Using System Dynamics to Model and Analyze a Distance Education Program

Sahana Murthy, Rohit Gujrati and Sridhar Iyer

Abstract—**Significant investments are being made into distance education programs around the world. Yet there is no clear understanding of the effectiveness of such program, or what makes a distance education program successful. This is in part because the analysis of a distance education program involves studying the behaviour of a complex interactive system. It is therefore worthwhile identifying a suitable tool for a theoretical study of such systems. One such tool is system dynamics modeling, a powerful approach to understand the behaviour of a complex system over time. In this paper, we present a system dynamics simulation model of a distance education program at a leading engineering institute in India. We describe how the model is constructed from the individual components of the program and how a system dynamics approach is used to analyze the program. The results of the simulations gave us insights into the distance education program and helped us plan future investments.**

Index Terms— **Distance education, system dynamics modeling**

I. Introduction

EDUCATIONAL reading systems around the world are facing the challenge of providing high quality education at low cost to growing numbers of students. With the availability of information and communication technologies (ICT) a large number of institutions are meeting this challenge via distance education. Significant investments are being made by universities in starting and running distance education programs. Some of these programs are successful while others fail. Studies from the student retention perspective have shown that some important factors for success of distance education programs are planning, marketing, financial management, quality assurance, student retention, faculty development, and online course design and pedagogy [1]. Failure of distance education programs could be due to increased competition in attracting students, invalid assumptions regarding demand and the presence of interacting technological, social and economic factors [2,3].

Yet, there is no theory underlying the success of distance education programs. Universities that are starting these programs have to wait a few years and gather empirical data to study the impact of their programs. Decisions made often are based on incorrect assumptions. These decisions sometimes prove to be costly and could lead to adverse consequences for the program. What would be useful for universities starting and running distance education programs is a theoretical tool that can be used to model and study the programs. In this paper we identify system dynamics modeling [4] to be one such useful tool to model and analyze distance education programs.

A. *Distance education programs in India*

In India, distance education and the use of information and communication technologies are increasingly being seen as a solution to the problem of providing quality education to large numbers of students. Only 2.5% of the population in that age group enroll in undergraduate engineering education programs in India every year [5]. Out of this select group, only 25% of graduates have employable skills, according to a McKinsey study [6]. The main factors responsible for this unsatisfactory state are a lack of trained teachers at the college level, inability of the faculty to teach advanced courses and a need for the availability of good quality courses. Distance education programs from top rated universities are seen as one possible solution to this problem.

The elite Indian Institutes of Technologies (IIT) have taken a leading role in implementing various ICT-based initiatives to disseminate their high quality instruction to the students enrolled in engineering colleges all over India. These include studio-recorded video and web-based courses offered by IIT faculty, [7] as well as live synchronous transmission of the regular courses of the IITs. Significant among these initiatives is the role played by the Centre for Distance Engineering Education Program (CDEEP) at IIT Bombay[8]. CDEEP coordinates the live transmission of IIT Bombay's courses via satellite [9] and real-time streaming on the internet [10].

While CDEEP has been successful in achieving its goal of ensuring availability of IIT Bombay's courses everywhere in the country, the impact of its activities is not well understood. For this, we need to first understand the structure the CDEEP system and its behaviour over time. The CDEEP system involves many complex variables such as the number of students participating in the distance education program, number of transmitted courses, syllabi of courses, technical quality of transmission, availability of bandwidth, student satisfaction and so on, each affecting another variable in the

Manuscript received April 2, 2010.
Sahana Murthy is in the Centre for Distance Engineering Education Programme with the Indian Institute of Technology Bombay, Mumbai, India. (phone: +91-22-25764860, email: sahanamurthy@iitb.ac.in).
Rohit Gujrati is in the Department of Computer Science and Engineering at the Indian Institute of Technology Bombay, Mumbai. (email: rohitg@cse.iitb.ac.in)
Sridhar Iyer is in the Department of Computer Science and Engineering at the Indian Institute of Technology Bombay, Mumbai. (email: sri@iitb.ac.in)

system. A suitable tool to model and study such a complex system, with numerous feedback interactions is system dynamics simulation modeling.

The central idea of a system dynamics approach is to analyze the structure of the interactions in a system with multiple interacting objects, thereby getting an insight into the behaviour of the system. Section II describes an overview of this approach. The system dynamics approach has been shown to be useful in modeling complex feedback systems with nonlinear behaviour, such as environmental, social and economic systems [11], including feedback interactions between diverse components of the system.

In this paper, we:

- Suggest a model for the CDEEP framework that the captures its key features, including complex feedback interactions (section III)
- Use systems dynamics approach to analyze the behaviour of the CDEEP system over time (section IV)
- Make policy recommendations for refining the structure of the system, which in turn could improve its behaviour (Section V).

II. Methodology: System Dynamics

A. *Overview of the system dynamics modeling approach*

System dynamics is a powerful methodology and computer simulation modeling technique for understanding, and analyzing the behaviour of complex systems. It was originally developed in the 1950s for helping corporate managers to improve their understanding of industrial processes [12], but currently it is being used in analyzing problems in wide areas ranging from ecosystem models [13], population dynamics, healthcare systems [14] and even software engineering.

The basis of the system dynamics method is to recognize that the overall structure of any system is just as important in determining its behaviour as the individual components themselves [15,16]. It considers a system to be made up of interacting parts, and takes the view that the behaviour as a whole cannot be explained in terms of the behaviour of the parts. In a system dynamics approach, one first identifies the variables in the system which have potential to change over time. At the same time, one identifies the relations and dependencies among various variables, i.e. how a change in one variable will cause a change in another variables, which will further affect a third variable and so on. Eventually, one traces the relations between variables back to the original variable. Thus, any change in a variable in the system influences its own behaviour in the future (sometimes through a complex route), thereby creating a feedback loop. Identifying and analyzing the feedback loops (also called causal loops) is one key concept of system dynamics. In section III, we describe how feedback loops are identified in the CDEEP system starting from individual components of the system.

Real systems are generally very complex and consist of many such feedback loops. The overall behaviour of the system is determined by the interaction of all these loops together. Solving these complicated interaction and determining the future behaviour of the system using pen and paper is neither feasible nor easy. Instead the models are solved as simulations on the computer. The feedback structure of a system is represented by diagrams called *causal loop diagrams* and *stock-flow diagrams*. Examples and descriptions of these diagrams for the CDEEP system are present in Sections III.B & III.C. These are the graphical representations of a system as composed of different variables and their relation with one another. As explained in section III.B, first a causal loop diagram of a system is constructed, then the corresponding stock-flow diagram is used in the computer simulations.

The results of the simulations are used to predict the future behaviour of a system. Corrective action can be taken if any deficiency is found. The advantage of a simulation model is that potential policy decisions can be first applied to the computer model to check their impact before applying those policies on actual systems.

B. *Why system dynamics is a suitable tool to study the CDEEP system*

The CDEEP structure is a complex system containing variables in different domains such as technological, operational, economic and social. There are strong interactions between the variables, often in different domains. Major variables of our concern are the number of students benefiting from the CDEEP live transmission, student satisfaction, number of courses being transmitted, quality of lecture videos transmitted in presence of bandwidth constraints and so on. The relation among these variables results in formation of feedback loops and could cause non-linear behaviour of the system. Presence of many such feedback loops in the structure of the CDEEP system and our need to analyze and improve its behaviour makes this a classical problem to be studied by the system dynamics approach.

III. The Detailed CDEEP Model

A. *The CDEEP system and model*

CDEEP's primary goal is to make IITB's courses available to large numbers of students in India and around the world. Currently there are three modes of dissemination:

i) Live transmission of via Webcast.

Currently CDEEP has 4 studios [6] from which courses are recorded and transmitted live and free over the Internet. This is through live streaming, or Webcast, at a bandwidth of 100 Kbps. Although CDEEP has access to a much higher bandwidth, a policy decision was taken to transmit courses at a bandwidth which a typical student in any part of India has access to. A maximum of 15 courses can be transmitted from each studio. Participants can access live Webcast lectures on their PC free of charge at the scheduled time.

ii) Live transmission via satellite.

One of the four CDEEP studios has a link to EDUSAT, a satellite dedicated to the education sector by the Indian Space

Research Organization (ISRO) [17]. CDEEP transmits live courses through EDUSAT. Students can access these courses through Student Interactive Terminals provided by ISRO to a number of institutions known as Remote Centres (RC). Through the Student Interactive Terminals, two-way live interaction is possible between students at the RCs and the instructor at IITB. Currently there are 72 Remote Centres across the country which take advantage of this educational program. These Remote Centres are generally other engineering institutes who want their students to take IITB's courses through live transmission. Each Remote Centre has a co-ordinator who acts as a liasison between CDEEP and the students and administration in the Remote Centres.

iii) Video on Demand (VoD)

CDEEP also makes available the videos of recorded classes and important seminars. Currently, these are available within the IITB intranet or for purchase on DVDs.

In this paper we focus on the live transmission of courses (i & ii above). In simulating the CDEEP system, we considered the two modes of live transmission – Webcast and EDUSAT as two independent sub-systems and devised a different model for each. We decided that this approach was preferable than treating the entire CDEEP system as one large entity for two reasons: one, having two sub-systems would give us independent insights about each transmission mode and two, it was easier to run mathematical simulations of the individual sub-systems, at least at the first try. We believe that our two independent models represent a reasonably realistic view of CDEEP, since the courses transmitted through Webcast and EDUSAT have different sets of viewers, and use different technologies in their mode of transmission. Hence there are not many feedback loops between the two sub-systems.

In this study, we did not consider the VoD mode, since there were no strong interdependencies between the variables of the VoD sub-system.

B. *Webcast model*

To develop a model of this sub-system, we followed an iterative approach. We first identified the key variables that could determine or change the behaviour of the system, for example: the number of students viewing a Webcast, the quality of the broadcast video and the bandwidth available. At the same time, we looked for feedback loops, that is, interdependencies between these variables, through which they affect each other's behaviour in time. In Fig. 1, we show a preliminary causal loop diagram containing a feedback loop between the above variables.

The interdependencies between the variables are represented by curved arrows, or causal links in the feedback loop. A double line on a causal link indicates a delay for the effect to take place (see the link between Quality of Video and Number of Students in Fig. 1). A causal link between two variables can be positive if a change in one variable causes a change in the other variable in the same direction, and negative if the change in one produces a change in the other in the opposite direction.

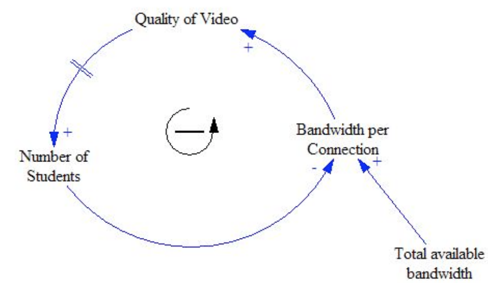

Figure 1. A feedback loop in the Webcast model

In Fig. 1, the link between the quality of video and the number of students is positive (better quality of video implies more number of students are likely to view it). The link between the number of students and the bandwidth per connection however is negative (if number of students increases, bandwidth per connection decreases assuming total bandwidth is a constant).

A loop overall is either positive or negative depending on the product of all the positive or negative links. The loop in Fig. 1 contains two positive and one negative loop, hence the loop is overall negative. The structure of the feedback loop, that is, its overall sign determines the pattern of behaviour of the system. The presence of a positive feedback loop leads to rapid growth at an exponential rate while a negative feedback loop results in goal seeking or oscillatory behaviour [15,16].

To build an initial model, we look for other important feedback loops such as the one in Fig. 1. For the Webcast model, we identified a few other key variables: number of transmitted courses, student satisfaction and server performance. The more complicated model is shown in Fig. 2. We then simulated and analyzed the system using the causal loop diagram in Fig. 2. The results of these simulations provided us with the broad features of the system's behaviour.

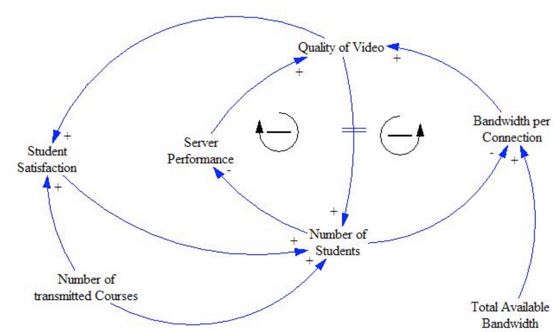

Figure 2. : The initial causal loop diagram for the Webcast model

To construct a more realistic model, we refined the initial model by introducing new variables. The choice of these new variables is based on their importance and relevance. We consulted CDEEP's staff members to gather information needed to make the model more realistic and detailed. Some variables were identified based on the results of student feedback surveys conducted by CDEEP's staff. Wherever possible, we used real data to identify and set values for variables. Where this was not possible, we made reasonable estimates. The detailed model for the Webcast sub-system is shown in the Causal Loop Diagram in Fig. 3.

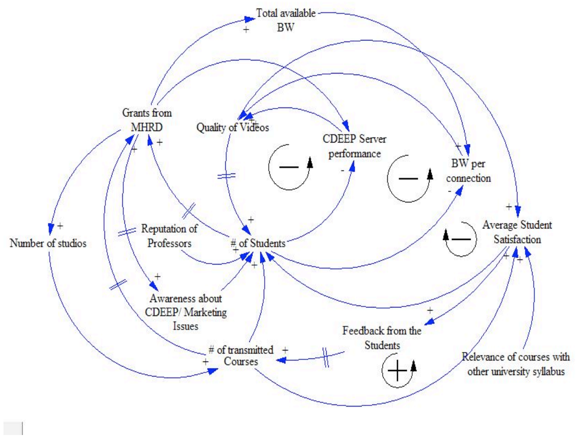

Figure 3: Detailed causal loop diagram of the Webcast sub-system

This model includes technological, economic, academic, social, operational and affective factors. Each variable has to be quantified before running the computer simulation. The quantification process is straightforward for some variables, such as the total bandwidth available. For other variables, such as quality of videos, or student satisfaction, it is not obvious how to assign quantitative values. In such cases, the variable is assumed to vary on a normalized scale of 0 (worst) to 1(best).

Below is a description of the key variables in the model and how we quantified each variable.

Central variable

- The central variable is the number of students viewing Webcast lectures. In the corresponding stock-flow diagram in Figure 4, this variable is a stock, whose value changes with inflows and outflows.

Technological

- Quality of video being transmitted. This variable consists of many parameters that determine the quality of video, such as jitter, audio-video synchronization, delay etc. To quantify this variable we assumed that it varies between 0 and 1, where 1 is the best possible quality when courses are transmitted at 100 Kbps bandwidth.
- Total available bandwidth. This is a constant and is taken as 8Mbps for our simulation.
- Network bandwidth per connection. For each connection, a 100 kbps network bandwidth is provided until it exhausts whole 8Mbps capacity.

Operational

- Total number of courses being transmitted in a particular semester. We estimated this value based on the average number of courses transmitted by CDEEP in the past few semesters. The initial value of this variable was chosen to be 20.
- Number of studios. Currently there are 4 studios from which live courses are recorded and transmitted. If numbers of studios us increased, then more courses can be transmitted simultaneously. We assume that number of studios is increased from 4 to 6 after receiving the grants.

Social

- Awareness about CDEEP videos. This variable describes CDEEP's efforts at disseminating information about its courses. Through various outreach means such as newsletters and workshops, more number of students are made aware of CDEEP's programs. This variable has been quantified from a 0 to 1 scale.

Economic

- Grants received. The CDEEP system runs on a steady annual budget allotted by IIT Bombay. CDEEP received a one-time large grant from the Government of India's Ministry of Human Resource Development. This event occurred only once. We have modeled this as a single event occurring after a delay of 24 months from the start of the time scale. It is important to decide which parts of the CDEEP this funding should be allocated to, and what would be impact of it.

Affective

- Student satisfaction. In surveys conducted with students, we found that this parameter was highly dependent on the quality of video being transmitted and number of courses being transmitted. This variable has been quantified from a 0 to 1 scale.
- Feedback from students. Students give feedback about their experience of CDEEP courses. We conducted surveys which asked students questions on video quality, their satisfaction with CDEEP courses, which courses they recommended for future transmission and so on. The feedback helps CDEEP staff improve the system. This variable has been quantified from a 0 to 1 scale.

Figure 4 shows the same Webcast model represented as a stock-flow diagram. These diagrams are derived from causal loop diagrams but contain more information about the nature of the variables. A stock-flow diagram distinguishes the variables among *stock*, a variable which accumulates something in it and *flow*, the rate, at which the stock is changing. It is necessary to convert the causal loop diagram into a stock-flow diagram in order to run the mathematical simulations.

While a variable in the causal loop Diagram can be represented as individually affecting another variable, in the stock-flow diagram, a variable identified as a stock can only change via a change in the inflow or outflow, each of which is some combination of individual variables.

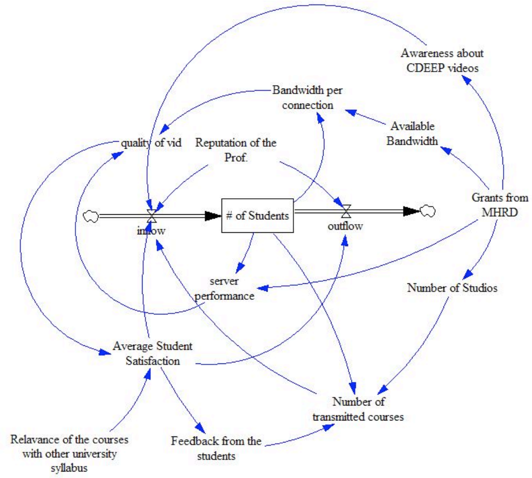

Figure 4: Stock-flow Diagram of the Webcast sub-system

The number of students participating in CDEEP's courses has been identified as a stock, since its value, or level, can be changed via the inflows and outflows. The inflow consists of variables such as number of transmitted courses which increase the value of the stock, i.e. the number of students. The outflow contains variables that deplete the stock, or decrease the number of students. Some variables such as the student satisfaction contribute to both inflow and outflow, depending on their exact value (a high value for student satisfaction implies an increase in the number of students while low student satisfaction will decrease the number of students).

C. *EDUSAT model*

The EDUSAT model is represented by a causal loop diagram in Fig. 5 and the corresponding stock-flow diagram in Fig. 6.

The variables have been identified and quantified in the same way as was done for the Webcast model. Some of the key variables in the EDUSAT model, that were not present in the in the Webcast model) are:

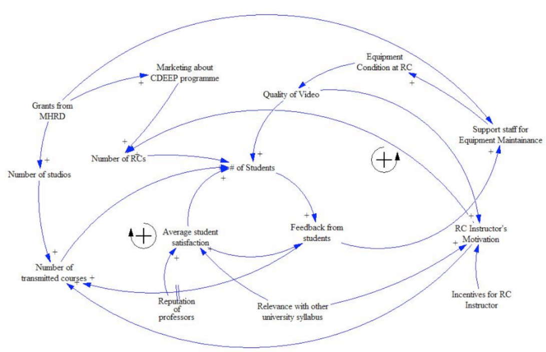

Figure 5: Causal loop diagram of the EDUSAT sub-system

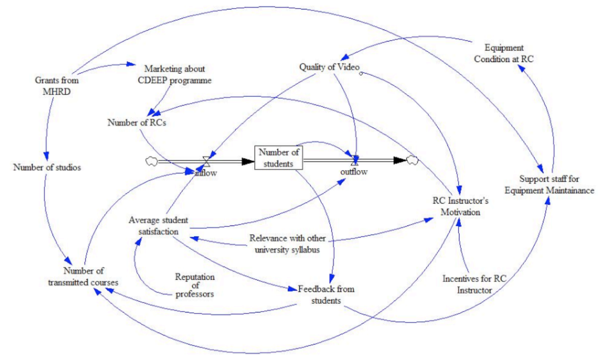

Figure 6: Stock-flow Diagram of the EDUSAT sub-system

- Relevance of course. In interviews with Remote Centre coordinators and students, we found that the alignment of the transmitted IIT Bombay courses to the university curriculum was an important factor in determining whether students would continue to participate in CDEEP's courses. We treated this variable as a constant parameter whose value could be fixed as a number between 0 and 1. In the Results section we discuss how the number of students depends on the relevance of the course.
- Remote Centre coordinator. The incentives offered to the RC coordinators and their motivation are partly responsible for the number of IITB courses that the students in the RC choose to participate in. This sets up a demand-and-supply-like chain wherein IITB transmits a specific course based on the demand for that course.
- Marketing. This variable captures CDEEP's efforts at marketing its courses. It has been quantified from a 0 to 1 scale.

Some variables are common between the webcast and RC model. Yet, the same variable is part of different feedback loops in the two models. One such example is:

- Quality of videos. In the Webcast model, the video quality of the course that a student participates in mainly depends on the availability of sufficient bandwidth. In the EDUSAT model, the video quality is affected by the condition of the Equipment at the RC. The last variable has again been quantified on a scale of 0 to 1, and it has been held at a constant value of 0.5 which represents the average condition of equipment at the RCs.

D. *Solving the system dynamics equations*

There are many commercial software packages available in the market for preparing and simulating system dynamics models . With these packages, we can start by entering a stock-flow diagram for the model. We then enter the initial values for the various stocks into the model, and also the equations for the flows. Once this is done, the system solves the set of equations and gives the simulation results. We used the Vensim PLE simulation package [18] for CDEEP systems modeling.

IV. Results and Discussion

A. Results from the Webcast Model

1) Change in number of students.

Fig. 7 predicts how the number of students changes over time. Since the number of students is a stock, it can depend only on the inflow and outflow, which are made up of some combination of variables (see Figs. 3 and 4).

2) Change in number of transmitted courses.

Fig. 8 shows the behaviour of the number of transmitted courses as a function of time. The number of courses in turn depends on other variables such as the number of students, feedback from students and the number of studios.

The implication of the feedback loop becomes evident in these two figures. The number of students depends on the number of transmitted courses (part of the inflow) but the number of students is also a cause that affects the number of transmitted courses (if more students participate, it is likely that the number of courses CDEEP decides to transmit will be higher). It is in situations like this that the power of system dynamics modeling is visible. It would be very difficult to analyze complex feedback loops without this technique.

3) Effect of the injection of the one-time grant.

From the graphs in Fig. 7, we see that there is an injection of a one-time grant into the system at month 24. These grants are utilized in increasing the number of studios. The grants are also partly used to increase bandwidth (not shown in figure). This makes the number of students go up, which in turn makes the number of courses go up, since students demand more courses. Note that the system can accommodate larger numbers of these courses only because we have also increased the number of studios.

4) Oscillatory behaviour at large times.

In Fig. 8 we see that when the students increase beyond 5000, the number decreases first and then oscillates.

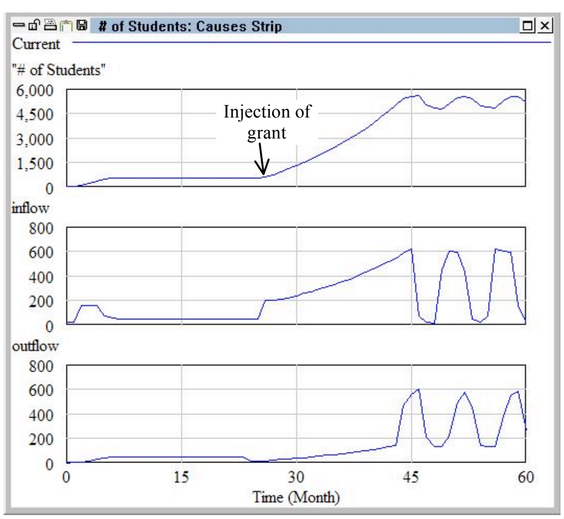

Figure 7: Number of students, inflow and outflow

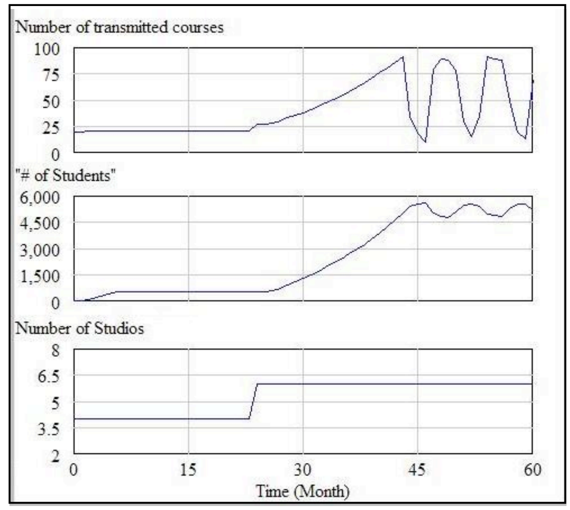

Figure 8: Number of courses and its dependence on number of students and studios

This oscillatory behaviour is related to the server performance. At some maximum capacity, the server gets overloaded and cannot handle as many requests. This decreases the number of students viewing the Webcast, which further decreases the number of courses. Once the number of students declines to a certain value, the server is able to take in more requests, thereby increasing the number of students being able to view the Webcast. This sequence of events leads to oscillatory behaviour. A point worth noting is that the time scale over which this behaviour occurs is a few months (3-6). The changes in the behaviour of the variables of the system will be seen only on longer timescales, corresponding to 1-2 semesters according to CDEEP’s calendar.

B. Results from the EDUSAT Model

1) Effect of incoming grants.

In Figs. 9 and 10, we see predictions of the future behaviour of the system. If the CDEEP system runs on its regular annual budget and no extra grants enter the system, then the maximum number of students is about 600 after a period of 5 years. If we include the one-time grant entering the system at month 24, then the number of students increases to 2500 after 5 years. It is worthwhile to note the effect of this single, one-time injection of funding into the system.

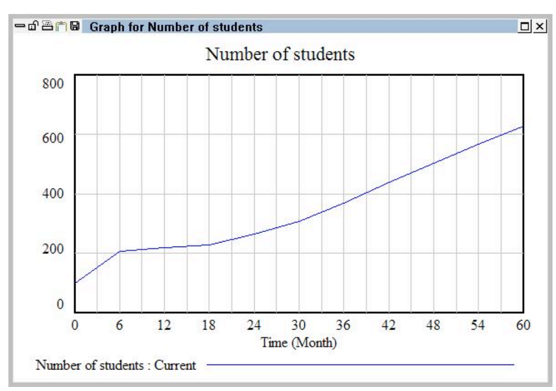

Figure 9: Increase in number of students when no grants enter the system

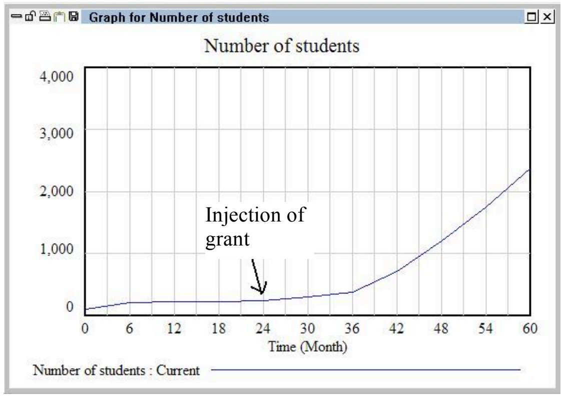

Figure 10: Increase in number of students if grants enter the system

2) Distribution of funds versus number of courses.

In the simulation, we considered several permutations of distribution of the extra one-time funds received. The simulation results showed that there was an optimal allocation of funds to different parts of the system, which maximized the number of students participating in the EDUSAT courses. As an example, if all the funding was allocated to marketing efforts, the number of students will increase up to a maximum of 315 (starting from a number of 100). On the other hand, if we utilize all the funding to increase the number of courses to 45, without concentrating on marketing, then the number of students would at most be 270 students. If we increment the number of courses to 20 as well as put some efforts in marketing too (say 0.6 on a scale of 0-1), we get a larger increase in the number of students and it reaches a maximum of 373.

3) Relevance of courses.

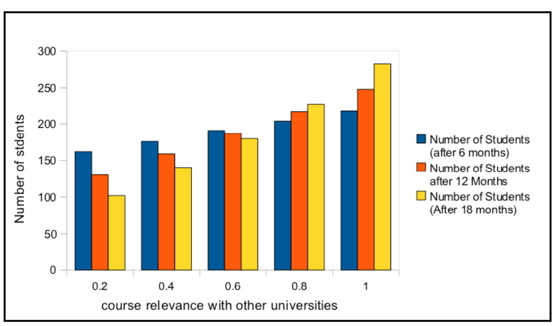

Figure 11: Effect of the relevance of the course on the number of students participating in the course

As mentioned in section III.C, the alignment of the syllabus of IIT Bombay's transmitted courses to the curriculum followed by the students in the RCs was of great significance. In Figure 11, we see the how the course relevance affects the number of students. If a course has low relevance, say 0.2 on a scale of 0-1, then the number of students in fact decreases from 6 to 12 to 18 months. If a course has high relevance, say 0.8, then the number of students increases. Further, the increase or decrease of students occurs at a faster rate at the 18 months than at 6 months. This shows that the impact of course relevance becomes even stronger as more time goes by.

V. Policy Recommendations for the Distance Education Program

The results from the system dynamics simulation offer valuable insights into making policy decisions in our program. A recommendation that emerges from this study is that sufficient attention should be paid to obtaining high quality servers, since server performance could be a bottleneck in increasing the number of students (Webcast model, result 4). We note the role injection of grants into the system. Even though this was a one-time event, its effect is significant. Even if CDEEP administrators seek extra funding for the system only once in while, it will help in improving the outreach of its courses, provided the funds are distributed in an optimal manner to various parts of the system. The system dynamics modeling tool is very useful in this case as a predictive mechanism. The distance education program's administrators could use the simulation results to determine what parts of the program should be allocated what percentage of funds, and at which times. If CDEEP wants to achieve its goal of reaching out to a large number of students, it is essential that the courses transmitted by CDEEP are well aligned with the specific curricula of students who are viewing the courses. This is true not only in terms of the subject matter in the course, but also in terms of the format and focus of the course. For example, the courses transmitted by CDEEP focus on problem-solving and application, while some distance students are used to courses that focus more on theoretical derivation of equations. This difference in focus is a large factor why students choose to opt (or not) for CDEEP's courses. This recommendation was brought out in an article on the reasons why the US Open University failed [19]. One main reason cited was the conflict between the curriculum of the university starting the distance education program and its target audience.

VI. Conclusion

In this paper we showed a detailed example of how to model a distance education program from a systems behaviour perspective. By analyzing the structure of CDEEP using system dynamics simulations, we obtained insights into performance of the program. Many of these results could not have been obtained by simply looking at isolated events and their consequences, due to the various interacting parts within the system. Results from the simulations gave us understanding into what could be possible factors to improve the behaviour of the system. We might not have considered some of these factors in CDEEP future plans without this study.

It would be worthwhile for institutions that are starting a distance education program to analyze their plan using a systems dynamics model. Early warnings of the possible pitfalls in the plan could emerge from the results of the simulations. New aspects that had not been anticipated could become visible. Distance education programs that are already functional would also benefit from running a system dynamics simulation of their program. Due to the complex nature of systems behaviour, results of a system dynamics simulation are often not obvious. These results prove to be useful for existing problems, making policy changes and strategic decisions. Program administrators could get an insight into questions such as: what would happen if a certain policy were changed, or how would we distribute existing resources into different parts of the system. System dynamics offers us a theoretical tool to analyze such a structure, and gain an understanding into the performance of the system.

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