A SYSTEMS DYNAMICS APPROACH TO COMPETING TECHNOLOGIES: EXPLORING UNCERTAINTY OF INTERACTION AND MARKET PARAMETERS

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ABSTRACT

Technology can be identified as the result of an innovation process that may be time-dependent. Furthermore, technology is both an input to the innovation process and an output of it. When two competing technologies are diffused into the market, they are evaluated as a technology system by means of a systems dynamics approach. It is shown that systems thinking can be used initially to identify and assess the important factors that influence the competitive behaviour of the two technologies. Interesting dynamics of this technology management system are presented and discussed in the context of uncertainty of interaction between the two technologies. It is specifically shown that the life span of the existing technology, which resists competition, may be adversely affected under conditions of uncertainty. The effect of uncertainty in more than one systems dynamics model parameter – specifically, the interaction and market parameter in the competing technology system – is also addressed. The Lotka-Volterra approach of predator-prey interaction is used to model the interaction between and diffusion of the two technologies in the system. A qualitative assessment of the systems dynamics model without uncertainty is attempted in the exploration of a real case study of two competing technologies.

OPSOMMING

Tegnologie kan beskryf word as die resultaat van 'n innovasie proses wat tydsveranderlik kan wees. Tegnologie is beide 'n inset sowel as 'n uitset van die innovasie proses. 'n Geval waar twee kompeterende tegnologieë in die mark diffundeer word met behulp van sisteemdinamika geëvalueer as 'n tegnologiestelsel. Dit word aangetoon dat stelselsdenke gebruik kan word as voorloper om die belangrike faktore wat die kompeterende gedrag van die twee tegnologieë beïnvloed, te identifiseer en te assesseer. Interessante dinamiese gedrag van hierdie tegnologiebestuurstelsel word aangebied en bespreek in die konteks van onsekerheid van interaksie tussen die twee tegnologieë. Dit word spesifiek aangetoon dat die bestaande tegnologie wat weerstand bied teen kompetisie se lewenspan nadelig geraak kan word in onseker toestande. Die effek van onsekerheid van meer as een sisteem-dinamikamodelparameter, spesifiek die interaksie en markparameter, word ook aangespreek. Die Lotka-Volterra benadering gebaseer op die interaksie van aanval en verdediging word gebruik om die samehang tussen en diffusie van die twee tegnologieë in die stelsel te modelleer. Kwalitatiewe assessering van die sisteemdinamikamodel sonder parameteronsekerheid word ook aangespreek deur 'n werklike gevallestudie van twee kompeterende tegnologieë.

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1. INTRODUCTION AND RESEARCH METHOD

1.1 Introduction

Technology, such as a technology-based product or service, is typically the result of an innovation process that may generally be time-dependent and non-linear. When two competing technologies are diffused into the market under conditions of uncertainty – such as market size and economic impact – the effect is evaluated by means of a systems dynamics approach. This paper is a continuation of previous research by the authors [13]. Sections of the previously published paper, specifically those about the effect of multiple combined uncertainty, will be expanded upon in this paper.

As an example of multivariate simulation, Talley et al. [14] demonstrate the effect of introducing uncertainty into model parameters. Their study focuses on the design of shock mount systems and the dynamic simulation of them. They also compare practical shock tests with sensitivity simulations.

Nair et al. [12] focus on the contextual dynamics of competing technologies. They state that the period of ferment influences competitive interactions before the emergence of a dominant technology or technologies. It is concluded that institutional factors may allow the coexistence of competing technologies – for instance, in the case of dialysis and organ transplants. In the context of this paper, the period of ferment may be uncertain. To some extent, this justifies the current research into uncertainty in systems dynamics simulations.

The work of Nair et al. [12] may also be related to the systems thinking approach discussed by Jackson [9]. He indicates that systems thinking offers a methodology that attempts to construct a framework for a deeper understanding of the problem by assessing the behavioural characteristics of a complex system. It also provides a practical way to define complex problems initially, and then proceed to design solutions.

Forrester [4] introduced the concept of 'industrial dynamics' (now known as 'system dynamics') in response to a need that arose because many problem-solving methods in the management sciences at the time were apparently not delivering the necessary strategic insights and understanding of complex systems. In support of these ideas, Wolstenholme [16] 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 modelling and analysis for the design of system structure and control".

Forrester [4],[5] also states that system dynamics use concepts from the field of feedback control to model, for instance, social and technical systems in a computerised environment. At the heart of system dynamics is the concept of the *system*. In this paper two competing technologies are considered and modelled as an interacting system, utilising systems dynamics. Some related previous work on systems dynamics modelling includes the channel management models of Dirker et al. [3].

A system can be seen as consisting of interacting components or sub-systems. A system can also form part of other systems, leading to the notion of the 'system of systems' (SOS) or even 'super systems'. The behaviour of systems is generally complex and time-dependent. Systems can be physical or conceptual, or a mix of the two – such as a computer used in a risk management system. System behaviour is generally non-linear.

Jackson [9] also positions systems dynamics as a complex systems approach. as opposed to hard systems thinking, which is seen to be more of a simple systems approach. On the continuum of simple to complex, systems dynamics may be thought of as an extension of systems engineering. In the words of Jackson [9], "hard systems approaches take it for granted that problem contexts are simple-unitary in character".

Hunger [7] describes systems engineering as "a team process with a single mission-driven responsible leader". There is, however, a pervasive focus on the systems perspective, the ability to see the bigger picture, throughout his approach to systems engineering. This again stresses the relationship between hard and soft systems thinking.

This paper attempts to illustrate the benefit of a combined approach using elements of systems thinking, systems engineering, and systems dynamics to analyse a competing technology system. The real possibility of the integrated use of systems engineering (SE) and systems dynamics is also illustrated in the general definition of SE proposed by INCOSE [8]: "An interdisciplinary approach and means to enable the realization of successful systems". It is informative to compare this definition with that for systems dynamics, which focuses on "the design for system structure" by Wolstenholme [16].

1.2 Research method

The research method used in this paper is qualitative and exploratory in nature. This method is useful in the early stages of research to identify and explore issues such as the competitive factors influencing technology diffusion. Furthermore, the case study method [11] is employed to assess the usefulness of systems dynamics modelling of the growth of computer-aided design (CAD) technology in favour of manual drafting.

Bae et al. [2] mention that bibliometrics is essentially a process of measuring text and information. In this paper, bibliometrics is used to assess the level of technology activity. Here it is assumed that the number of academic articles published can be used as a measure of the level of technology activity. Bibliometrics is used to obtain limited data for the CAD technology case study.

The aim of this research is then to establish a systems dynamics model for two competing technologies under uncertain competitive and market conditions, and to evaluate the performance of the technologies. The model may be usefully employed to assist in design specification, especially early in the life cycle, during the concept exploration phase, and to manage the life cycle of such a technology system. The research is specifically useful in emphasiing the role of systems dynamics early in the systems engineering life cycle of technology systems.

2. SYSTEMS DYNAMICS MODEL AND CONTEXT

Currently many computer-aided systems dynamic simulation tools are available to assist in the modelling of systems. One such simulation tool is Vensim PLE Plus [15], used in the systems dynamic simulation of two competing technologies presented in this paper.

Vensim PLE has been used to model two competing technologies, X and Y – the defending and attacking technologies respectively, as shown in Figure 1. In Vensim the boxes indicate level or stock variables that are generally the result of mathematical numerical integration. The values, such as Technology X change rate, are rate variables, in this case indicative of the innovation rate. The arrows indicate interactions between systems components, or (for example) variables.

In this paper the systems dynamics model shown in Figure 1 represents the Lotka-Volterrra system of first order differential equations adapted for the competing technology system. These equations are similar to those provided in Ahmadian [1] and Kim et al. [10]:

$$\begin{aligned} \frac{\mathrm{d}X}{\mathrm{d}t} &= (a_1 - b_1X - c_1Y)X = a_1X - b_1X^2 - c_1XY \\ \frac{\mathrm{d}Y}{\mathrm{d}t} &= (a_2 - b_2Y - c_2X)Y = a_2Y - b_2Y^2 - c_2YX \end{aligned} \tag{1}$$

a_i is the logistic parameter or growth rate for species (technology) i when it is living alone, b_i is the limitation parameter for niche capacity related to market size for species i, and c_i is the interaction parameter with the other competing technology. X and Y indicate the technology levels. In all the models and tables shown in this paper, reference is made to influence parameters in capital letters - A1, B1, C1, etc - to allow easy comparison with the models of Ahmadian [1] and Kim et al. [10].

As a first model, the parameters used by Ahmadian [1] are used. These model parameters are shown in Table 1. The effect of uncertainty in the interaction parameter C2 is modelled as a random distribution with a mean value of -0.02 and a standard deviation of 0.005. This modelling approach was not attempted by Ahmadian [1]. Thereafter the effect of combined uncertainty in interaction parameter C2 and market parameter B2 is also modeled, using the distribution values indicated in Table 1.

The complexity element introduced in the systems dynamics approach should be evident from Figure 1, where the number of interactions or interface relationships for this relatively simple two technology system is ten (10), not accounting for the time variation and combined uncertainty of the parameter values.

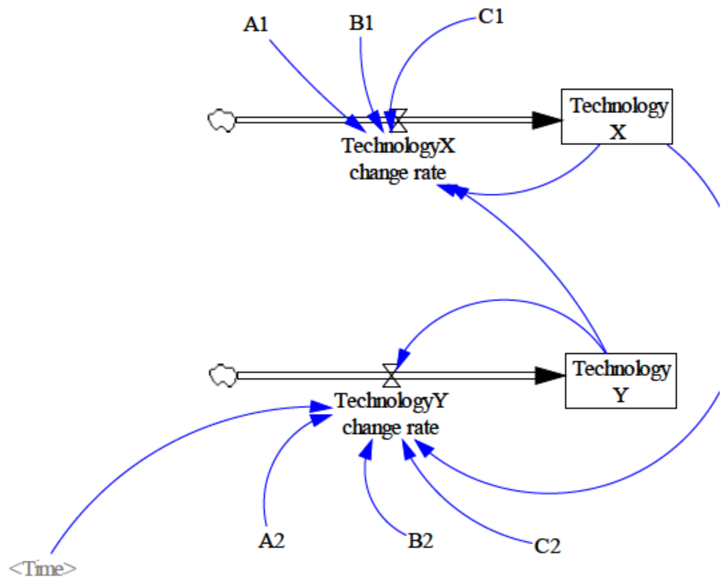

Figure 1: A systems dynamics model for two competing technologies

3. RESULTS

The technology system results given in this section are those simulated with the systems dynamics model (Figure 1) using the system parameters given in Table 1. For the case study of CAD technology growth, the model parameters in Table 2 are used. In this case no uncertainty is used in the model, as the results are used for qualitative application and demonstration purposes only.

	Model parameters					
	A1	B1	C1	A2	B2	C2
Certain	0.1	0.01	0.01	0.15	0.005	-0.02
Uncertain	C2=RANDOM NORMAL (-0.04, -0.001, -0.02, 0.005, 1046)					
	B2=RANDOM NORMAL (0.001, 0.5, 0.005, 0.0009, 1046)					

Table 1: Some typical model parameters

3.1 Results with uncertainty in the interaction

Table 1 contains the model parameters used for the simulation. The uncertainty introduced in interaction parameter C2 as a mean with a standard deviation of 0.005 (similar to a risk or uncertainty degree of 25% for this parameter) is worth noting. The initial values used at time 0 for Technology X and Y were 5 and 0.01 respectively, to enable comparison with the similar results without uncertainty presented by Ahmadian [1].

All simulations were done using the Euler time integration scheme with a time integration interval of 0.01 year. Uncertainty was simulated using the multivariate sensitivity approach in Vensim with 200 iterations.

Figure 2 is a histogram of simulated activity level values for Technology X at year 25. Note the distribution of values with a minimum of 2.25-3, most probable of 6.75-7.5, and maximum of 8.25-9. Note also that the resulting output distribution for Technology X is skewed to the right, although the input C2 has a normally distributed uncertainty.

Similarly, the simulated activity level for Technology Y is shown as a skew distribution to the left at year 25. A most probable value of 8-12 for Technology Y is evident from Figure 3.

The simulated sensitivity graph percentiles over a period of 50 years for Technology X and Y are presented in Figures 4 and 5, using the uncertain distribution of interaction parameter C2. The red traces represent certainty - in this case, the same as for C2 equal to -0.02. What should be evident is that uncertainty starts playing a definite role after year 14 for this case of competing technologies.

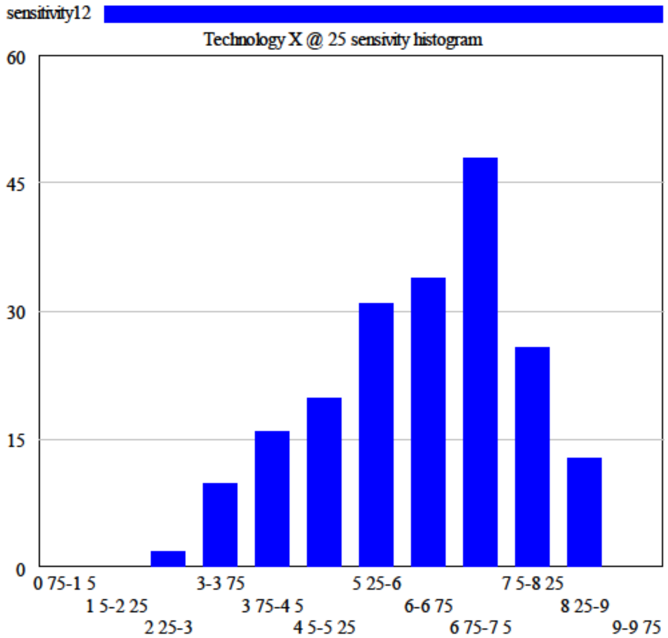

Figure 2: Typical sensitivity histogram for Technology X: Uncertain C2

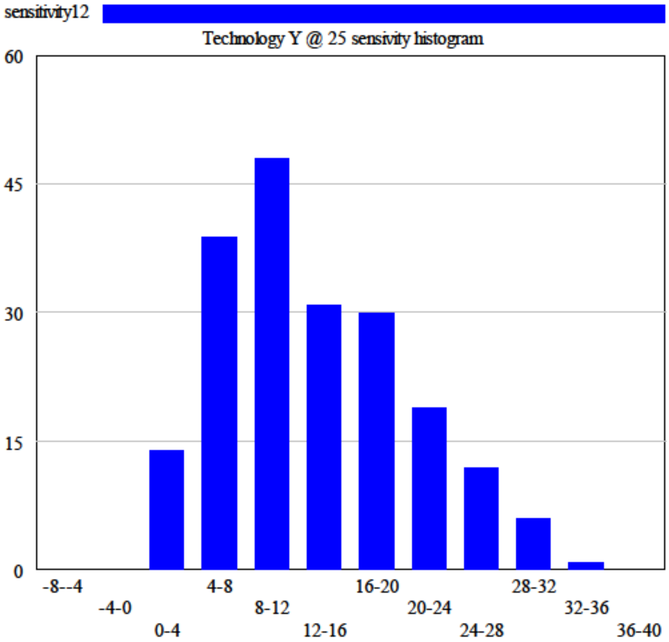

Figure 3: Typical sensitivity histogram for Technology Y: Uncertain C2

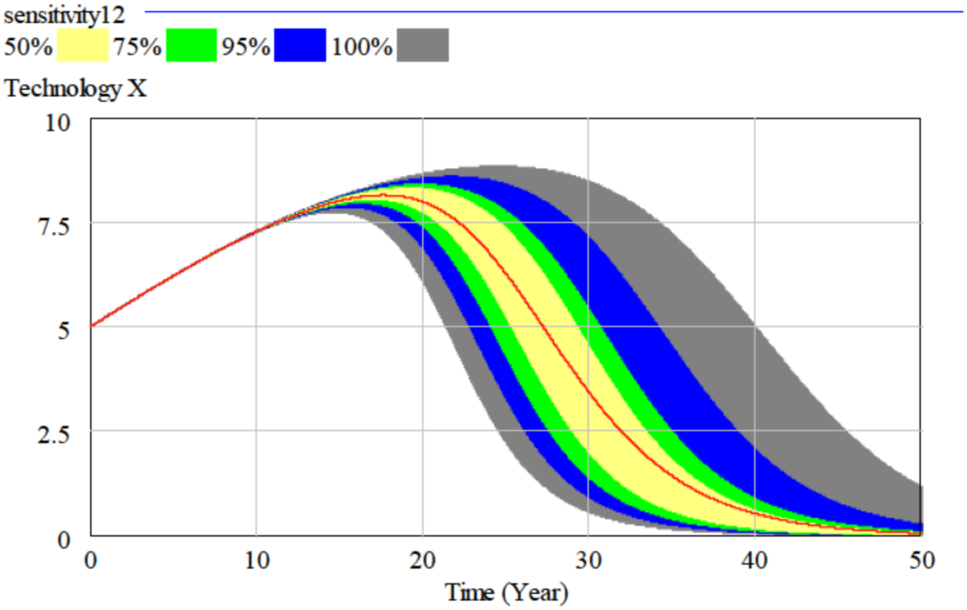

Figure 4: Technology X sensitivity graph percentiles: Uncertain C2

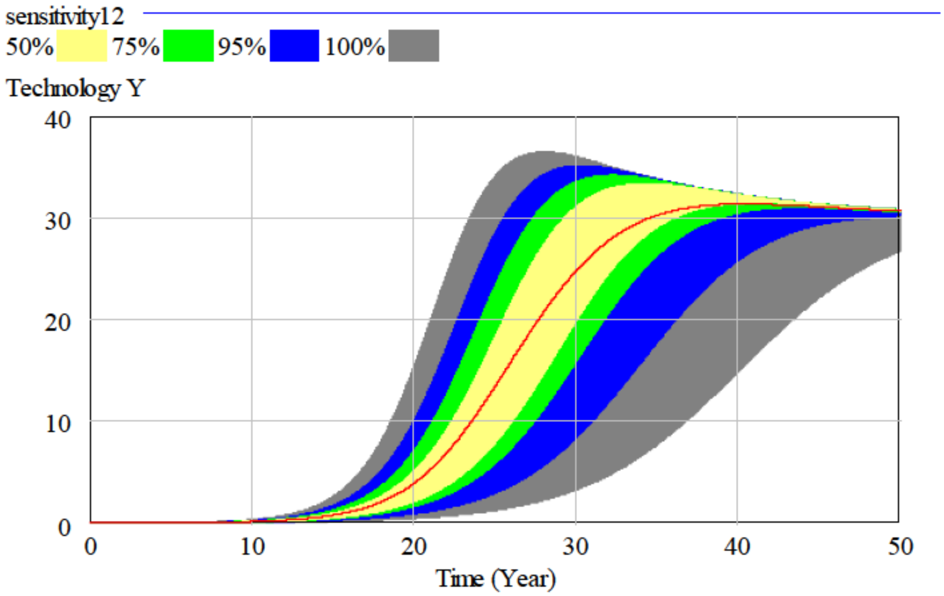

Figure 5: Technology Y graph percentiles: Uncertain C2

The effect of the eventual demise of the defending Technology X is also evident in Figure 4 as the technology level approaches zero at year 50 for all uncertain values of C2. The wide spread of times associated with the initial level of Technology X after the demise of the technology has started is rather dramatic: from approximately year 20 to year 40. This raises quite a number of strategic management challenges to defending the market position of the technology across such a possible time span.

The eventual steady state condition of attacking Technology Y is evident from Figure 5 as a value of approximately 30 for all uncertain values of C2. An optimum value of 32.33 at time 37.53 years can be determined from Figure 5 for C2 equal to -0.02 (red trace). At this value of time, most of the simulated values for Technology Y are below or just above this value (ranging from 10 to 33). This implies that the attacking Technology Y may perform more poorly than expected at some time in the far future. This may affect technology investment decisions that need to be taken today by the technology management executive.

Figures 6 and 7 depict the Technology X and Y change rates respectively under conditions of uncertainty in parameter C2. The wide dispersion of simulated values is again noteworthy. Furthermore, the generally negative change rates for Technology X are indicative of a technology under attack. For this technology (Figure 6) most of the simulated sensitivity graph percentiles already show negative change rates below year 25 (half the useful life of the technology). Increases in negative change rates for Technology X generally from year 25 onward are typically a result of the relative weights of the chosen market effect and interaction effect parameters shown in Table 1. In this case it may be (for instance) the result of increased marketing efforts (B1) due to a perceived threat of attack (C1) from Technology Y.

What is important to realize from Figures 2-7 is that uncertainty in one parameter (C2 in this case) apparently associated with one sub-system (Technology Y in this case) may affect other parts of the system as well. Uncertainty is evident in both Technology X and Y values, not just in Y.

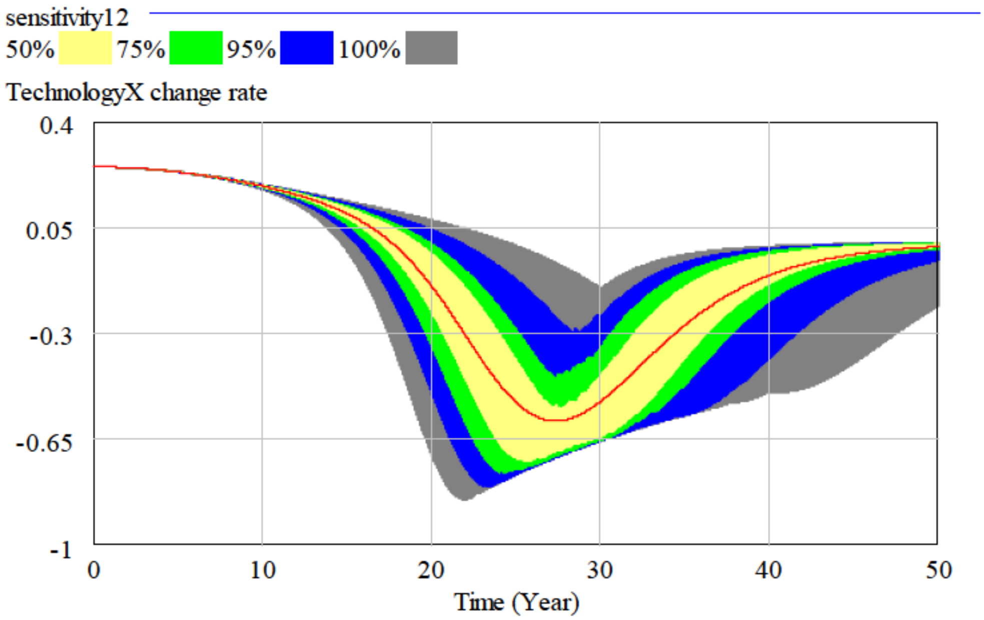

Figure 6: Technology X change rate sensitivity graph percentiles: Uncertain C2

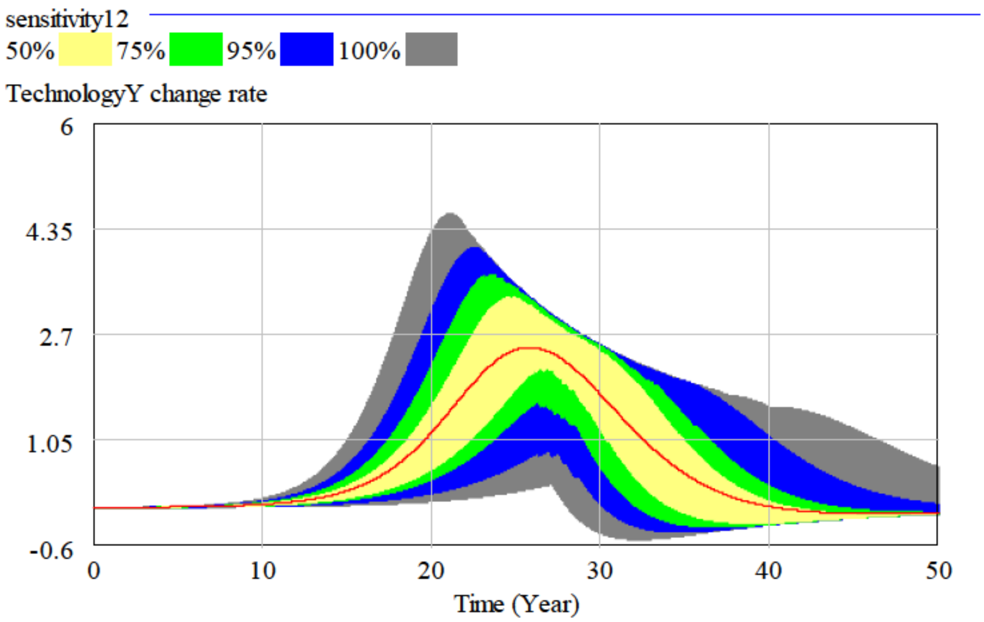

Figure 7: Technology Y change rate sensitivity graph percentiles: Uncertain C2

3.2 Results with combined uncertainty in interaction and market

Figures 8 and 9 show the simulated histogram for activity levels of Technology X and Y at time 25 years with the effect of combined uncertainty of C2 and market parameter B2 using multivariate simulation. The parameters used are random normal distributions with mean and standard deviation values, as indicated in Table 1, under the same initial conditions as used previously.

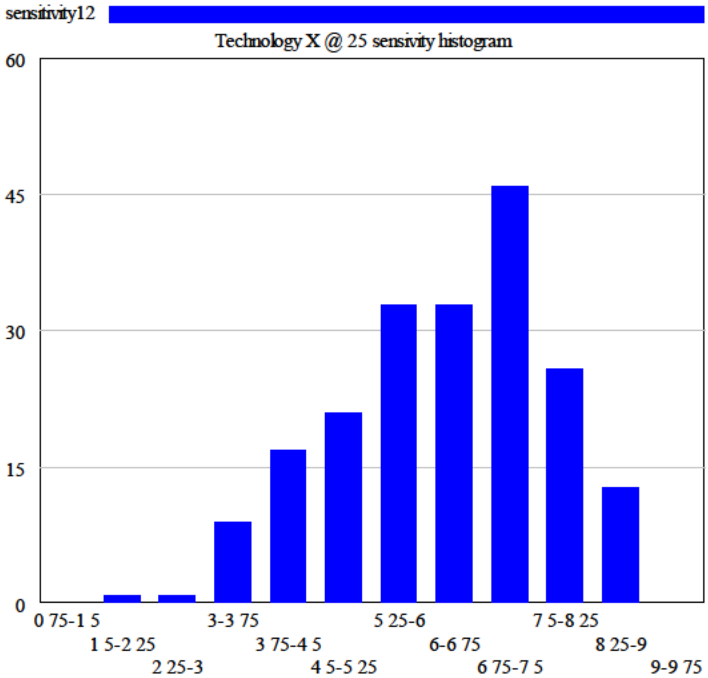

Figure 8: Typical sensitivity histogram for technology X under combined uncertainty in B2 and C2

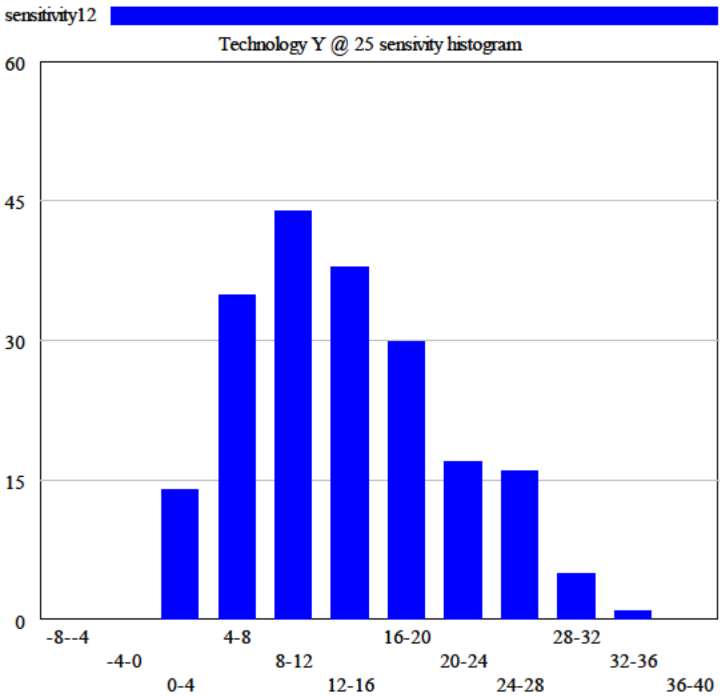

Figure 9: Typical sensitivity histogram for technology Y under combined uncertainty in B2 and C2

On comparison of Figures 3 and 9 it should be evident that uncertainty in more than one parameter (in this case, two: B2 and C2) tends to result in similar but somewhat more symmetrical distributions of simulated technology Y levels. In the combined case the most probable technology Y level occurs in the interval 8-12, but at a lower frequency than for the case indicated in Figure 3. From Figure 8 it is clear that the distribution of the defending technology under combined uncertainty is still somewhat skewed, with the most probable value occurring in the interval 6.75-7.5.

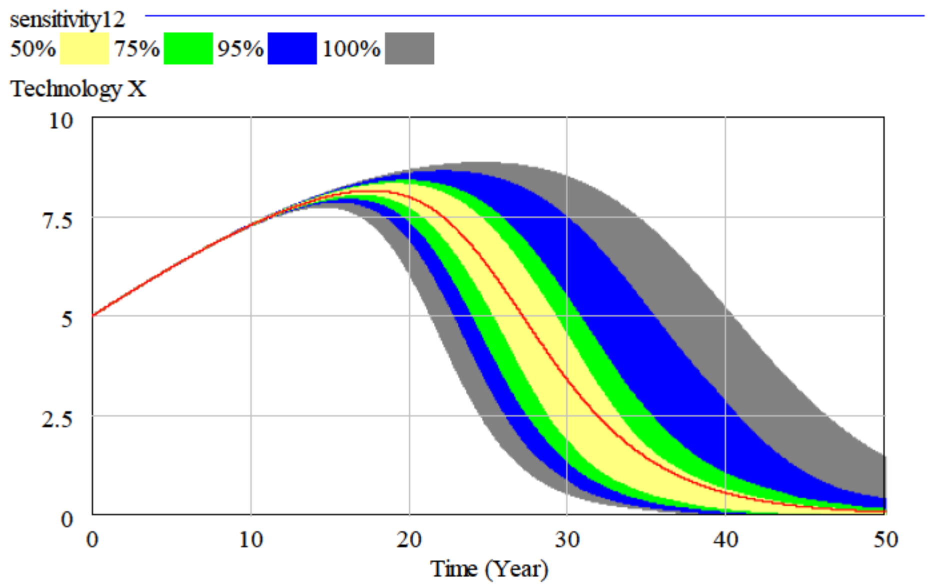

Figure 10: Technology X graph percentiles under combined uncertainty in B2 and C2

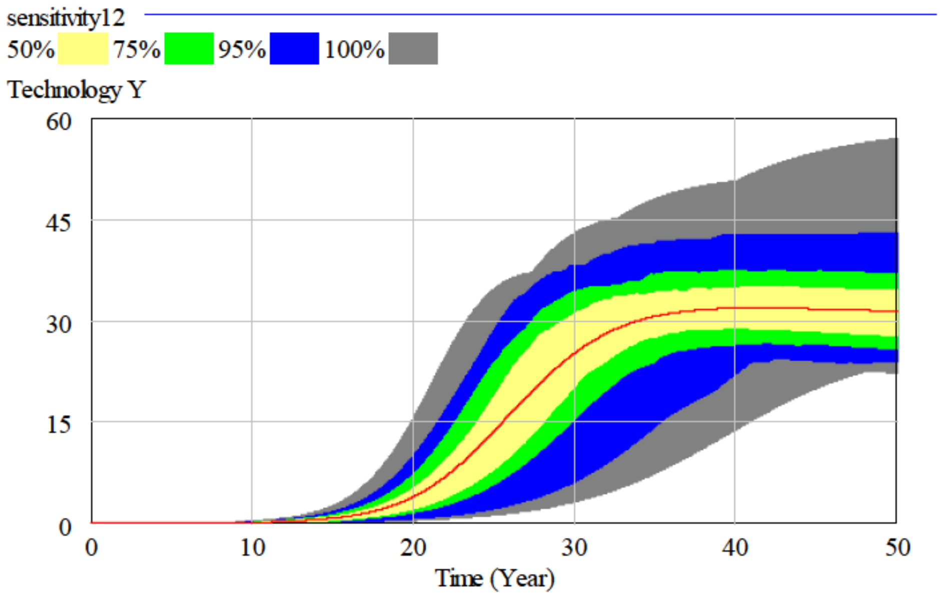

Figure 11: Technology Y graph percentiles under combined uncertainty in B2 and C2

On comparing Figures 4 and 10, it should be evident that the simulated traces for activity levels of Technology X are similar for the cases of both one and two parameter uncertainty. The spread of uncertainty for Technology X at year 40, however, is somewhat wider in the case of two parameter uncertainties. Figure 11 indicates the rather dramatic effect of uncertainty in two parameters (B2 and C2) on attacking Technology Y levels at (for instance) years 30 and 40. A wide dispersion of simulated probable technology levels is indicated in Figure 11 at these times. Furthermore, the wide dispersion of quasi-steady state Technology Y levels at a time where Technology X has virtually been fully replaced may be indicative of the vulnerability of the attacking technology to market conditions, as reflected by the chosen market effect parameter values B2 indicated in Table 1. It is conceivable that, even though Technology Y has replaced defending Technology X, uncertainty and changes in economic conditions, for example, as reflected by B2, may influence the potential market for the adoption of Technology Y. This will be researched in future work.

3.3 CAD technology growth results

As a practical case study of technology replacement, the competition between 'engineering design with CAD' (Technology Y in the context of the previous systems dynamics model) and 'engineering design without CAD' (so-called manual drafting or design, Technology X) between 1979 and 1984 can be considered. It was during this period that personal computers became more widely used and made the introduction of CAD in the workplace a more affordable option for designers.

Bibliometric data was gathered from Google Scholar [6] to illustrate the real growth of Computer Aided Design (CAD) technology in the years 1979-1984. For the bibliometric approach it was assumed that technology activity level is proportional to the number of academic articles published concerning the technology. The two technologies measured bibliometrically were 'engineering design with CAD' and 'engineering design without CAD' (so-called manual drafting or design). The bibliometric results are shown in Figure 12. The general growth pattern of the attacking CAD technology is evident from the bibliometric data in Figure 12, where the vertical axis indicates the number of articles, which is proportional to the technology activity level. At the same time there seems to be a declining tendency for the real bibliometric data for manual drafting. This is reminiscent of the predator-prey interaction illustrated in the model results earlier in this paper.

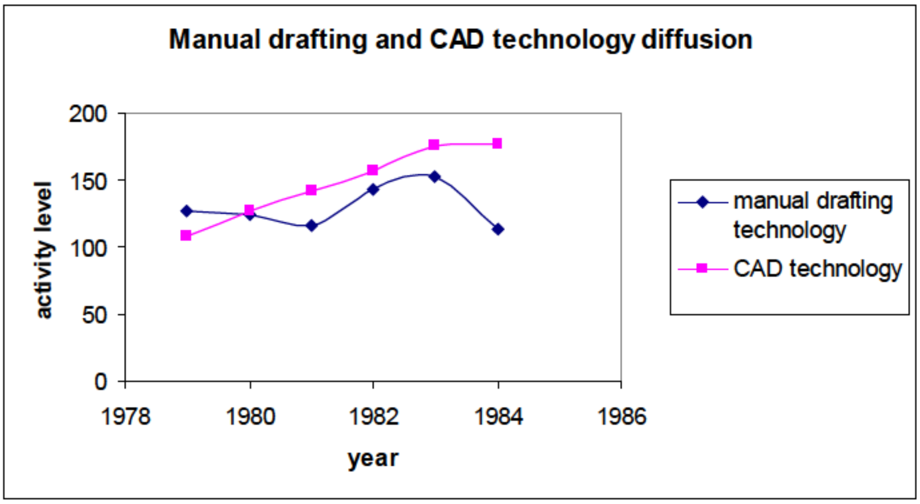

Figure 12: Bibliometric data for CAD and manual drafting technology

In an attempt to apply the systems dynamics model developed in the previous sections to the CAD growth case, different model parameters had to be determined. A first approach of iteratively choosing appropriate model parameters was used for illustration purposes, to show qualitatively that the predator-prey interaction characteristics of the CAD growth case can be approximated using the systems dynamics model. No uncertainty was introduced in the parameters for this case.

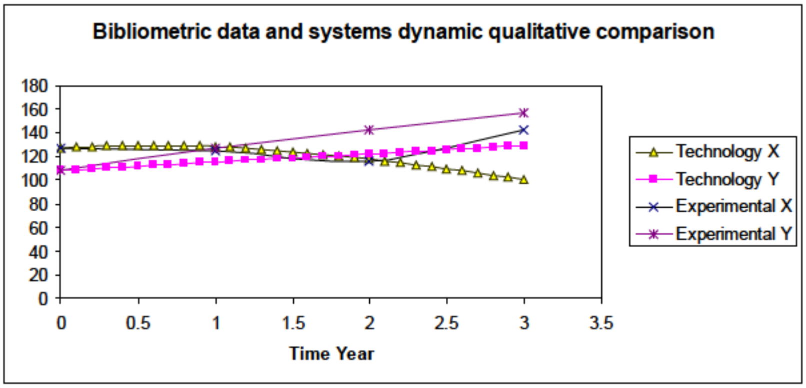

Figure 13: Systems dynamic model: Qualitative comparison with bibliometric data

The Lotka-Volterra parameter data shown in Table 2 were eventually used to illustrate that the systems dynamics model for competing technologies can emulate the general trend of bibliometric data for the CAD technology growth case over this short time span. For illustration purposes only, the bibliometric data gathered for the period 1979-1982 were considered. The simulated activity levels for Technology X ('engineering design without CAD' or manual drafting technology) as well as Technology Y ('engineering design with CAD' or CAD technology) without including uncertainty are shown in Figure 13. For ease of comparison the bibliometric data (experimental X and Y) are superimposed in Figure 13. The apparent increase of experimental X data between years 2 and 3 may have been a local reaction of the defending technology (manual drafting) against the CAD technology. This local increase in marketing efforts against the attacking technology is not modelled in the average values of parameters assumed for this case over the full period.

A1	A2	B1	B2	C1	C2
2	0.1	0.0025	0.00035	0.015	-2E-05

Table 2: Model parameter data for systems dynamics qualitative comparison

4. CONCLUSION AND DISCUSSION

The Lotka-Volterra approach incorporating systems thinking and systems dynamics has been used to model the interaction between the two technology systems under uncertainty. A practical application of the model without uncertainty has been attempted in the exploration of a case study of two competing technologies: CAD technology attacking a defending manual drafting technology in the period 1979-1982. For this case study the data evaluated have been obtained using bibliometrics and the Google Scholar database. For this CAD technology case, systems dynamics simulations have been done, assuming certainty in the input parameters.

Although the parameters have not been optimised, the parameters shown in Table 2 provide a reasonable qualitative fit of systems dynamic simulations to bibliometric CAD and manual drafting data. The CAD technology growth trend is simulated reasonably well.

The systems dynamics model developed for two competing technologies has been shown to emulate previously documented simulation results for parameters under certainty [1] very well. Dynamic trends of technology activity levels have been approximated well using the current model.

The simulation results under uncertainty of one parameter have interesting technology management implications. If no strategic defense action is taken, there is a real risk of the early demise (before year 25) of Technology X. However, on the upside there is the possibility of extending the life of Technology X with proper strategic planning. And the possibility of extending the life of Technology X even to year 40 at technology level 5, for example, is indicated in Figure 4. The systems dynamics model developed here may be usefully employed for strategic decision-making concerning technology development under risk.

What is important to realize from Figures 2-7 is that uncertainty in one parameter (C2 in this case) apparently associated with one sub-system (Technology Y in this case) may affect other parts of the system as well. This is analogous to seeing the bigger picture. Furthermore, it has been illustrated that uncertainty in parameters is important in assessing the simulation results from systems dynamics models for competing technologies.

The effect of uncertainty in two parameters (B2 and C2) on attacking Technology Y levels has been illustrated, as indicated in Figures 8-11. A wide dispersion of simulated probable values after year 25 has also been shown for attacking technology levels. This may be indicative of the vulnerability of the attacking technology on economic conditions, for example, as reflected by B2, which can influence the potential market for adopting the technology. This effect needs to be researched in more detail.

Further research may also include optimising the parameters for comparing the systems dynamics results with more bibliometric data for other competing technologies and for extended time spans. The role of systems dynamics in assessing competing technology systems has been illustrated to some extent in this paper. Although the role of systems dynamics in the systems engineering (SE) process has been touched on, it may be more extensively evaluated in future research into competing technology systems.

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