A System Dynamics Approach to Study Virtual Communities

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Abstract

In recent years, extensive studies of many interesting aspects of virtual community dynamics promoted a better understanding of this area. One of the most challenging problems facing builders of virtual communities is the design of incentive mechanisms that can ensure user participation. However, running virtual community experiments in the real world is expensive, and requires a great deal of motivation from users. In this paper we advocate a system dynamics approach to simulate the overall behaviors of participants in the communities, which can provide insights into the user motivation process, incentive mechanism evaluation and community development. A simulation model for a virtual community called Comtella is presented, and the results are very promising.

1. Introduction

A virtual community is a group whose members are connected by means of information technologies, typically the Internet [1]. People use the term “virtual community” frequently refer to computer-mediated communication (CMC) groups. There is no accepted definition of the term “virtual community”, but in 1996 a group of academics held a workshop and identified the following key characteristics of a virtual community [33]:

• People have a shared goal, interest, need, or activity which is the primary reason for belonging to the community;

• People engage in repeated, active participation, and often, intense interactions, strong emotional ties, and shared activities among participants;

• People have access to shared resources, and policies determining the access to those resources;

• There is reciprocity of information, support, and services among members;

• There is a shared context of social conventions, language, and protocols.

Virtual communities are important for many reasons. First, they help replace the relationships lost as more and more informal public spaces disappear from our real lives [25, 26]. They allow people with similar interests to connect with each other and to get benefits from the presence and activities of other people in virtual communities. Virtual communities provide not just information, resources, and conversations which people can use and participate in, but they also provide a way to form social relationships that allow them to do things together with others in a new way. This may, to some extend, help "increase involvement within people's face-to-face communities by increasing democratic participation and other community activism" [3]. Second, when people experience the feeling of belonging to a virtual community, the positive emotion becomes an intrinsic incentive for further participation in the community, which makes virtual communities self-sustained.

Since the early nineties the popularity of virtual communities has increased dramatically. Millions of people join into the virtual environment (such as BBS, discussion groups, chat rooms) day and night to not only share papers, music/video files and other kinds of web-resources online, but also interact with others, exchange opinions, publish news, debate issues, etc. This provides a great opportunity for knowledge exchange and helps people to connect across boundaries. At the same time, spurred by the rapid emergence of virtual communities, studying the complex dynamics involved in communities becomes an exciting new research area. One of the most challenging studies within this vision is to explore the factors that contribute to specific virtual behavior (such as contributing new resources) which can help to encourage and sustain the social engagement among members in the community [13, 15, 17, 18, 31]. Under-contribution and lurking are phenomena that cause problems in virtual communities [21]. For example, Adar and Huberman [2] found that in Gnutella two-thirds of users share no files and 20 percent provide 98 percent of all the music files available on Gnutella. In some open source development communities the situation may be even worse [19], with an estimated 4 percent of developers contributing nearly 88 percent of new code and 66 percent of code fixes. In some particular instances these low levels of participation are not detrimental, e.g. in file-sharing communities, because of the nature of shared materials (shared music files do not expire, can only be multiplied). However, even such communities can only become sustainable after reaching a "critical mass" of contributions. Therefore, user motivation processes and incentives mechanisms are quite important to virtual communities in particular phases of their lifetime and are worth further study.

Previous work has dealt with factors that attract people to participate in virtual communities [16, 30]. Many researchers tried to motivate users by applying social psychology theories (such as building a social reputation system and introducing reward mechanisms) [3, 5, 7, 11, 14, 20] or by improving the framework and user interface [6, 32]. However, the knowledge of dynamic online behaviors and user motivation in the communities is still deficient. Running virtual community experiments in the real world is expensive, and requires a great deal of motivation from users. Besides, complex dynamics involved in this problem and bounded human judgment [27] prevents us from fully understanding the problem. Faced with the overwhelming complexity of the real world, time pressure, and limitations in information availability and processing capabilities, computer simulation modeling offers an attractive and inexpensive means of investigating such phenomena without risk [24]. For these reasons, simulation becomes the most promising tool that helps researchers to study complex phenomena like user participation in virtual communities and evaluating the effects of incentive mechanisms.

The main objective of this paper is to study through system dynamics simulation the user motivation process and incentives mechanisms to participate in a particular virtual community, for sharing URLs of online articles, called Comtella. The paper is organized as follows. In the next section we describe the Comtella virtual community and related work of system dynamics modeling in the context of virtual communities. In Section 3 we present the simulation model in detail. Section 4 provides the parameters and simulation results. We conclude in the last section and present the directions for future work.

2. Related work

2.1 A virtual community for sharing papers: Comtella

An educational virtual learning community called Comtella [8] has been developed at the MADMUC Lab of University of Saskatchewan. It is used in several senior Computer Science courses where students can share class-related digital resources on the web, such as bookmarks to news, articles, etc. Another version of Comtella is used by research groups where researchers can combine their literature research efforts and create a digital library with low maintenance costs.

Normally a particular Comtella community is used for one particular course and hence the number of participants is small. As in any virtual community, there are users in the community who do not share anything, and they are called free-riders. Typically they enter the community, search and download what they need, then log out. Especially for small-scale virtual communities like Comtella, free-riders might have an even more harmful impact to other users compared to large-scale open source virtual communities. According to Dunbar [10] and Shirky [28], for a smaller social group, the quality of communal connections is higher, and the members are better connected. As a result, in Comtella both over-contributors and free-riders can affect the overall participation levels faster and stronger than in large-scale open source virtual communities. So an efficient incentive mechanism is needed to motivate users.

The incentive mechanism [31] of Comtella rewards contributions using hierarchical memberships in the community (gold, silver, bronze and common member) based on the user participation level. A user membership is determined by the activity points are awarded for each dimension of participation (e.g. contributing many links or the best links, or participating in discussion, providing comments and ratings, etc.). In this way the incentive mechanism in Comtella provides a combined measure of user participation, which is quite effective and understandable. The expectation is that users will more readily engage in competition to achieve a higher level of membership than competing along the multiple dimensions of participation.

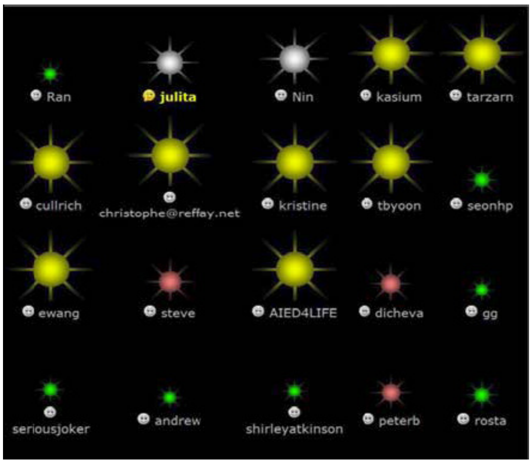

Figure 1. Visualization of the memberships of users in the Comtella community

Users are visualized as stars in a night sky (as showed in Figure 1), where the size and brightness of the stars are determined by the contribution level of the users. Higher-level memberships result in better interfaces and services (such as personalized messages), and more privileges or special rights. The incentive mechanism in Comtella is presented in Figure 2, which shows the important relationships between different factors in the community. Users can get rewards (called activity points) by contributing new resources, and they can be motivated by these activity points because when the number of points becomes large enough, the user's membership is upgraded to a higher one, and the user is shown with a brighter and larger star in the visualization and a corresponding color user interface. The reward of each contribution is determined by the reward unit (Weight of Sharing).

In our study we try to gain insights into this user motivation process and incentives mechanisms in Comtella by simulation in a system dynamics framework and identification of the important factors in this incentive model such as the reward factor, thresholds for membership upgrading, etc.

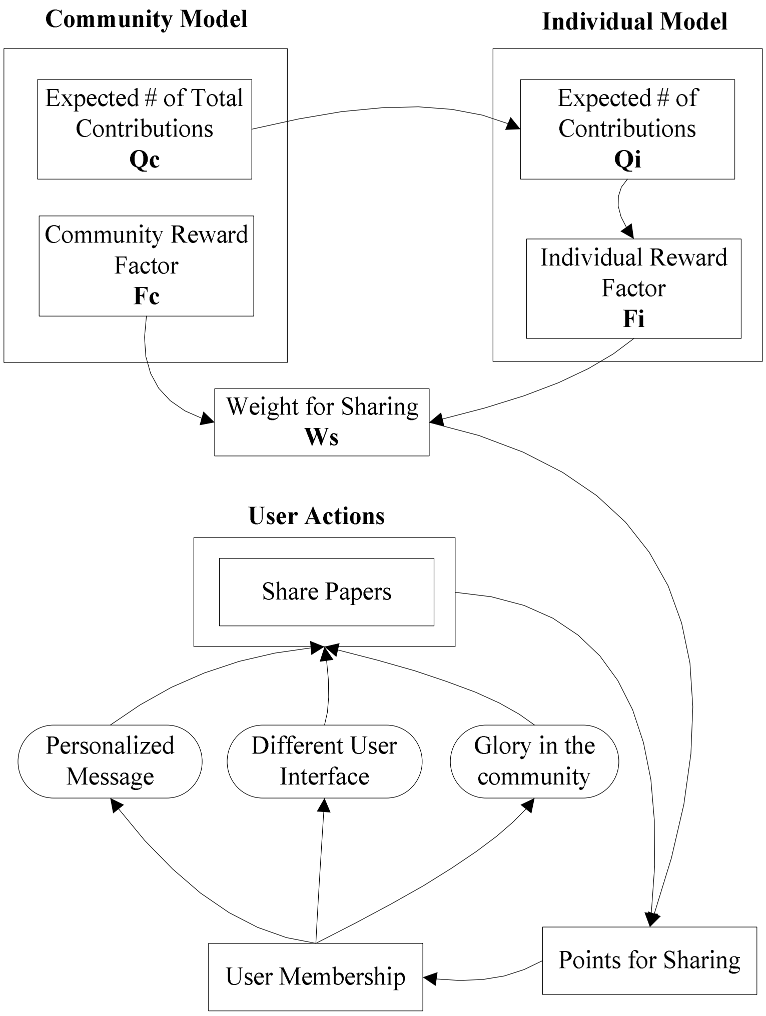

Figure 2. The incentive mechanism in Comtella

2.2 Modeling systems: system dynamics vs. agent-based approach

Agent-based simulation (ABS) and system dynamics (SD) are two major widely acknowledged modeling methodologies in the computational area. Both of them can help to generate complementary insights and increase the researchers' understanding of the dynamics of systems and processes.

Agent-based simulation developed from the research of Distributed Artificial Intelligence (DAI) in the 1970's, and models the essential characteristics of the individual, as well as the rules and the global consequence of the interactions. The basic building block of a system is the individual agent. In ABS the model consists of "a set of agents that encapsulate the behaviors of the various individuals that make up the system, and execution consists of emulating these behaviors." [22]

Compared to ABS, the system dynamics approach [29] emphasizes the use of stocks and flows as well as feedback structures to understand behavior. Stocks and flows are central concepts in dynamics which are formulated mathematically. What SD attempts to do is to understand the basic structure of a system, and thus understand the behavior it can produce. The model is "a set of equations and execution consists of evaluating them" [22]. SD models may be considered more conceptually descriptive than ABS models, and they force the modeler to consider carefully the appropriate level of aggregation. Table 1 compares the agent-based modeling and system dynamics modeling approach.

Table 1. General comparison of agent-based vs. system dynamics modeling approach

	Agent-based Modeling	**System Dynamics Modeling**
Focus	Rules of interaction among agents	System structure
Building block	Individual agent	Stocks and flows, feedback loops
Level of Modeling	Micro/Individual	Macro/Aggregate
System Structure	Not fixed	Fixed
Time	Discrete or continuous	Continuous

It is believed that the agent-based approach is a powerful way to study human behaviors in virtual communities. Each participant in the virtual communities can be modeled as an agent, which has several features. Yiwen Zhang and Mohan Tanniru [35] proposed an agent-based model for virtual learning communities and analyzed the characteristics of a participant agent using experiments. The characteristics considered included expertise level, activeness level, sharing level, loyalty, intellectual gain, social gain, etc. Kazuaki et al. [34] discussed the multi-agent based simulation approach to analyze virtual community activities, and the design problem of the decision-making model of the agents that form multi-agent systems.

However, running agent-based simulations is time-consuming. Moreover, the extra complexity (time to build, difficulty of calibration and difficulty of formally analyzing) significantly increases the computational requirements and the agent-level detail becomes a cognitive burden of understanding model behavior [23]. Thus in recent years more and more people argued that the system dynamics approach is also well suited to study virtual communities. For example, Diker [9] reported a research study which developed a system dynamics model to study growth problems in open online collaboration communities. Quentin Jones [12] used a system dynamics approach to examine internet based group communication as "mass interaction" in a virtual community, and described the non-linear feedback loops generated by user information overload.

Like these research efforts, we seek to study virtual communities in a system view. However, our work is distinctive in several ways. First, instead of the general growth problems in open virtual collaboration communities, the system dynamics model proposed in this paper focuses on the particular incentive mechanism and user motivation aspect in the Comtella community. We are interested how users in the community behave according to different memberships, and how can they impact the whole system. Secondly, we focus on a small-scale educational virtual community which maintains certain number of users which distinguishes it from the previous studies in open virtual communities. Third, we have access to the Comtella database in the real world which can be used for model evaluation.

3. Model development

We build up the system dynamics simulation model for an early version of the Comtella community by using a visual modeling tool called Vensim [36]. It provides a simple and flexible way of building simulation models from causal loop or stock and flow diagrams.

3.1 Model description

The causal loop diagram shown in Figure 3 presents the basic conceptual model of the incentive mechanism in Comtella. In this version of Comtella, quality control is not included in the incentive mechanisms, so the feedback structure is quite simple. The participants in the community get rewards by sharing resources in the community according to their share rates; as a result, their memberships are upgraded, which should encourage them to share more.

The most important system inputs in the model are:

- **Reward unit**

For each contribution, the number of activity points given to users as an award.

- **Membership upgrading threshold**

The number of activity points needed (threshold) for upgrading the current membership to a higher one. For a fixed reward unit, if the membership upgrading threshold is too low, users in the community can reach a high level in the membership hierarchy easily and therefore stop participating and contributing new resource after they secure the highest level of membership. On the other hand, if the membership upgrading threshold is too high, users will gradually lose the passion of sharing and become free-riders.

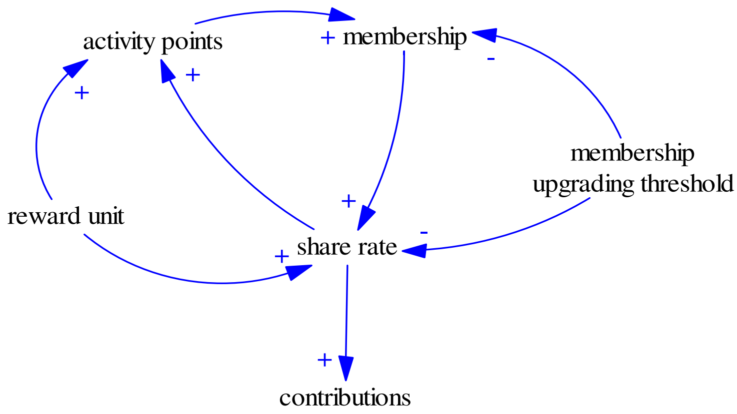

Figure 3. Basic concept model

The most important system outputs in the model are:

- **Membership**

In our case we divide the whole population in the Comtella community into four user groups according to different levels of membership. To measure how these user groups change over time, we make use of an aging chain, which is widely used to capture the demographic structure of a population. It includes a set of member groups (according to different memberships of Comtella users). Also we have to determine the rates of inflow and outflow of different user groups, which cause the population of different user groups to change over time.

- **Contributions**

The total number of contributions is an important factor which measures whether the virtual community is successful or not. We want to measure the share rates of the different user groups according to how much they contribute to the total number of contributions in the community.

Figure 4 further expands the concept model (Figure 3), and shows the main reinforcing loop in the model. It focuses on the feedback relationships among user memberships, activity points and share rates of different user groups. Thresholds have balancing effects towards both memberships and share rates. Details will be given in Section 3.2.

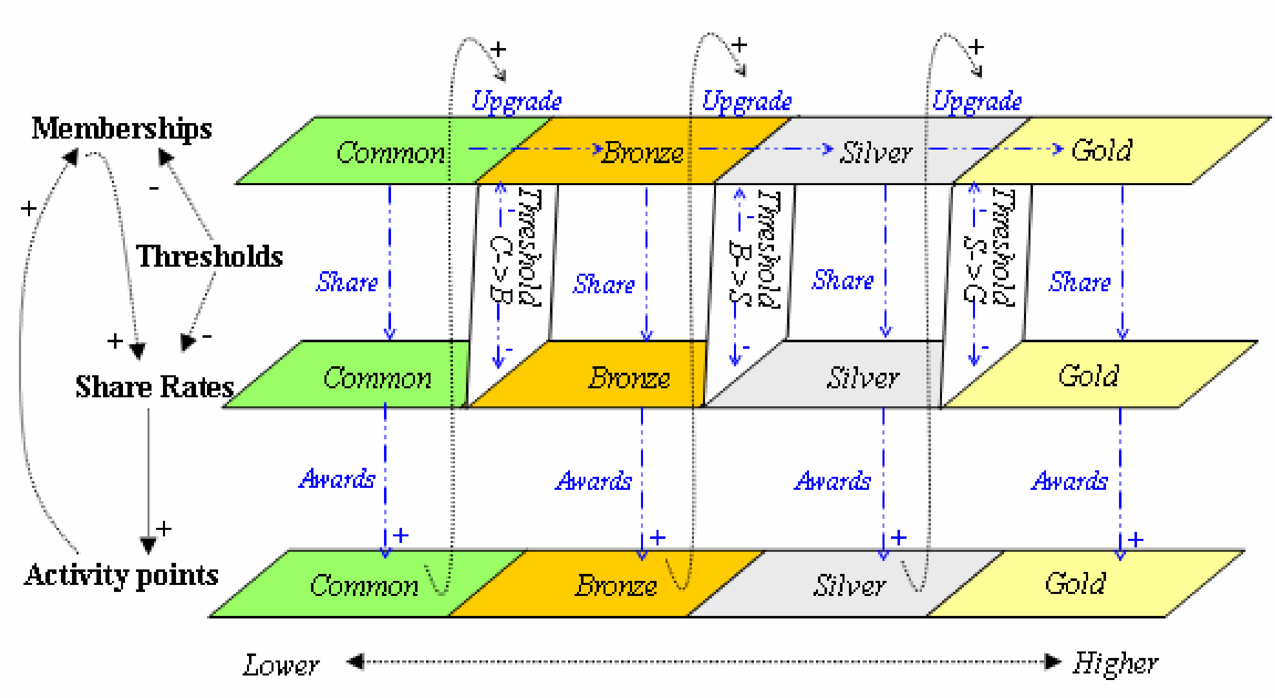

Figure 4. Expanded concept model

3.2 Model Structure

In order to measure these important factors, the model is divided into two sectors that we will discuss later in detail:

1. The Population sector uses an aging chain to represent the demographic structure of the population. The population of each user group is modeled as a stock with its own change rate.

2. The Share rate sector models the share rate control for different user groups.

3.2.1 Population sector

The population sector (Figure 5) models the demographic structure of Comtella population. The time unit of this model is set to be one week, so all the parameters represent weekly quantities. In this sector, the population in the community is the sum of all the numbers of users in different user groups. Each user group is modeled as a stock, which changes weekly according to inflow and outflow:

$$Weekly\ \ change\ \ rate = inflow\ \ rate - outflow\ \ rate$$

Take the stock "Comtella Bronze Members" as an example. The inflow is the weekly change rate of common members to become bronze members, and the outflow is the weekly change rate of bronze members to become silver members.

$$\frac{d}{dt}(Comtella\ \ Bronze\ \ Members) = Rate\ \ to\ \ Bronze - Rate\ \ to\ \ Silver$$

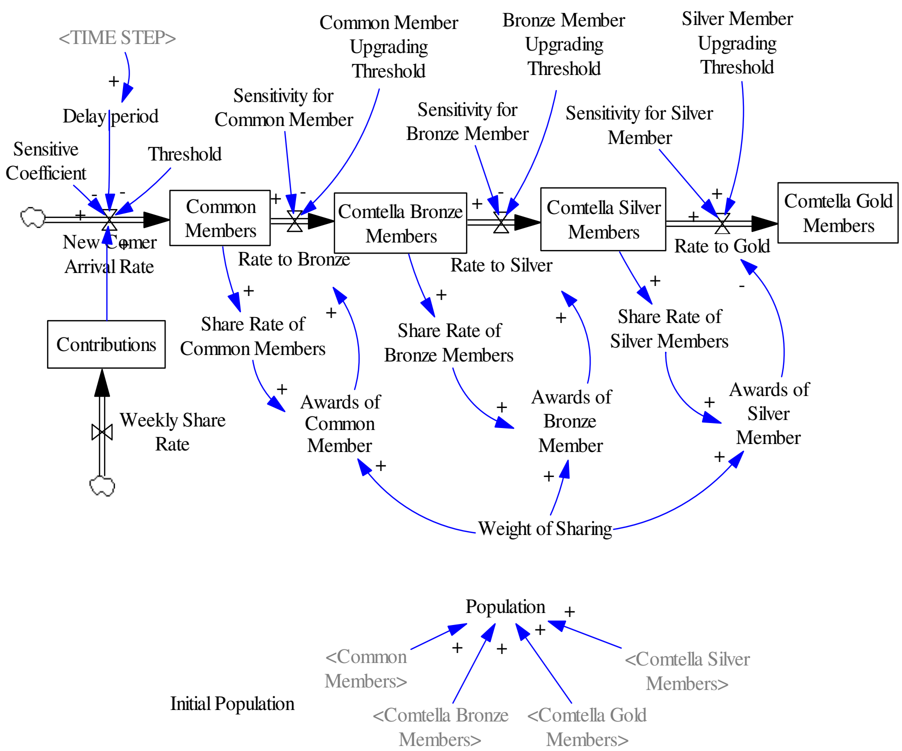

Figure 5. Population sector

We define the formula for the change rate of common members to become bronze members is:

$$Rate\ \ to\ \ Bronze = \frac{Sensitivity\ \ for\ \ Common\ \ Member * Awards\ \ of\ \ Common\ \ Member}{Common\ \ Member\ \ Upgrading\ \ Threshold}$$

where

$$Awards\ \ of\ \ Common\ \ Member = Share\ \ rate\ \ of\ \ Common\ \ Member \\ *\ \ Weight\ \ of\ \ Sharing$$

In order to make it more general, we also add a positive feedback to encourage new user by increasing total contributions with delay:

$$New\,Comer\,Arrival\,Rate = \frac{Sensitive\,Coefficient * Contributions}{(Threshold * Delay\ period)}$$

In these formulas the Sensitivity for Common Member and Sensitive Coefficient work as dimensionless scalars. In case of Comtella where there is no inflow of new users, the scalar Sensitive Coefficient is set to be 0 because we assume that the number of students in a particular course is fixed.

3.2.2 Share Rate Sector

The share rate sector models the share rates of different user groups. The total number of contributions is modeled as a stock with weekly change rate *Weekly Share Rate*:

$$\begin{aligned} Weekly\ Share\ Rate = & \ Share\ Rate\ of\ \ Bronze\ Members \\ & + Share\ Rate\ of\ \ Common\ Members \\ & + Share\ Rate\ of\ \ Gold\ Members \\ & + Share\ Rate\ of\ \ Silver\ Members \end{aligned}$$

We divide this sector into two parts, one corresponding to non-gold members (Figure 6) and one corresponding to gold members (Figure 7). Common, bronze and silver members can be motivated by the membership upgrading process, which is affected by the reward unit and membership upgrading thresholds. In the non-gold member case, the formulas of the share rates for common, bronze and silver members are similar and have the potential applicability of arraying. Users are motivated by the rewards. In order to get higher membership, they will contribute more when their membership upgrade.

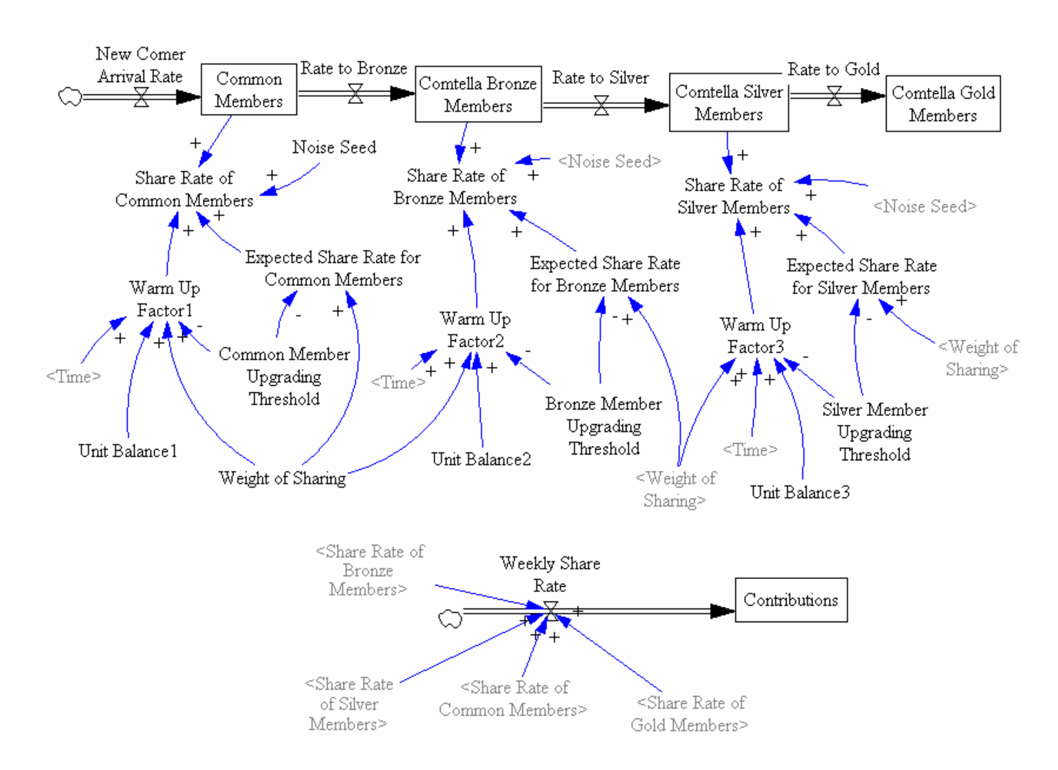

Figure 6. Share rate of common, bronze and silver members

Taking "*Share Rate of Common Members*" as an example, the formula is:

$$\begin{aligned} Share\ Rate\ of\ Common\ Members \\ &= Common\ Members \\ &* RANDOM\ UNIFORM\ (0.3, 1, Noise\ Seed) \\ &* Expected\ Share\ Rate\ for\ Common\ Members \\ &* Warm\ Up\ Factor1 \end{aligned}$$

In this formula the units of *Common Members*, *Expected Share Rate for Common Members* and *Warm Up Factor1* are Person, Link/Person and 1/Week respectively, which implies that the *Share Rate* has the unit of Link/Week.

According to our experience, users share less in the beginning, so there is a warm-up stage in the process measured by warm-up factors which have similar formulas:

$$\begin{aligned} Warm\ Up\ Factor1 = Unit\ Balance1 * (1 - 1/(1 + Weight\ of\ Sharing \\ /Common\ Member\ Upgrading\ Threshold \\ * Time))) \end{aligned}$$

This warm-up stage is modeled as a logistic curve and is affected by the reward unit, membership upgrade threshold, and time. It measures how fast the share rate can reach the expected share rate.

We also introduce a stochastic control factor which is a random number (dimensionless) with uniform distribution: *RANDOM UNIFORM (0.3, 1, Noise Seed)*. Thus, the share rate per person per week is measured by Expected Share Rate*Warm-up Factor* random number, which has goal-seeking behaviors with stochastic control.

The total share rate of a particular user group equals the production of the number of users and the share rate per person per week.

In gold member part, there is no incentive for gold members to upgrade their membership, so the reward unit and thresholds have no impact to the share rate.

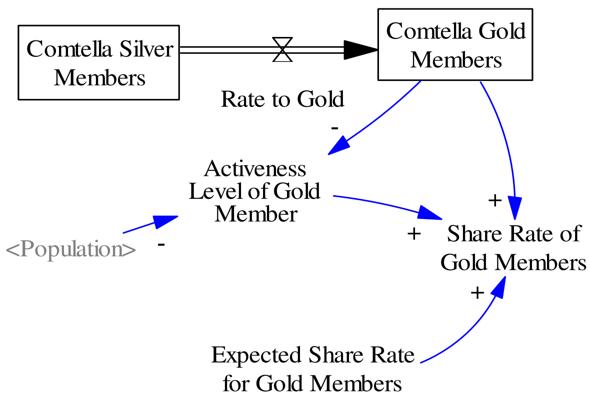

Figure 7. Share rate of gold members

We assume that they can be motivated by the average activeness level of the whole user group. Here the activeness level is a variable with range [0, 1] that affected by the percentage of gold members in the population:

$$Activeness\ Level\ of\ Gold\ Member = 1 - \frac{Comtella\ Gold\ Members}{Population}$$

Then the formula of share rate is defined as:

$$\begin{aligned} Share\ Rate\ of\ Gold\ Members = {} & Expected\ Share\ Rate\ for\ Gold\ Members \\ & * Activeness\ Level\ of\ Gold\ Member \\ & * Comtella\ Gold\ Members \end{aligned}$$

4. Results

The simulations are based on the assumption that users in the community are mainly motivated by activity points. The reason is that the current incentive mechanism in Comtella uses activity points as the only measure of user memberships because it provides a simple notion of competition. Besides, memberships do not decay over time.

We first show the model behavior during the base simulation. In order to test the simulation model and the behaviors it can produce, we will test the parameters and compare the results with historical data of actual Comtella use in the database to see whether the simulation model truly measures the actual Comtella community and captures the effect of incentive mechanism on the demographic structure of Comtella population. The real data was collected during one academic term experiment with 32 fourth-year students of the Department of Computer Science while taking a course on Ethics and Information Technology in 2003-2004 winter sessions. The parameters are listed in Table 2.

Table 2. Parameters

Name	Unit	Value
Initial Population	Person	32
Noise Seed	Dimensionless	0.5
Weight of Sharing	Point/Link	4
Common Member Upgrading	Point/Person	24
Bronze Member Upgrading	Point/Person	32
Silver Member Upgrading	Point/Person	40
Expected Share Rate for Gold	Link/Person/Week	3.5

In the experiment, we further investigate the impact of membership upgrading thresholds on different user groups and total number of contributions.

4.1 Base run

Once the model is developed, it is possible to experiment with different parameters in order to analyze different scenarios. However, it is useful to have a base run to validate basic model behavior.

In the base run the length of simulation is 16 weeks, and the sensitivity parameters for common members, bronze members and silver members are 0.175, 0.575 and 0.29 respectively.

We can see from Figure 8 that at the very beginning everyone is a common member, and as time goes on, their memberships upgrade, and the population of common members decreases to 33 percent of the whole population at last.

After 9 weeks the population of gold members and silver members increase. At the same time the population of bronze members decreases slightly in the end as a result of the balancing effects among the growing rates of these user groups. After 16 weeks, the population of bronze, silver and gold member increases to 18.7, 26.7 and 13.4 percent respectively.

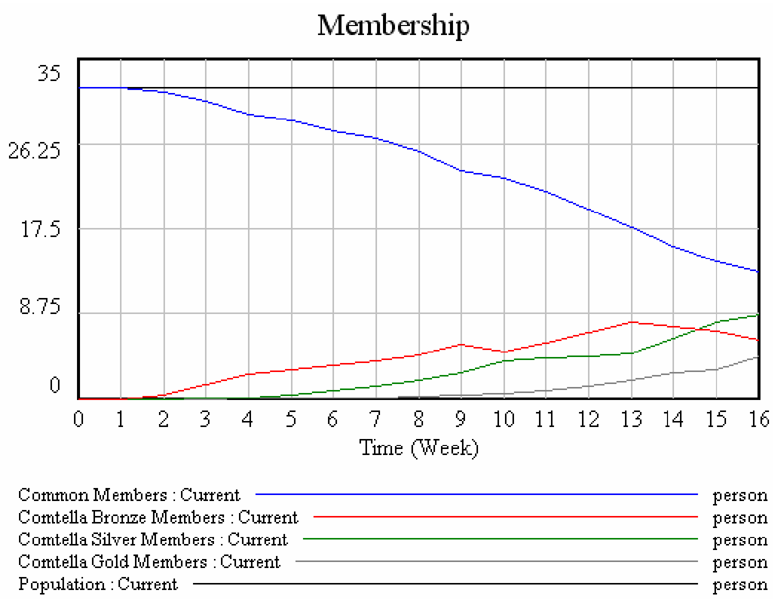

Figure 8. Base run results

We also compare the results with the real data, which was collected during one academic term experiment. Figure 9 shows a fairly good fit between the real data and the data generated by the simulation model, and it shows that the model still needs further calibration and carefully formulation because there is a slight deviation of the change rate of gold members.

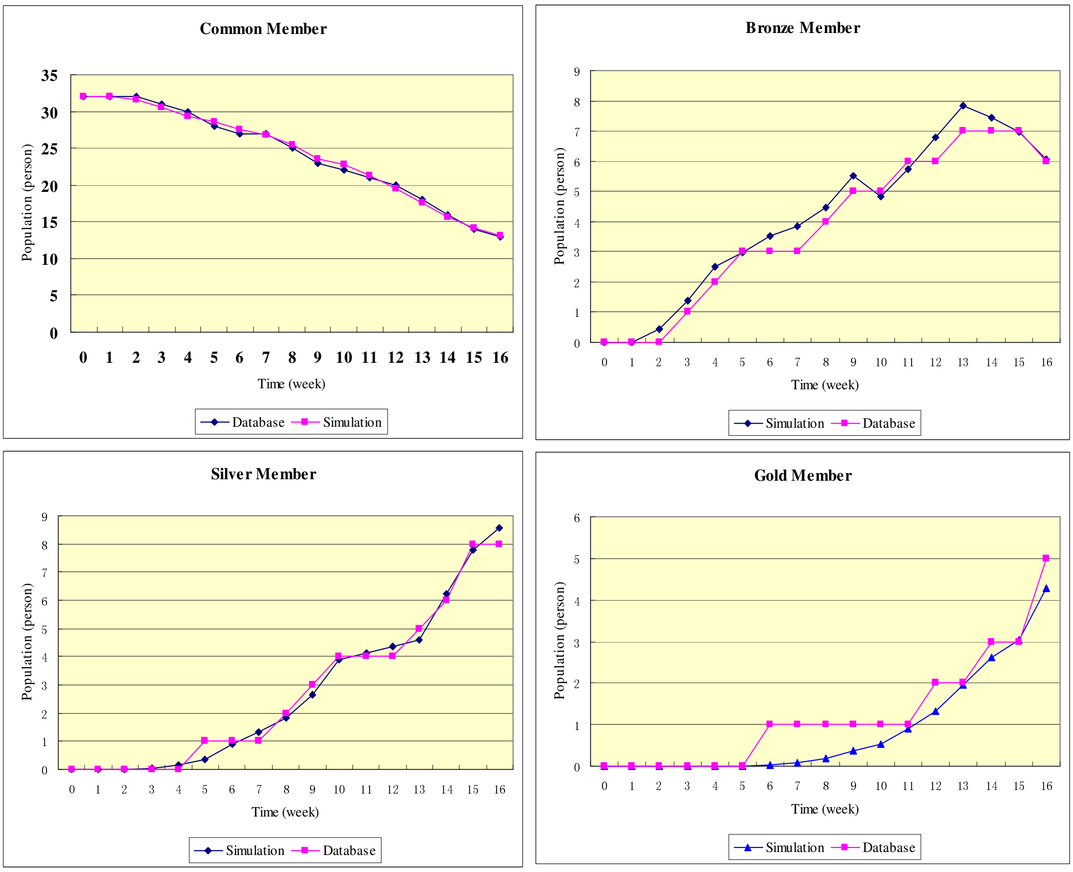

Figure 9. Comparisons with historical data

Figure 10 presents the simulation result of the stock "Contributions".

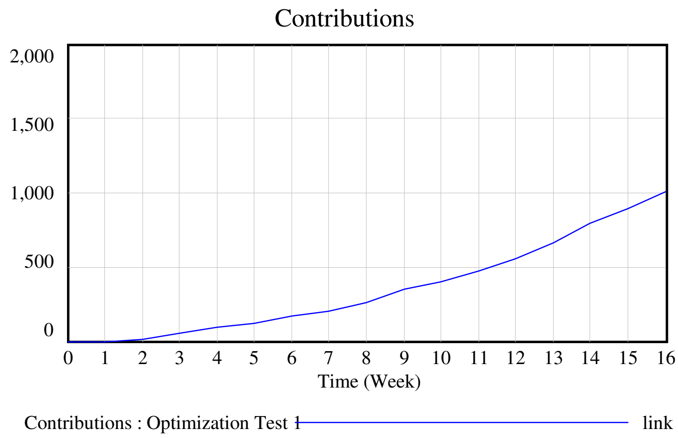

Figure 10. Contributions

4.2 Validity tests

After developing the model, we always want to know how sensitive the model is to different assumptions. Vensim has a sensitivity capability that makes it easy to run Monte-Carlo sensitivity simulations.

Monte Carlo simulation is used to explore the future possibilities and uncertainty of the selected output variables through hundreds or thousands of repeated simulations, representing unknowns as a pool of possible values from which values are drawn at random. Given the uncertainty of model parameters, we use confidence bounds to demonstrate the validity of the model.

Table 3. The range of values of input variables

Parameters	Value	Range
Common Member Upgrading Threshold	24	[18, 32]
Bronze Member Upgrading Threshold	32	[24, 40]
Silver Member Upgrading Threshold	40	[32, 48]
Sensitivity for Common Member	0.575	[0.4, 0.65]
Sensitivity for Bronze Member	0.175	[0.15, 0.2]
Sensitivity for Silver Member	0.29	[0.25, 0.32]

Table 3 presents the range of values of several input variables that we need to change in order to do the validity tests. Through the Monte Carlo simulation, we get the confidence bounds (or the uncertainty) of five selected output variables, as shown in Figure 11.

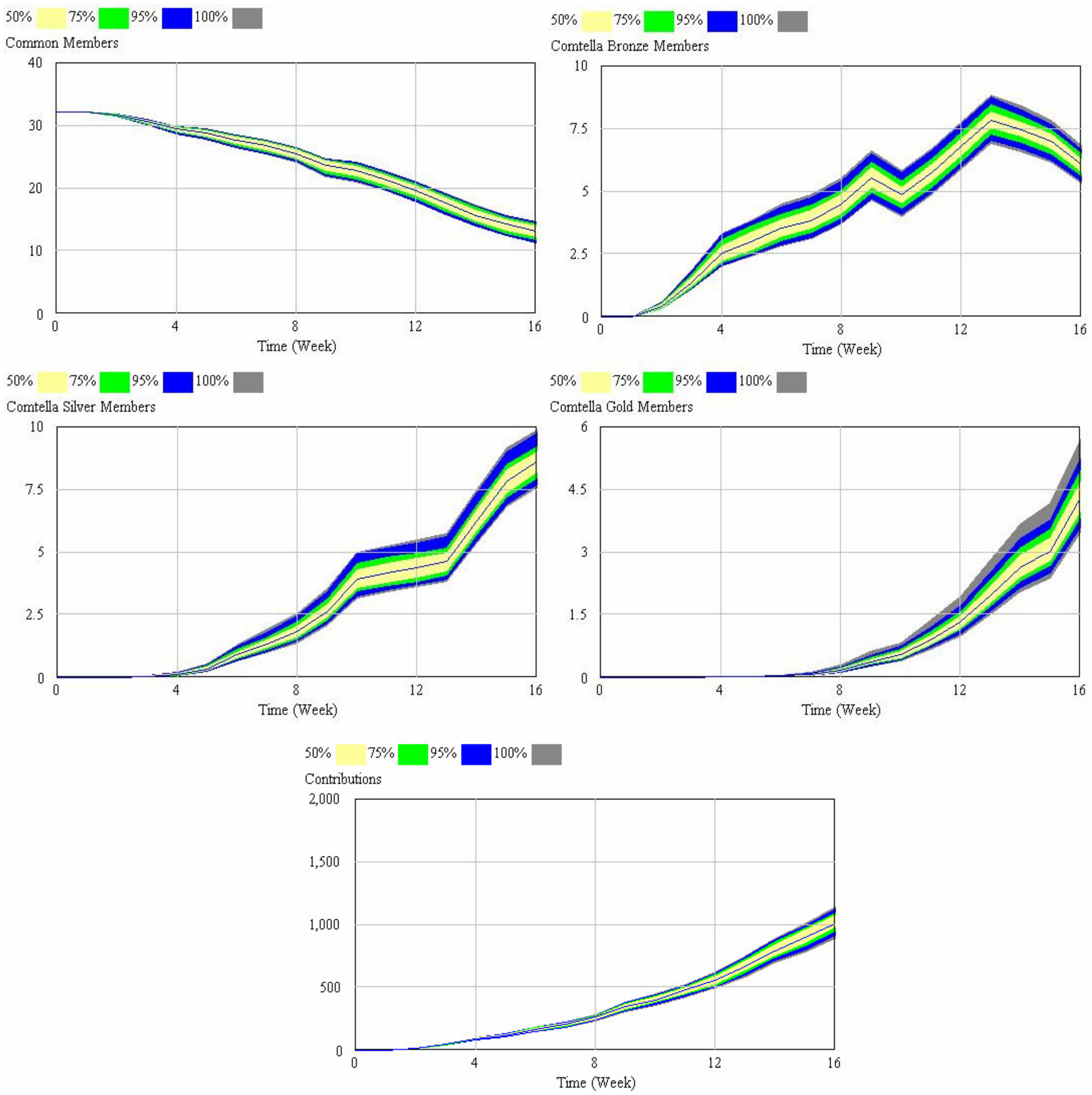

Figure 11. Validity test results

4.3 Experiments

The experiment is conducted to analyze the impact of the three thresholds to the demographic structure of Comtella population. We want to find the factors that can control the number of gold members and common members. The free-riders in the common member group should be reduced to a certain level, but on the other hand users should not be able to upgrade their memberships too fast.

Table 4 presents the population variation of different user groups by changing the three thresholds respectively. “Threshold1”, “Threshold2” and “Threshold3” are short for the membership upgrade thresholds of common, bronze and silver members respectively. The unit of variation is 1 reward unit.

From the results we can see that the common membership upgrading threshold has the greatest impact to the population of silver and gold members. In order to decrease the percentage of free-riders we have to decrease the threshold for common members in order to encourage them to share more resources. But on the other hand, we have to prevent the population of gold member from increasing too fast. We also found that decreasing the threshold for common members will result in the decrease of total number of contributions. Consequently we have to change the threshold for bronze and silver members to balance this effect.

Table 4. Impact of variation by changing different thresholds

	Common members	Bronze members	Silver members	Gold members
Increase threshold1	+5.99%	-1.84%	-4.45%	-6.82%
Decrease threshold1	-6.56%	+1.61%	+4.89%	+8.03%
Increase threshold2	-	+10.26%	-3.41%	-6.61%
Decrease threshold2	-	+5.20%	-1.70%	-3.41%
Increase threshold3	-	-	+3.33%	-6.34%
Decrease threshold3	-	-	+1.72%	-3.27%

We also have to investigate the optimal value of the thresholds that can motivate users in the community, which is one aspect of our future work.

5. Conclusions and future work

Simulation models are very helpful to study the dynamics of virtual communities and also useful for measurement and further improvement of incentive mechanisms in virtual communities. In this paper we advocate a system dynamics approach to study the user motivation and incentive mechanism in the Comtella virtual community. When creating a simulation it is useful to start from a very simple model exhibiting only the basic system behavior. Thus we model an early version of Comtella, and the model described in this paper is prototypical. More complex models can be developed in future work.

For the complexity of human and social dynamics which involves a number of factors in the area of psychology and sociology, we can not build a model that exactly reproduces the real world, but the results from the system dynamics model match the historical data quite well and demonstrate the dynamics of user motivation and incentive mechanism in Comtella.

Our future work will apply the system dynamics modeling approach to model more recent versions of the Comtella community which involve adaptive incentive mechanisms and multiple motivation factors. Several areas of such future work in the model are listed below:

1. Find the optimal state of the community: By changing the parameters we can simulate the system and get insights into possible improvements of the incentive mechanism. We would like to find the optimal state of the community, the state that can create the highest contributions and maintain a low percent free-riders and high activeness of gold numbers.

2. Dynamic reward unit: In our model the reward unit is constant. In the extended model we will use adaptive individual reward units which are used in the current version of the Comtella community. Each user has an expected number of contributions according to their membership level. The individual reward factor is a function of the expected number of contributions, and thus becomes adaptive for a particular period of time.

3. Dynamic memberships: A membership decay may encourage users to continue to contribute new resources after they have reached the highest level of membership. In this case it would be useful to use simulation models to test the decay function and the length of the decay period.

4. Introduce “C-points” and quality control: In order to make the community sustainable in the long run, we must not only encourage users in the community to share new resources, but resources of good quality. Ratings become a vital factor that measures the quality of the resources shared in the community. In the current version of the Comtella community, users can rate any resources shared by others. A virtual currency called “C-points” was introduced in the new Comtella incentive mechanism to motivate users to rate. Users can use C-points as an “ad fee” to make their contributions more visible in the search result list. To extend the model we would like to take into account these factors as well.

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