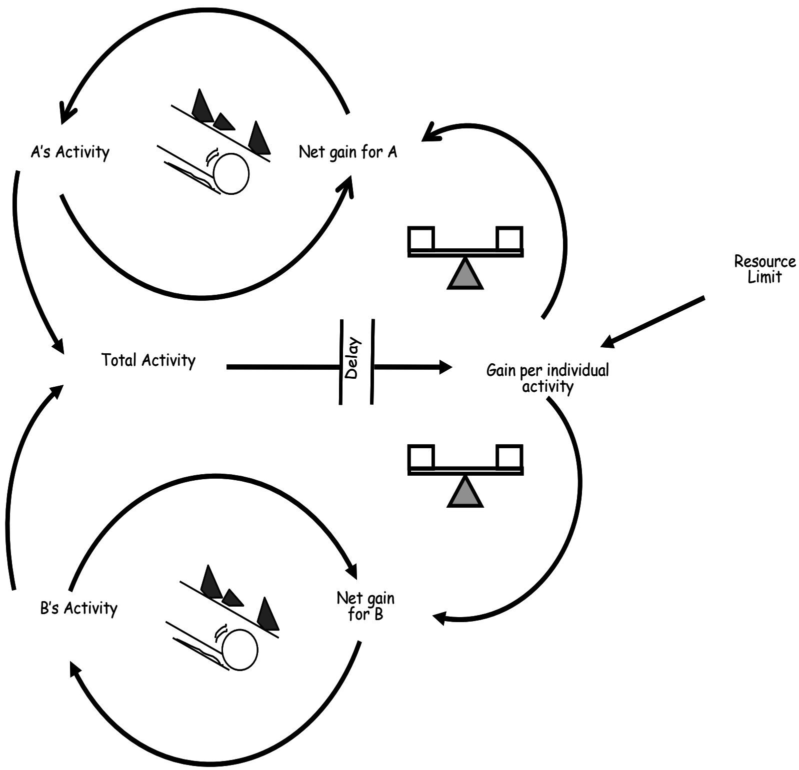

Figure 1: Tragedy of the Commons – Systems Archetype Source (Senge 2006)

The archetype illustrates that an increase in the activity of one party brings in a net gain to that party, which in turn leads to an increase in that party's activity. This is a positive feedback loop. In the diagram this is shown for both Party A and B. There are additional feedback loops that affect the behaviour of the system, however. As the total activity increases it brings the system closer to its resource limit and hence after a time delay, negatively impact the gain made by each individual activity. This total systemic impact may not be apparent to the individuals until it is too late, when the system has exceeded the 'carrying capacity' of the resource and its associated regeneration rate. This means that the resource has eroded to such an extent that it adversely affects the net gain to each of the individuals, or it has been completely depleted, hence the tragedy. The template above only shows two parties, but it is equally applicable to many parties. The net result is that they 'collectively conspire', without knowing that they are doing so, to undermine the very system that supports them and that has been the source of their individual gains.

We may now proceed to apply this archetype to one element of the sugar supply chain, namely transport by growers. This is shown in the diagram below, where I have 'instantiated' the tragedy of the commons systems archetype, with the particular transport application.

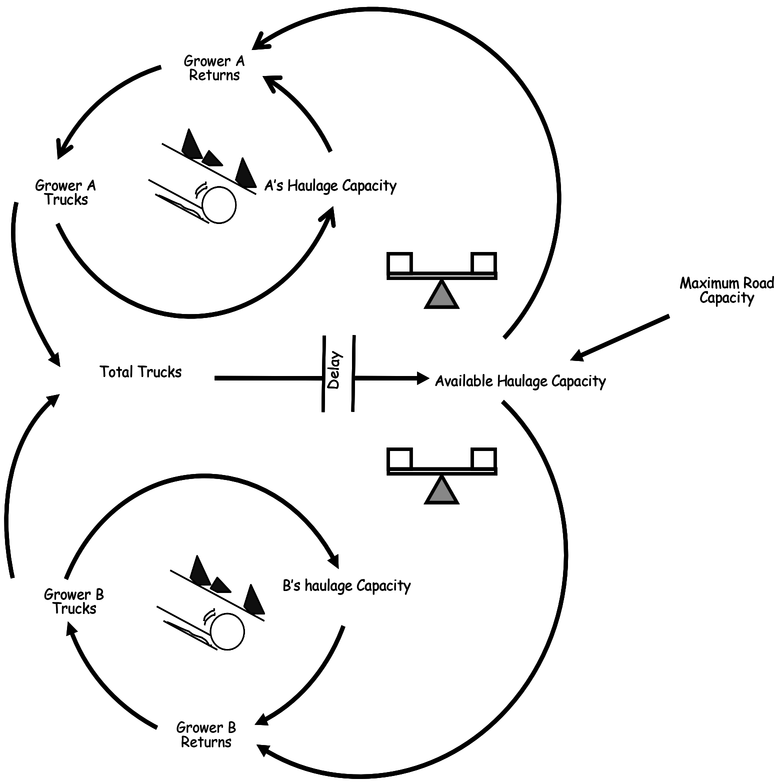

Figure 2: Tragedy of the Commons in Sugar Cane Transport

The higher is the haulage capacity of a grower the higher the returns that it receives. Each grower is therefore incentivised to increase its haulage capacity by investing in new trucks. This stimulates the positive feedback loop. As the total number of trucks on the road increases the available haulage capacity is gradually reduced over time. This triggers a negative feedback loop as it negatively affects the returns of each of the growers. This process continues until the maximum road capacity is reached, which equates to the depletion of a resource. We may view the Available Haulage Capacity as a common resource in this little transport system. Individual stakeholders probably do not even consider it as a resource, as they are focused on the incremental gains out of their activities, little realising that they are depleting this common resource that underpins the system.

A *Concept Model* to Understand the Tragedy of the Commons

In this section, I extend the systems archetype to a concept system dynamics model. By a *concept model* I am referring to a basic model to explore a concept or a phenomenon. The purpose of such a model is neither prediction nor optimised decision making but rather for contributing to learning about the phenomenon. For this reason, the *concept model* is not a detailed model and may not necessarily be parameterised with actual data, but rather with illustrative data. It may be considered a transitional object that stimulates double loop learning (Morecroft & Sterman 1994). Off course, a *concept model* may also serve as a basis for more comprehensive analysis and be extended into a full model, with real world parameters and subject to rigorous validation. The following system dynamics stock-flow model is formulated as a *concept model* to explore the phenomenon of the tragedy of the commons.

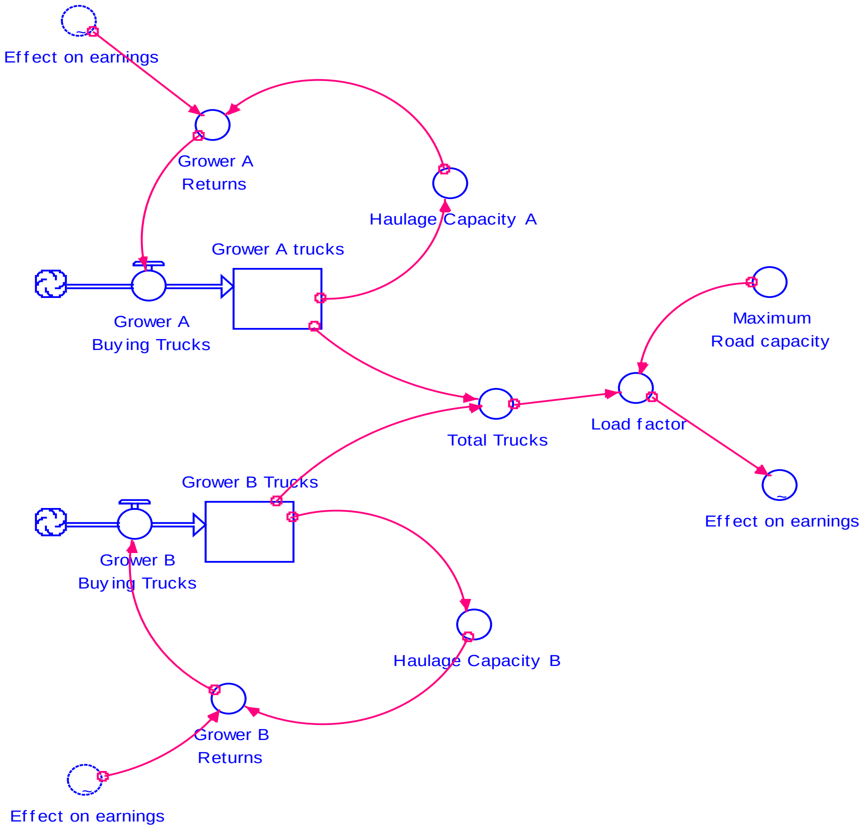

Figure 3: A Concept Systems Dynamics Model to Illustrate the Tragedy of the Commons

The basic conventions of system dynamics modelling is that of asset-stock accumulations (Dierickx & Cool 1989; Warren 2002), referred to as stocks which accumulate or deplete through flows. A stock is represented by a rectangle and the flows are represented as pipes with a 'tap' icon. The circles are known as converters, and may be used to represent other model variables such as constants and other model parameters. The single arrows are referred to as connectors and represent relationships between variables in the model. Stocks are variables that accumulate and deplete over time. The values of the inflows and outflows accumulate in stocks.

In the model above, we have two growers each of whom invests in trucks to increase their respective haulage capacities. As the haulage capacity increases the returns to the grower increases. This in turn stimulates the grower to invest in more trucks, thereby creating a positive feedback loop, which is a form of reinforcing behaviour. The model structure for both growers is identical. It is therefore clear that the investment in trucks offers utility to the growers. There is also another set of negative feedback loops that leads to pernicious system behaviour. As each grower invests in trucks, the value of total trucks gradually increases over time to approach the maximum road capacity. This is captured in load factor. The higher the number of trucks relative to the maximum road capacity, the higher is the load factor. The load factor is therefore a measure of the overall system blockage. The impact of such system blockages on individual growers is represented by the converter, effect on earnings. This is a fraction from 0 to 1, which has a reductive effect on returns to grower when its value is less than 1. When the load factor is 0, representing a complete absence of system blockages, the effect on earnings is 1 and therefore has no effect on the returns that accrue to the growers. A load factor of 0 would equate to frontier conditions in Hardin's terms. By contrast as the load factor increases, the effect on earnings begins to reduce the returns to grower. This is the process that models the phenomenon of diminishing returns to increasing investment that underlies the tragedy of the commons.

The model has been run for a period of 80 months. The system behaviour is represented in the graphs below:

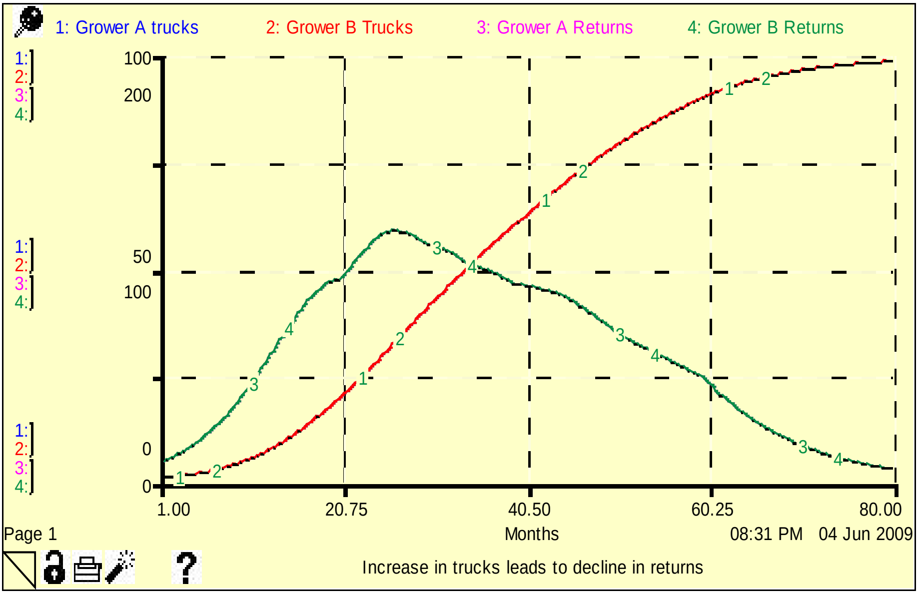

Figure 4: System Behaviour

Figure 4 shows the stock of trucks and the returns for Grower A and Grower B respectively for the 80 month period. Since the model represents the same investment proclivity for both growers, the graphs are identical for both. If Grower A had a more aggressive investment strategy then the graphs would be phase shifted such that Grower A will have achieved a higher stock of trucks and associated investment returns much earlier. This would have been at the expense of Grower B.

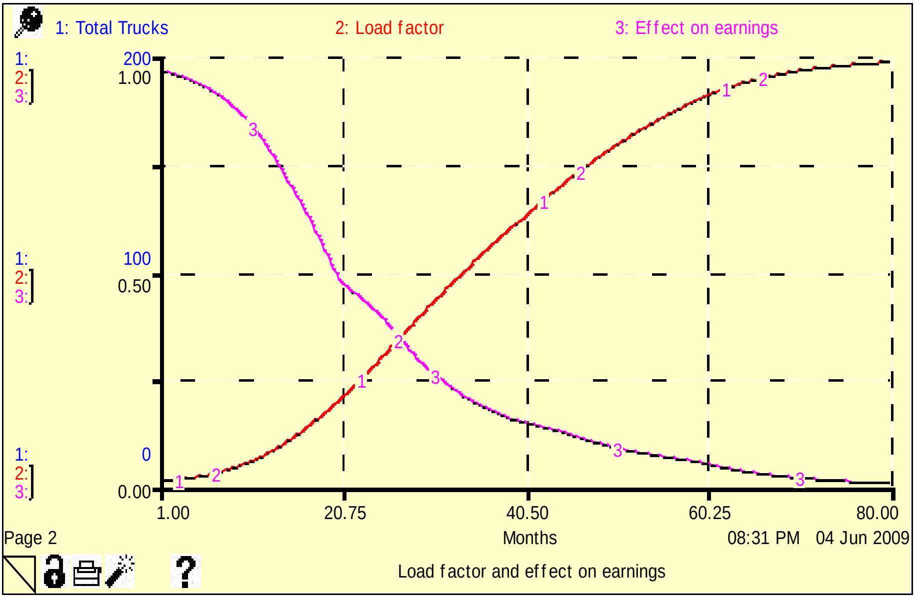

Figure 5: System Behaviour: Load Factor and Effect on Earnings

Figure 5 shows the impact of an increase on the stock of total trucks on load factor, and the concomitant effect on earnings. Total trucks follow typical s-shaped growth. Early on when there are high returns there is a sharp increase in investment, but it slows down when the negative utility resulting from system blockages begin to affect the growers adversely.

Figure 6: Overshoot and Collapse – The Tragedy

Figure 6 clearly demonstrates the phenomenon of the 'tragedy of the commons' which is exemplified in the overshoot and collapse behaviour. The total returns increases sharply at first, driven by the positive feedback loops, as a result of aggressive investment by growers. It peaks at a value of 236 in 26¼ months. Thereafter, any additional investment in trucks brings a net reduction in returns at the system level, when the negative feedback loops become dominant. Individual firms do not realise this and continue to invest in haulage capacity beyond the optimum point. By inspection from the graph, the optimum number of trucks is 64.

The question that has to be addressed is why do growers continue to invest in new haulage capacity? From Figure 4 it is evident that growers merely need to continue investing as long as their individual returns increase, and to cease investment in new trucks as soon as there is a decrease in their returns. The model above represents only two growers, whereas there are actually a large number of growers and other stakeholders in the sugar cane supply chain. A slightly different formulation of the model is presented below.

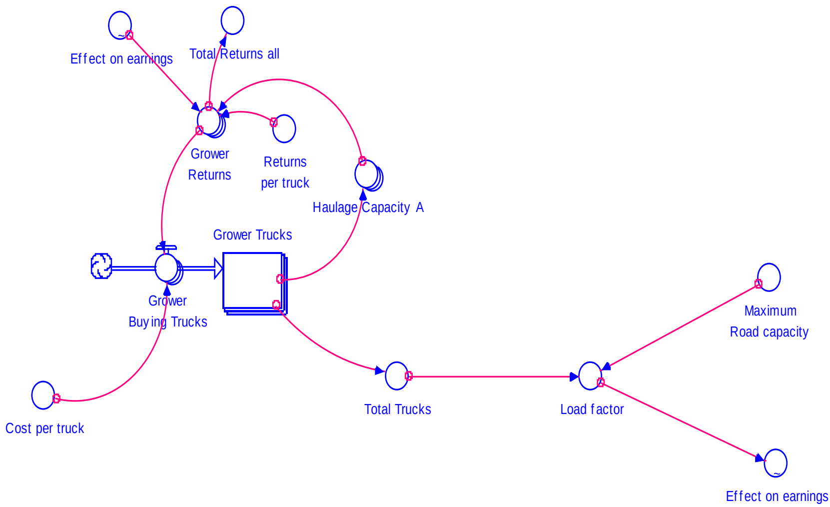

Figure 7: A Systems Dynamics Model to Illustrate the Tragedy of the Commons Using Array Formulation

This formulation still represents two growers only but uses arrays so that a larger number of growers may be included, if desired, using the same basic model architecture without having to explicitly represent grower components graphically for each extra grower. Two additional converters are included to explicitly model the cost per truck and returns per truck. The results of this model are identical to that as shown in Figures 4, 5 and 6. This basic model formulation is now extended and presented below:

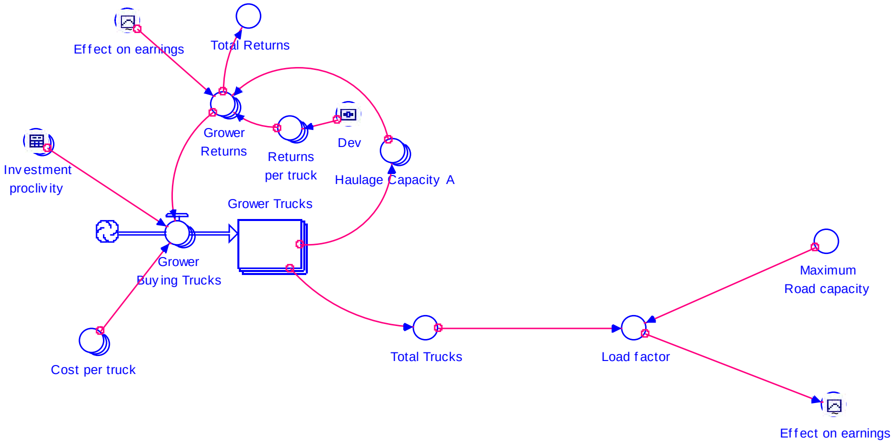

Figure 8: A Systems Dynamics Model to Illustrate the Tragedy of the Commons Showing Individual Investment Proclivities

This formulation depicts 10 growers. A new converter, investment proclivity, has been included to represent the fact that different growers have different investment proclivities and strategies. The results are shown in Figures 9, 10 and 11 below.

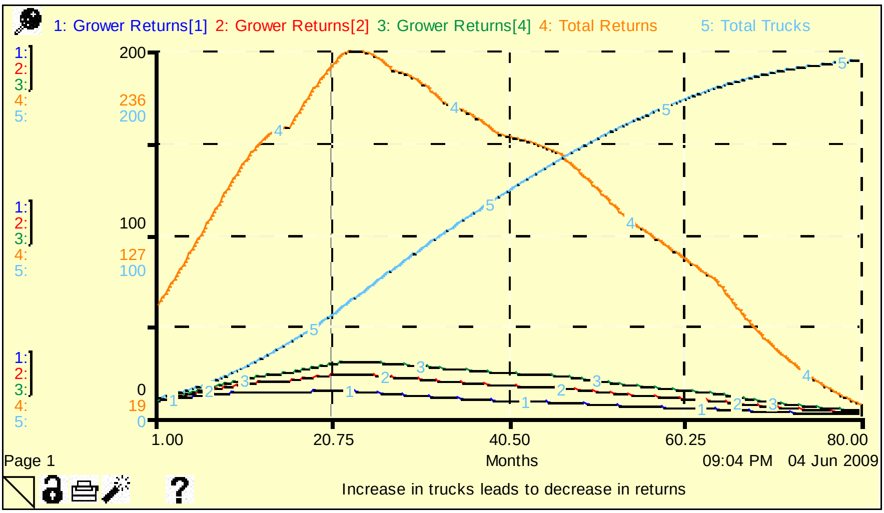

Figure 9: System Behaviour

Figure 9 depicts grower returns for growers 1, 2 and 4 as well as total returns and total trucks. Separate graphs based on the underlying model may be generated to show returns for all 10 growers if required. A comparison between Figure 4 and Figure 9 indicates that the total returns are spread across a larger number of growers. In the case of two growers, it is much easier to detect when the returns to growers are decreasing relative to that when there are 10 growers. In other words, the peak for each individual grower is also much smaller with 10 growers than with 2 growers. As a result, the negative utility of adding an extra truck is likely to be indiscernible to the individual grower, but when accumulated at a system level has disastrous consequences. These system level results are shown in Figures 10 and 11 and are analogous to the results shown in Figures 5 and 6.

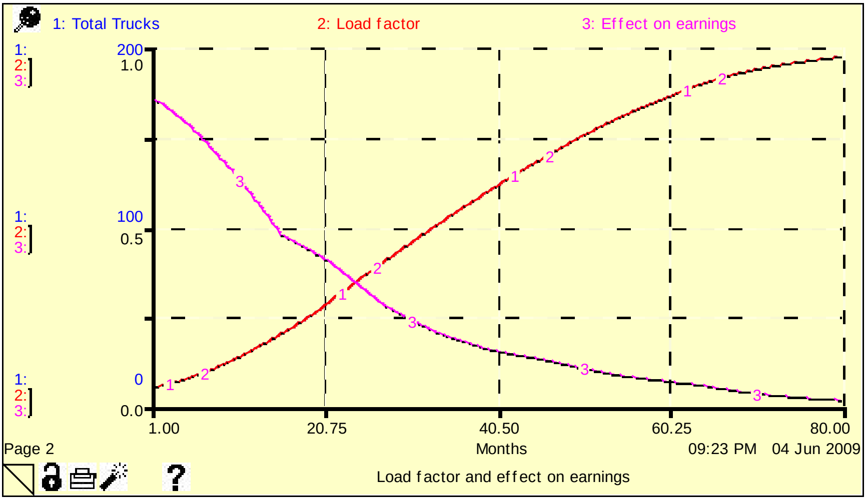

Figure 10: System Behaviour: Load Factor and Effect on Earnings

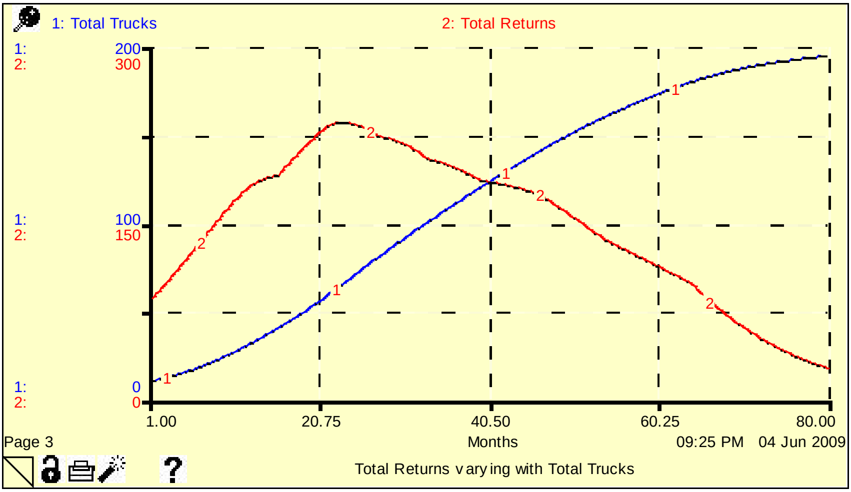

Figure 11: Overshoot and Collapse – The Tragedy

The returns to growers are affected by a number of factors other than just the number of trucks that have been deployed. This will include weather, quality of the sugar cane, burn-to-crush delay, sucrose content and so forth. For the purposes of illustration only, this may be modelled by including a small random component. The returns to grower is no longer a constant value but is now formulated using the normal distribution with a mean of 10, and a standard deviation of 1.2. The results are shown in Figure 12 below.

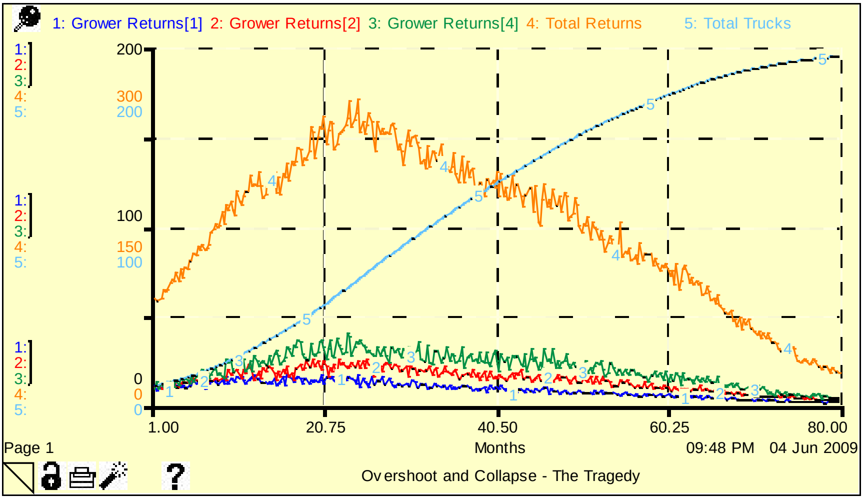

Figure 12: Overshoot and Collapse – The Tragedy of the Commons

The tragedy of the commons is vividly displayed in Figure 12, as it is now clear that the point at which to stop investing in trucks is completely indiscernible to individual growers.

It must be noted that the load factor is a model artifact that is invisible to individual growers. The striking conclusion from the model is that while the optimum number of trucks (which is unknown to individual growers) is 64, the sugar cane supply chain may indeed have a very high over-capacity of trucks much closer to the resource limit, which reduces their overall returns drastically, because of system blockage. This is even without taking into account the cost of maintaining large fleets etc.

Conclusion

Since the sugar cane supply chain is highly fragmented with large numbers of mutually interacting but independent stakeholders, it is speculated that it will be characterised by many examples of the 'tragedy of the commons'. Stakeholders act based on their own individual incentives without necessarily taking into account the impact on the collective whole system of which they are part. As a result they tend to optimise their own sub-systems while sub-optimising the whole sugar cane supply chain. In addition, they share common resources often without realising it. These together render the conditions typical of the tragedy of the commons.

The application of a system archetype and a 'toy' model was used to explore the tragedy of the commons in one small component of the sugar cane supply chain, namely that of transport from individual growers to the respective mill area. The purpose of the *concept model* is to explore and understand a phenomenon, and not for prediction or optimised decision making. Nevertheless, the model indicates that there are an optimum number of trucks for the system as a whole but this would be invisible to individual growers. The results also indicate that because of the underlying system structure and respective feedback loops the system will be operating sub-optimally. The utility to individual growers drives the system relentlessly towards the tragedy of the commons.

The work here may be extended in several directions. There ought to be effort expended in discovering other examples of the tragedy of the commons in different parts of the sugar cane supply chain. There are a whole suite of other systems archetypes, such as eroding goals, success to the successful, growth and underinvestment, escalation and so forth that are also applicable. These will offer unique insights and understanding of the supply chain. Further experimentation could be carried out on the model to identify leverage points and to explore different forms of intervention to improve the situation at a system level. One example would be to identify some kind of measurement for actual load factor as it varies. This then acts as an information signal that is fed back to individual growers who may then change their behaviour. The *concept model* may be extended into a full, rigorous and validated model. Other *concept models* could be developed exploring other facets of the sugar cane supply chain.

Finally, the work conducted here could be extended and used as a means of educating the various stakeholders in the supply chain of the unknown, but pernicious impact of their individual behaviours that could lead to collective loss. There could also be the application of group model building with stakeholders in the supply chain (Anderson & Richardson 1997; Anderson, Richmond & Vennix 1997; Vennix 1996; 1999). This would hopefully act as a stimulus to intervene such that some of the supply chain problems are ameliorated.

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Shamim Bodhanya
Leadership Centre (UKZN)
bodhanyas1@ukzn.ac.za