A SYSTEM DYNAMICS APPROACH TO UNCERTAINTY IN BRIDGING TECHNOLOGY INTERACTION.

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ABSTRACT
This paper is an extension of previous research on the simulation of three technologies that interact in competition. Technology is considered as a result of innovation, a rate dependent process. Technology growth patterns can be traced in a number of ways. One interesting way that has been recently used very effectively is using bibliometrics as a data source for technology. In this paper the technology system is treated as a coupled system where the interacting dynamics is described by the Lotka-Volterra system of differential equations. The uncertainty in the interaction of the bridging technology with the mature defending technology and the newly introduced attacking technology is addressed in this research using a Monte Carlo multivariate simulation technique and a system dynamics approach. The research method is exploratory and case based a method that has been established as useful especially early on in research. Some exploration into cyclic behaviour of a modified version of the three technology system is also attempted.

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1 INTRODUCTION AND RESEARCH METHOD

The focus in this paper is on exploring technology diffusion in competing technologies such as information technology, biomedical technology, energy technology and others. Some of these competing technologies have been addressed recently in system dynamics \cite{15}\cite{16} and bibliometrics \cite{2} and diffusion modeling \cite{10}\cite{17} research. This research is an extension of recent research on simulation of bridging technology dynamics \cite{15}\cite{16}.

Technology can be considered as a body of knowledge as well as the result of an innovation process that can be non-linear and time dependent. In this sense technology can thus be modeled as the integrated result of innovation that is a rate dependent process. This results typically in the diffusion of technologies that can co-exist. Nair et al \cite{14} refer to the possibility of co-existence of technologies such as dialysis and transplantation of organs in the medical arena. This technology diffusion process can be modeled in a number of ways. One way is using the Bass diffusion approach \cite{3} with numerical discretization as illustrated previously in the diffusion of Computational Fluid Dynamics (CFD) technology \cite{18}. The aim in that research was to compare different CFD technologies.

Another technology modeling approach that has been shown to be effective \cite{15}\cite{16} especially in exploratory parametric studies is the system dynamics approach. System dynamics was introduced in the 1960’s by Forrester \cite{6}\cite{7} in his pioneering research on modeling socio-technical systems using concepts derived from the theory of feedback control. Wolstenholme \cite{21} in his research defines system dynamics as “A rigorous method for qualitative description, exploration and analysis of complex systems in terms of their processes, information, organizational boundaries and strategies; which facilitates quantitative simulation modeling and analysis for the design of system structure and control”. This definition also points to the roots of feedback control as well as the ability of system dynamics to address the inherently complex nature of systems that interact.

This paper also illustrates the inherent effectiveness of system dynamics to elucidate the complex behaviour of interacting technology systems. The systems thinking approach is also discussed and evaluated extensively by Jackson \cite{9} when he addresses system dynamics as a complex system approach as opposed to hard systems thinking considered more of a simple system approach. Meadows \cite{13} adds more fundamental methodological insights on the complex behaviour of systems with her thinking in systems approach to system dynamics simulations. Hunger \cite{8} focuses on the system or holistic perspective in his work and effectively stresses the relationship between soft and hard systems thinking. Elements of the systems thinking approach are used in this paper to shed light on the system dynamics approach used to model the current technology system.

The research method used in this paper is qualitative and exploratory in nature and is useful in the early stages of research as indicated by Cooper and Schindler \cite{5}. Some of the issues explored in this research relates to the diffusion of technologies under uncertainty of interaction. The technology system considered comprises three interacting technologies. In the first part of the research the model parameters are chosen to reflect a situation where one technology acts as a bridge between the development phases of two other technologies. The model presented is based on previous work by Ahmadian \cite{1} for deterministic conditions without uncertainty. For this part of the research a case study method also supported by Leedy \cite{11} is used to explore the effectiveness of system dynamics as a theoretical modeling basis for simulating the technology interaction under uncertainty.

The aim of this research focuses on evaluating to some extent a technology system dynamics model incorporating a bridging technology and uncertainty of interaction between the technologies. In this case only the uncertainty of interaction between the defending technology and the bridging technology is considered to address the main research question of the extent of the interaction effect. This is also based on previous research on related topics \cite{15}\cite{16}.
A secondary research objective is to establish the effect that the technology system dynamic model parameters may have in describing for example possible cyclic behaviour of the technology system. In this case the system dynamic model is modified to some extent to show under what circumstances limit cycle behaviour can be observed. This work is also based on some research presented by Mamat et al [12] considering a three tier food chain. The modified technology system dynamics model presented in this paper is based on the Lotka-Volterra model encapsulated by Mamat et al [12]. The effect of model parameters on limit cycle behaviour for this technology system is explored using the system dynamics model.

Part of the research presented here is an extension of the research of Mamat et al [12] as well as Chauvet et al [4]. Both these researchers [4][12] explain the possibility of existence of periodic solutions of the Lotka-Volterra system of dynamic differential equations. They focus on the existence of a Hopf bifurcation point pointing to periodic solutions around this point. The analytical Lotka-Volterra periodic solutions for two competing species are qualitatively shown to be similar to the periodic occurrences of hare and lynx in the Hudson Bay area.

Schmoch [19] provides some evidence of cyclic technology behaviour using bibliometrics [2] and patent analysis. He shows that industrial robot technology went through a double boom cycle across a period of approximately 15 years. This research paper qualitatively compares some system dynamics simulation results for a technology system containing three interacting technologies with the results shown by Schmoch [19].

2 A TECHNOLOGY SYSTEM DYNAMICS MODEL

In this research paper the technology system dynamics model developed and shown in figure 1 relates to the non-linear system of differential equations similar to that used by Ahmadian [1]. The competing technologies are denoted by X, Y and Z respectively. In this first version of the Lotka-Volterra system of differential equations all the parameters used have non-zero values associated with them. In these equations Ai denote the growth rate or logistic parameter for technology i when it is living alone, Bi is the limitation parameter for species i related to niche market capacity and Ci as well as Di are the interaction coefficients:

\[
\begin{align*}
\frac{dx}{dt} &= A_1 X - B_1 X^2 - C_1 X Y - D_1 X Z \\
\frac{dy}{dt} &= A_2 Y - B_2 Y^2 + C_2 X Y - D_2 X Y \\
\frac{dz}{dt} &= A_3 Z - B_3 Z^2 + C_3 X Y - D_3 Z Y
\end{align*}
\]  

(1)

In this first model Technology Z is considered to be a bridging technology and the parameter values used and shown in table 1 relate to this mode. The parameter values used in table 1 are similar to those used by Ahmadian [1] in his deterministic system dynamics simulations. This is done to be able to evaluate the current system dynamics model referred to in figure 1 against some previously published data.

| Table 1: Some typical model parameters for equation set (1) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Model parameters - equation set (1) | A1 | B1 | C1 | D1 | A2 | B2 | C2 | D2 | A3 | B3 | C3 | D3 |
| Certain | 0.1 | 0.01 | 0.1 | 0.1 | 0.1 | 0.01 | 0.1 | 0.1 | 0.1 | 0.01 | 0.1 | 0.1 |
| Uncertain | C3=RANDOM NORMAL(0.01,0.3,0.1,0.05) |

Currently there are a number of computer simulation tools available to simulate system dynamics models such as the one of the competing and interacting three technology system indicated in figure 1. The one used in this research is Vensim DSS [20]. In the Vensim system...
The dynamics model the boxes denote level variables (for example the emerging Technology Y in this case). The level variables are generally the result of numerical integration of rate variables such as for example Technology Y change rate denoted in figure 1 as a valve symbol. In this context the rate variables can be considered as the innovation rate of the relevant technology. The arrows indicate the respective relationships between the variables. The technology system shown in figure 1 with more than 20 relationships indicated by arrows can thus be considered to be a complex or complicated system with multiple interactions.

Figure 1: The technology System Dynamics Model

To illustrate the effect of system parameter values the following modified system of non-linear differential equations describing an alternative competing technology system is also considered. Here some parameter values (B1,D1,B2,B3 and C3) are considered to be zero. All further parameter values shown are considered to be positive. The parameter values used to do model computer simulations in Vensim [20] are shown in table 2:

\[
\begin{align*}
\frac{dx}{dt} &= A1 \times X - C1 \times X \times Y \\
\frac{dy}{dt} &= -A2 \times Y - C2 \times Y \times Z + D2 \times X \times Y \\
\frac{dz}{dt} &= -A3 \times Z + D3 \times Z \times Y
\end{align*}
\]

(2)

Table 2: Some typical model parameters for equation set (2)

<table>
<thead>
<tr>
<th></th>
<th>Model parameters -equation set (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certain</td>
<td>A1  B1  C1  D1  A2  B2  C2  D2  A3  B3  C3  D3</td>
</tr>
<tr>
<td>Uncertain</td>
<td>A1=RANDOM NORMAL(0.3,0.8,0.5,0.05)</td>
</tr>
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The parameter values used in this simulation are chosen to be similar to the ones used by Mamat et al [12] to be able to compare the current results to some previously published
values for deterministic conditions. The parameter values are furthermore chosen to illustrate the possibility of cyclic behaviour of interacting technologies. Both Mamat et al [12] and Chauvet [4] indicate the possibility of sustained periodic solutions for the combination of parameters:

\[ A3 = A1 \times \frac{D3}{C1} \]  

Equation (3) indicates the Hopf bifurcation point for equation set (2) and if D3 is chosen as 0.5 A3 is calculated as 0.5 from table 2.

The technology system modelled using equation system (2) pertinently differs from equation (1) in the sense that parameters A2, A3, C2, D2 and D3 have opposing signs in equation (2). From a systems thinking perspective [5] this reflects the dynamic hypothesis that for this case the innovation of Technology X is positively influenced by the existence of Technology X through A1 and negatively influenced by the existence of competing Technology Y through the interaction coefficient C1. In the same systems thinking approach it is hypothesised that the Technology Y change rate is negatively influenced by the existence of Technology Y through the obsolescence rate A2 of Technology Y whilst it is positively influenced by learning experiences gained from interaction with Technology X through interaction coefficient D2. At the same time Technology Y change rate is negatively influenced by its interaction with Technology Z that is preying on Y through the interaction coefficient C2.

3 SOME RESULTS WITH UNCERTAINTY IN BRIDGING INTERACTION

The following system dynamic simulation results using equation set (1) and the model depicted in figure 1 have been obtained using Vensim. All the system dynamics results shown have been obtained using numerical integration and a fourth order Runge Kutta method combined with time intervals of 0.01 year.

The parameter values used in these simulations and indicated in table 1 have been chosen to be similar to those used by Ahmadian [1] for comparison purposes. The initial technology levels used in the system dynamics simulations were 5, 0.01 and 0.01 for Technology X, Y and Z respectively. Monte Carlo multivariate simulations with 200 iterations were done in the cases where uncertainty was modelled.

The system dynamic simulation responses shown in figure 2 for deterministic parameters indicate quite clearly the bridging effect of Technology Z from year 6 to year 24 where Technology Y still show very small responses whilst the defending mature Technology X has already started its demise. The bridging Technology Z reaches a peak in activity level just below 8 at approximately year 17. These results are similar to those obtained by Ahmadian [1] for deterministic conditions and thus reinforces confidence in the current system dynamics model developed in Vensim.

To explore the effect of uncertainty of interaction during introduction of the bridging Technology Z, C3 representative of the interaction or learning between Technology X and Technology Z was introduced in the systems dynamics model (equation set (1)) as a random normal distribution with a mean value of 0.1 and a standard deviation of 0.05 indicated in table 1. The focus here was to explore the effect of this uncertainty in development of Technology X on the development of Technology Z the bridging technology. Multivariate Monte Carlo simulations using 200 iterations were done in Vensim with the model shown in figure 1 (equation set (1)). This resulted in uncertain (stochastic) distributions of Technology X, Y and Z levels. This allows scenarios for Technology development under interaction or learning uncertainty C3 to be simulated. These scenarios can be useful in early planning
phases of technology management. Some Monte Carlo simulations for Technology Z using uncertainty in parameter C3 are shown in figures 3 and 4.

Figure 2: Technology X, Y and Z simulated transient response indicating bridging effect of Technology Z

Figure 3: Technology Z sensitivity trace ranges under uncertainty of interaction parameter C3
The results for sensitivity traces of Technology Z under uncertainty of interaction parameter C3 are shown on figure 3. The wide spread of on-going activity for Technology Z should be evident. From this graph it is evident that even at year 25 there is a chance of 25% that Technology Z level activity will still be more than 5. However at year 6 it is indicated that activity levels can be lower than 3 with a probability of 75%. This is possibly indicative of the power of learning from defending Technology X if proper interaction learning strategies are employed.

Figure 4 shows the simulated sensitivity histogram for Technology Z activity levels at year 10. What should be evident is that although the distribution for parameter C3 is normal and thus symmetrical the simulated response for Technology Z is not symmetrical. It seems to be skewed to the left with two Technology Z activity level maxima one in the range of 0-1.5 and another at 9-10.5. These simulated distributions of Technology Z activity levels may for example be used to do technology risk management in typical product development projects.

4 SOME RESULTS WITH CYCLIC BEHAVIOUR
This section aims to explore the effect that a somewhat drastic change in technology system dynamic model parameters can have on the technology response. The following system dynamic simulation results using equation set (2) and the model in figure 1 have been obtained using Vensim. The parameter values used in the computer simulations and indicated in table 2 have been chosen to be similar to those used by Mamat et al [12] for comparison purposes. These parameter values differ somewhat drastically from those on table 1 used for simulations presented in the previous section. Notable are some zero and effectively negative parameter values in table 2 compared to table 1. The initial technology levels used in the system dynamics simulations were 0.5, 0.5 and 0.5 for Technology X, Y and Z respectively. Monte Carlo multivariate simulations with 200 iterations were done in the cases where uncertainty was modelled.

Two cases of interaction were considered for Technology Z where parameter D3 was chosen as 0.5 and 0.45 respectively to illustrate the possibility of limit cycle behaviour for three technologies similar to the cyclic behaviour illustrated by Mamat et al [12] for food chain behaviour. Figures 5 and 6 show simulation results for parameter D3=0.45 and figure 7 indicates the effect of change in parameter D3 from 0.5 to 0.45.

**Figure 5: Technology X, Y and Z simulated transient response indicating co-existence and cyclic behaviour; D3=0.45**

If one compares the results of figure 2 and 5 the qualitative difference in technology response should be evident. Technology X in figure 2 shows an asymptotic behaviour to zero with no oscillations. In figure 5 Technology X shows an oscillatory cyclic behaviour. Furthermore the bridging role of Technology Z seems to have fallen away giving rise to cyclic behaviour for Technology Z as well.

In Figure 5 the maximum levels of technology activity for Technology X occurs at year 5.6 with value 2.822 and at year 17.3 with value 2.678. This indicates a simulated period of oscillation of approximately 11.7 years for Technology X. For Technology Y the maxima occur
at year 7.4 with a value of 2.643 and at year 19.21 with a value of 2.575. This reflects a period of oscillation of approximately 11.8 years for Technology Y.

The non-linearity embedded in the current systems dynamics model is evident from the transient simulation responses for Technology X, Y and Z change rates depicted in figure 6. The response for Technology X change rate is not sinusoidal as for the typical linear differential equations. The difference in maximum negative and positive change rates is also evident. At year 6.8 the minimum value is -1.274 and at year 15.91 the maximum value is 0.6346. The difference in duration of negative and positive Technology X change rates also has important Technology Management implications in the sense of for example different expenditures for the different phases of the technology cycle. For Technology X the duration of negative change rates is 4.46 years, from year 5.57 to year 10.03. The duration of positive change rates for Technology X is 7.26 years, from year 10.03 to year 17.29.

Figure 6: Technology X, Y and Z change rates simulated transient response indicating non-linear innovation; D3=0.45

For the case where D3 is chosen as 0.5 a Hopf bifurcation point for parameter A3 is calculated as 0.5. For this set of parameter values sustained limit cycle periodic behaviour for all three technologies is simulated as shown for Technology Z in figure 7. In Figure 7 Technology Z has a periodic response with constant amplitude for D3=0.5 and A3=0.5 at the Hopf bifurcation point. If D3 is changed to 0.45 the response of Technology Z changes to a periodic response with decreasing amplitude as shown in figure 7. For the case of D3=0.5 the minimum value of Technology Z occurs at year 5.56 with a value of 0.0878 and at year 16.56 with a value of 0.0879. This implies a period of oscillation of 11.0 year for Technology Z. This is effectively the same period of oscillation for Technology X and Technology Y simulated as 11.03 years. These values concur with values indicated by Mamat et al [12] in

Selected Variables

![Selected Variables Graph]
their research for this parameter values. This further establishes confidence in the current system dynamic model for three interacting technologies.

![Technology Z](image)

**Figure 7: Technology Z simulated transient response indicating effect of interaction parameter D3; D3=0.45 and D3=0.5**

To further explore the effect of model parameters in this technology system dynamics model for equation set (2) the effect of uncertainty in diffusion parameter is considered. As indicated in table 2 the effect of uncertainty is modelled here by introducing a random normal distribution on parameter A1 with a mean value of 0.5 and a standard deviation of 0.05. Multivariate Monte Carlo simulations using 200 iterations were also done in Vensim with the technology system dynamics model shown in figure 1 (equation set (2)). This resulted in the simulated sensitivity traces for Technology X and Technology Z under uncertainty of diffusion parameter A1 as shown in figures and 9. It is notable that the cyclic behaviour is maintained for the range of uncertainty considered. There seems to be a tendency for some of the outlier 95%-100% ranges of simulated traces for both Technology X and Technology Z to diverge with time (increasing ranges of oscillation amplitudes).

At time 7 years from figure 7 it can be deduced that under uncertainty of diffusion there is a 25% probability that Technology Z level activity will be less than 1.1 and a 25% probability that the activity level will be more than 2.

Figure 10 shows the simulated sensitivity histogram for diffusion parameter. It is noted that the simulated response seems symmetrical with a mean of approximately 0.5. This is in line with the specified normal distribution for parameter A1. Furthermore the simulated sensitivity histogram for Technology X activity levels at year 20 shown in figure 11 represents a skew distribution with maximum of 0.25 to 0.5. Of importance to note here from a technology management perspective is that uncertainty associated with one part of the
technology system (parameter A1 and Technology X in this case) results in uncertain responses in other parts of the system (Technology Z) as well. This can be related to the concept of holism in systems.

**Figure 8: Technology X sensitivity trace ranges under uncertainty of diffusion parameter A1**

**Figure 9: Technology Z sensitivity trace ranges under uncertainty of diffusion parameter A1**
To evaluate the simulation results obtained for the three technology systems in this section an attempt was made to find real case technology data that reflects some oscillatory behaviour. The work of Schmoch [19] for industrial robot technology is considered for comparison purposes with the current simulation results.

For the case of industrial robot technology Schmoch [19] describes the existence of cyclic behaviour of the technology. He uses bibliometric analysis [2] in the form of patent and publications analysis over a 33 year period from 1970 to 2002 and illustrates the existence of a double boom cycle over a 15 year period as shown in figure 12. The data shown in figure 12 has been normalized to year 32 data (210 for patents and 968 for publications).

He specifically states that the scientific trends for industrial robot technology as described by publication indices precede the technological trends by several years. These technological activity trends for industrial robot are shown in figure 12 where the phase
difference between patent and publication cyclic behaviour can be seen from approximately year 10 onwards.

![Typical sensitivity histogram for Technology X under diffusion uncertainty](image)

Figure 11: Typical sensitivity histogram for Technology X under diffusion uncertainty (A1) at year 20.

On comparison of figure 5 and figure 12 it is evident that both the simulated and real case data show evidence of cyclic behaviour for the technologies considered. The simulated period of oscillation for Technology X (11.7 years) is also in the same range as that for the industrial robot technology data. This also supports the confidence in the system dynamics model for the case of cyclic behaviour of the technology. A word of caution is necessary; this is a case study simulation only. Schmoch [19] also warns that not all technologies exhibit cyclic behaviour. For this case however qualitative similarity of simulated technology responses and real case data for industrial technology has been successfully demonstrated.
Figure 12: Typical technology activity for industrial robots adapted from Schmoch [19].

5 CONCLUSION

A technology system dynamics model considering three interacting technologies has been introduced using elements of the systems thinking approach also supported by Jackson [9] and Meadows [13]. Two cases of general application of the system dynamics model have been considered.

In the first case it has been illustrated how a bridging technology (Z) effect can be constructed by appropriate choice of positive system dynamics model deterministic parameters. The simulated system dynamics results for this case concur with previously published results [1][16] showing asymptotic transient behaviour of the technologies. This provides some confidence in the model. The effect of uncertainty in interaction between the bridging technology (Z) and the defending technology (X) has been illustrated with model simulation results using a Monte Carlo approach. A wide-spread of on-going activity for the bridging technology over more than 20 years has been indicated and simulated for the normally distributed interaction uncertainty. The simulated bridging technology activity levels may be employed in technology risk management in typical product development projects.

A second simulation case has attempted to show the rather drastic effect that choice of system parameters can have on the simulated behaviour of the technology system dynamics model. For this case some parameters have been chosen as zero and negative similar to the work of Mamat et al [12] on food chain behaviour. This resulted in a change of asymptotic to cyclic transient behaviour for all three technologies (X, Y and Z) indicated by simulation results. This is essentially similar to the results reported by Mamat et al [12] again resulting in more model confidence. Uncertainty of diffusion for the first technology (X) has also been modelled using a Monte Carlo approach in the system dynamics model. Simulation results for two technologies (X and Z) with uncertainty in diffusion still show nominally cyclic transient behaviour for all uncertainty ranges considered. Although the simulated diffusion parameter (A1) is symmetrical the simulated technology histogram for the first technology (X) is skewed to the left at time 20 years. This has specific technology risk management implications for the technology considered. This implies that the system dynamics model developed may be used as technology risk management tool in for instance product development projects.

A real technology, industrial robot technology, has been found for which patent and publication indicated oscillatory behaviour over a period of approximately 15 years. This
technology behaviour described in detail by Schmoch [19] has been successfully compared to current technology system dynamics simulation results. Qualitative agreement has been found between real and simulated data again establishing confidence that certain technologies exhibit cyclic behaviour that may be modelled successfully using a system dynamics approach.

The exploratory research and case base method has been shown to be useful to establish the effectiveness of a system dynamics approach to model competing technology system behaviour.

Future research may include identifying and simulating more real cases where technologies exhibit cyclic behaviour. The stock exchange using technology stock data as a proxy for technology behaviour may be explored as a possible source of case data. The effect of uncertainty in other system parameters including those that may possibly lead to chaotic technology system behaviour may be explored.

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7 REFERENCES


