Constructivist project based learning design, a cybernetics approach

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ABSTRACT

We approach the progress dynamic of project based learning from a systems theory point of view. We model open loop PBL mathematically and analyze its robustness and show its weakness. Then we propose an effective model of conducting complex PBLs by dividing the whole PBL process into sub processes of lower complexity and introduce feedback for each one. In the course of this paper, we show how adopting the proposed model could significantly improve the process of PBL tuition. We present simulations of the higher robust performance of the new model. This paper presents one novel approach of educational design based on cybernetic methods.

Keywords: PBL, Pedagogy, Cybernetics, Constructivism

1. INTRODUCTION

Constructivist pedagogy is a paradigm that perceives learning as a process of constructing knowledge by learners themselves, instead of the teacher taking the role of passively pouring information in their minds [1]. In constructivism, learning is a continuous journey of searching for meanings. The meanings require getting the whole picture first and understanding the parts that this picture is composed of. That is, learning should focus on concepts and contextualization instead of instructing isolated facts [2]. In the process of knowledge creation, students link new knowledge with their previous knowledge. The student's social interaction with peers and the teacher, the student's individual learning style and learning capabilities are all important factors that constructivism shed light on. Since constructivism emphasizes the learner's important role in knowledge construction, constructivism strategies in teaching are often called student-centered instruction.

The constructivist pedagogy as a theory has its origins back over many decades. However, the empirical research on constructivist pedagogy started only by early 1990s [3]. One of the recent constructivist pedagogy practices is Project Based Learning (PBL). Project based learning as an educational methodology draws on the constructivist pedagogy philosophy. It transforms education from a teacher-centered to a student-centered approach by designing curriculum emphasizing more on projects than classroom lectures. Hence, the student has the principal role in constructing the knowledge. Normally the assigned projects are real or quasi-real; hence, relevance of the provided tuition to the students in higher education is facilitated. This has particular impact on increasing student's motivation to the studied subject [4]; students can master the specific learning outcomes of the curriculum through the PBL more efficiently than they will do through the classical classroom based tuition [5].

There is no one unique model of PBL and the literature on this subject varies considerably. However, there are some generalities; for instance, PBL projects are not trivial tasks [5], projects should have clear goals [6], it should improve student autonomy and foster the experiential learning skills [4]. Students' develop necessary life-long learning problem-solving skills [5]. Projects are complex with emphasis on non trivial challenges [7]. Thomas emphasizes that the PBL assignments must involve students in constructivist work and that they are student-centered in nature [5].
It should be noted that teachers embracing the PBL as a learning method are faced with many difficulties due to the complex nature of the projects, and the dominance of

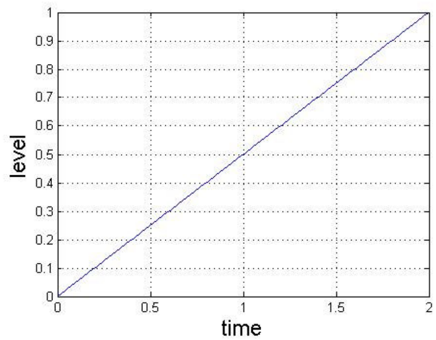
the older teaching methods in schools [8]. **We think that the lack of an efficient tuition model of PBL has contributed considerably to the constraints on spreading this teaching and learning methodology in higher education. To show the cognitive and logistical difficulties associated in delivering effective PBL, we will approach modeling and design PBL from cybernetics perspectives.**

The term cybernetics was introduced by the mathematician Norbert Wiener during the 1940s of the 20th century to define the branch of science that tries to understand the communication and control in the animal, the machine, society, and individual human beings. It has its roots in Shannon's information theory and the concept of feedback in control systems engineering. Wiener popularized the social implications of cybernetics, drawing analogies between automatic systems such as a regulated steam engine and human institutions in his best-selling "The Human Use of Human Beings: Cybernetics and Society" [9]. Cybernetics as a generic term is used in many related subjects that are distributed over a wide variety of science fields but all share in the concept of a system and control. Examples of such fields are: control systems, artificial intelligence, management control, bioengineering, ergonomics, socio cybernetics, game theory, information theory, dynamical systems, systems theory, and complexity theory.

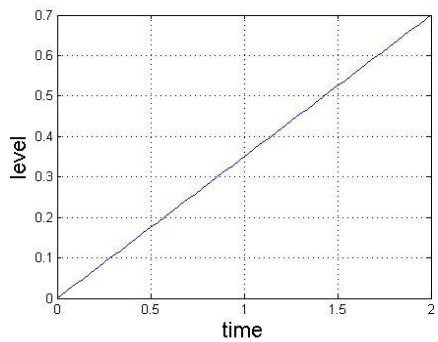
Though cybernetics methods have been utilized in a wide variety of applications and domains, it is noticeable that pedagogical research has barely focused on exploiting some beneficial cybernetics tools such as dynamical control systems or game theory for modeling and analyzing the pedagogical processes. In this work, we try to contribute to what we called the pedagogical cybernetics field of research by utilizing control systems engineering instruments for modeling and dynamical analysis of the PBL pedagogical process.

2. Dynamical Analysis of The PBL

Conceptual models are the most used models for representing pedagogical processes. Though having many advantages, conceptual models have their limitations when it comes to dynamical analysis, because they do not provide a mathematical representation. However, mathematical modeling is not a trivial task, in control engineering problems 80% of the effort needed in the project is devoted to mathematical modeling of the physical system. In this paper, we are approaching the dynamics analysis of problems that involves humans in the loop, which makes the mathematical modeling even more complicated. However, we follow the approach in technical systems modeling which considers only some important aspects of the problem for modeling and tries to derive simpler models. We will derive a mathematical model of the project based learning process, then we will utilize dynamical system theory tools to further analyze



(a)



(b)

Figure 1
Simulation results of 30% weaker student vs. nominal student .

the process dynamics, we will propose enhanced an PBL organization scheme, and suggest the control algorithm for improving the process performance.

Mathematical Modeling: Any accurate proposed model would depend on the project type, which may vary very much from one project to another, and from one domain to another. However, we will try to approach the problem of defining a uniform indicative model. For modeling the PBL we will interpret the definitions of constructivist knowledge implementation from pedagogy into a mathematical model.

According to Kolb, learning is a process of constructively accumulating knowledge [10]. In their definition of PBL, Bereiter and Scardamalia recognize only those projects whose central activity is knowledge constructing as PBL projects [5]. The whole theory of constructivist pedagogy is centered around individuals that are learning through self construction of knowledge [3]. If we consider that the project based learning is a process where the students are constructing accumulated knowledge, practical skills, theoretical background, progress, etc. this can be mathematically aggregated and represented by integral action. Integration is the mathematical counterpart of an accumulating physical phenomena, i.e. tank filling, or capacity charging. Hence, we can write a state space equations of one open loop accumulating learning or project implementation process as follows:

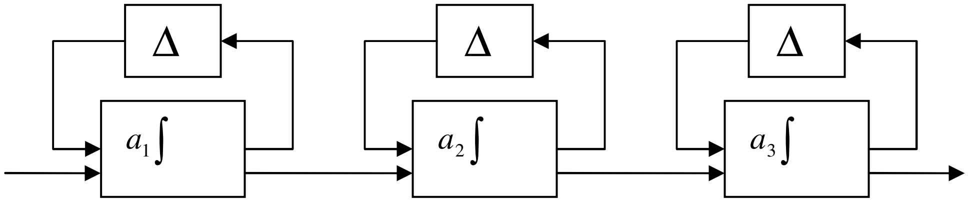


FIGURE 2
THREE CASCADED PROJECT SUB STAGES WITH LEARNING UNCERTAINTY.

$$\frac{dx}{dt} = a\, r$$
$$y = x \qquad (1)$$

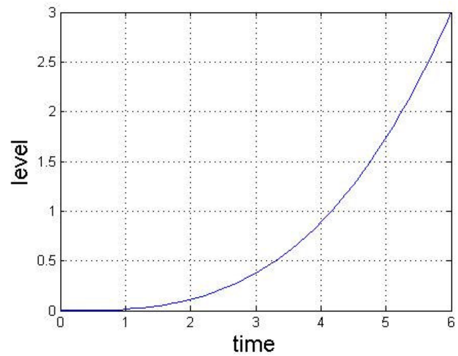
Where, r is the process input that represents the project accumulation speed, x is a process internal state that represents the progress in accumulation, or lets say, the task implemented so far, y is the process output which is identical to x, a is the accumulation process constant which reflects the students capability of conducting the project. The system given by (1) has one pole at the origin which means it is on the border of the stability, so it may be driven from the desired attractive point easily under small disturbances or model uncertainties [11].

Uncertainty Robustness Issue

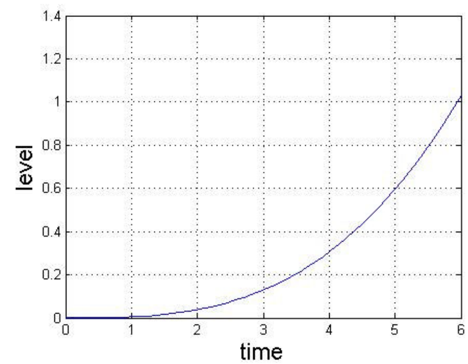
Let us assume that the actual learning ability (accumulating knowledge, or achieving progress) for one student is about 30% weaker than the presumed average by the teacher of nominal students learning ability, i.e. a is less by 30%. Then there will be less progress in the project implementation. Simulations are shown in Figure 1, where (a) shows the nominal students, while (b) shows the weaker student performance.

It is even worse in case that the learning process is more complex. If the project is composed of sequentially cascaded accumulating stages such as shown in Figure 2, the drop in delivering the needed level by the end of the deadline will grow exponentially. To show this effect, we simulate three cascaded accumulating processes with 30% uncertainty for each one as in Figure 2. The simulation plots in Figure 3 (a) and (b) shows that in case of uncertainties, the system's output will differ significantly from what is expected due to the lack of feedback.

We notice that the weak student could deliver only about 35% of the required workload by the end of the deadline compared with the average nominal students. This could leave a negative impact on the student's self confidence and his motivation towards learning among his peers. The previous simulation clearly shows the weak robustness features of open loop accumulating processes. The



(a)



(b)

FIGURE 3
SIMULATION RESULTS OF 30% WEAKER STUDENT SKILLS THAN AVERAGE VS. NOMINAL STUDENT

Robustness issue is very important in the pedagogical process, where students are coming from different backgrounds, each has his/her own learning style, own learning capability, and own surrounding environment during the learning period. Hence, it is very likely that the presumed teacher model of students learning will be significantly different from one student to another. Constructivist pedagogy emphasizes the importance of taking into consideration differences among students during the learning process and accommodating these differences. This will require greater effort of the teacher to meet this important demand. One cure of this dilemma is to develop pedagogical methodologies that can

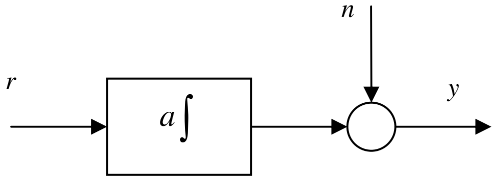


FIGURE 4
SCHEMATIC OF INTEGRATOR WITH OUTPUT DISTURBANCE.

compensate the differences among students during learning and at the same time does not demand larger teaching resources.

Disturbance Rejection Issues

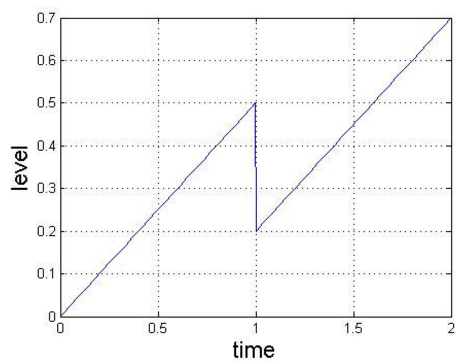


FIGURE 5
DISTURBED OUTPUT OF OPEN LOOP ACCUMULATOR.

Another aspect of open loop learning systems whose dynamic behavior is governed by (1) is their inability to reject output disturbances. Output disturbances are additional noise added to the system output as follow:

$$y = (P + \Delta)\, r \quad + \quad n \tag{2}$$

Figure 4 shows system representation of plant with additive output disturbance.

In the simulation shown in Figure 5, we perturb the project based learning process by some constant disturbance on 30% of the required level of learning to be achieved after about half the assigned time. We notice, how this will diverge the learning outcome from reaching the desired level by the deadline, compare Figure 5 with Figure 1 (a).

So far, open loop PBL appears to suffer from many deficits, in particular, weak robustness and disturbance rejection. In the next sections, we will show how scaffolding and feedback can solve this dilemma.

3. CLOSING THE LOOP, FEEDBACK CONTROL METHOD

Feedback is normally used in control systems design to enhance system performance, compensate the model

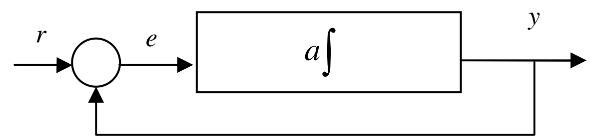


FIGURE 6
CLOSED LOOP ACCUMULATOR

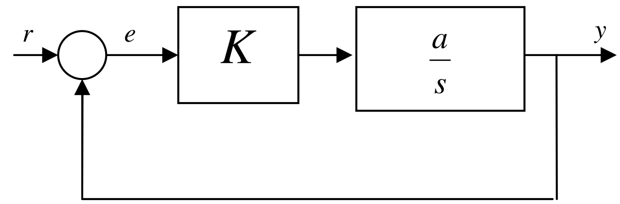


FIGURE 7
CLOSED LOOP INTEGRAL SYSTEM WITH PROPORTIONAL CONTROLLER.

uncertainties and to reject system disturbances. Feedback can be either teacher-centered, i.e. it is performed by the teacher to inform the student about his current knowledge level, or student-centered, i.e. the student has self awareness of his current level and what is assumed to achieve, or hybrid, i.e. multiple feedback loops are achieved by the teacher and the student, which will lead for more robust performance.

We can represent the closed loop learning construction or project progress process in Figure 6. Where e represents the difference between the given reference r (i.e. the presumed learning or project delivery outcomes) and the actual output y that represents the student's current knowledge, learning, or project progress level. We call e the learning or achievement gap. From Figure 6, we can derive the mathematical model of the closed loop learning process as follow:

$$\begin{aligned} \frac{dx}{dt} &= -\frac{1}{a}x + r \\ y &= x \end{aligned} \tag{3}$$

Where a is a positive number and represents the students learning capability and x is the internal state presenting the project progress. The transfer function between the input *r* and the output *y* of system (3) is given as follow:

$$y = \frac{1}{\tau s + 1} r \tag{4}$$

Where $\tau = 1/a$ is representing the first order dynamic time constant which depends on the process nature. System (4) has one pole $s = -1/\tau$ located in the left domain of the complex space, which means it is asymptotically stable. The response of system (4) depends inherently on its time constant $\tau = 1/a$ which causes a lag in reaching the desired reference. However, one of the feedback advantages is that this lag can be improved by introducing a controller action to the system. One simple control strategy to add is a cascaded proportional controller with gain *K*, i.e. magnifier, as shown in Figure 7. System (4) can be rewritten as follows:

$$\begin{aligned} \frac{dx}{dt} &= -K\frac{1}{a}x + K\,r \\ y &= x \end{aligned} \tag{5}$$

The proportional controller is technically implemented as an *energy magnifier unit*, the question is *how it can be implemented in the PBL process*? By considering that system (5) will represent a controlled closed loop project based learning process, the controller in student-centered learning process can be implemented in the following way: *the student will make continuously more effort on bridging the gap between the required and the actual accumulated level of achievement,* in other word, effort or energy is mainly provided by the student.

Uncertainty Robustness Issue

Let us now introduce an additive plant uncertainty of 30% less ability on achieving the task, this uncertainty can be modeled as shown in Figure 8. Simulations in Figure 9 shows no major difference in the project based learning dynamic between a relatively weaker student and the average, since feedback is continuously achieved and is compensating the uncertainty. This is significantly different from the way of progress in the case of open loop accumulating project or learning process.

Disturbance Rejection Issues

Another advantage of feedback control systems is their ability on rejecting constant output disturbances.

If we consider additive disturbance to the closed loop PBL system given by (3), then the controlled perturbed system can be modeled as follow:

$$\begin{aligned} \frac{dx}{dt} &= K(-\frac{1}{a}x - n + r) \\ y &= x + n \end{aligned} \tag{6}$$

Where *n* represents the additive disturbance, which can be an external additive load (which will have negative value in this case), noise, or some sort of bias in estimating or measuring the output progress of the PBL, etc. To show this capability, we consider the same sort of output disturbance simulated in Figure 5 for the open loop process. We apply it on the closed loop PBL process (6). The simulation in Figure 10 shows the ability of the closed loop in compensating the output disturbance.

We notice that this capability can be enhanced when the student puts more energy on the task, i.e. *K* increases.

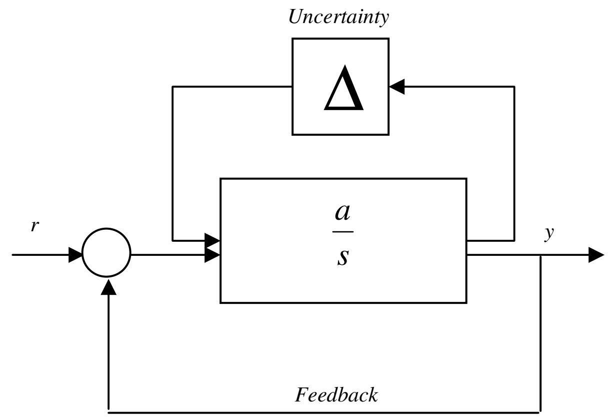


FIGURE 8
CLOSED LOOP LECTURE WITH STUDENT'S UNCERTAINTY

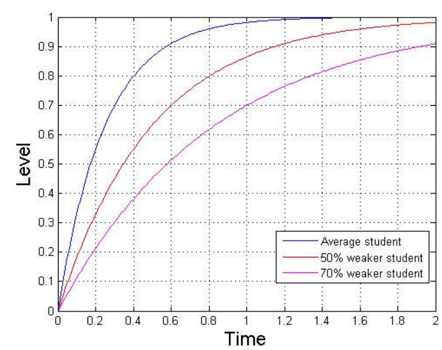


FIGURE 9
DISTURBED OUTPUT OF OPEN LOOP ACCUMULATOR.

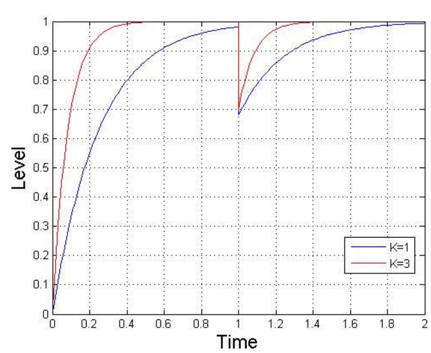


FIGURE 10
COMPARISON BETWEEN CONTROLLED AND UNCONTROLLED CLOSED LOOP.

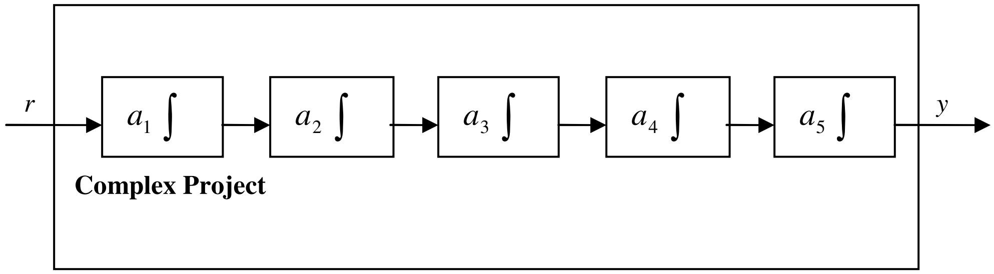


FIGURE 11
COMPARISON BETWEEN CONTROLLED AND UNCONTROLLED CLOSED LOOP.

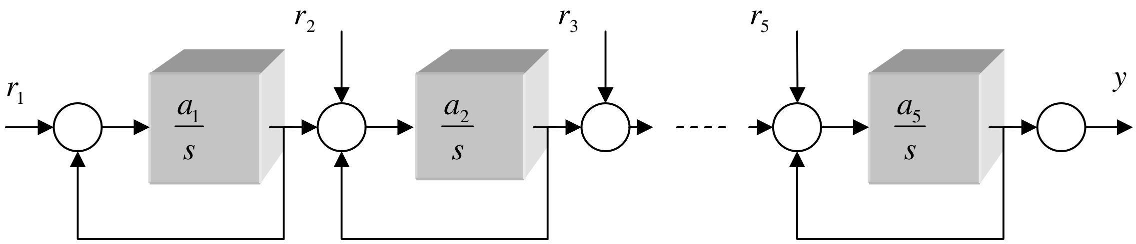


FIGURE 12
COMPARISON BETWEEN CONTROLLED AND UNCONTROLLED CLOSED LOOP.

4. DESIGNING AN EFFECTIVE COMPLEX PBL MODEL

Here we would approach the problem of modeling and controlling complex process of PBL from control engineering perspectives. It is expected that PBL projects should introduce students to solving complex problems [3], [12], and [5].

In complex technical problems, it is preferred to have a decentralized control strategy and internal feedback loops for the sub systems. This can be done by breaking down the complex system into smaller sub systems and designing a suitable controller for each one. Blumenfeld and others argue that dividing the complex projects into smaller pieces is better for the students from cognitive point of view [13].

To show how the order of complexity may affect the student progress and how feedback, control systems analysis and design tools help in coping this complexity, we will consider modeling PBL complex task with the aim to achieve five units of implementation spanned along one academic year (about 10 months). When each accumulating stage depends on the previous one, this can be approximated by a 5th order accumulation system. In other words, it is composed of five cascaded accumulating sub stages as shown in Figure 11.

Simulation of the complex project shown in Figure 8 is presented in Figure 13 (F “blue”), where we notice that there is no significant advance in the project during the first six months due to the complexity of the project, lack of feedback, and lack of clear objectives; hence student drop out of the assigned project is very probable. Furthermore, uncertainties in the students learning level as well as disturbances will deviate the delivered project output (y) considerably from the set ones (r) such as shown in Figure 13 (F “red”).

Now, with the addition of control system design guides we break down the complex task into smaller ones and introduce feedback loops to each sub process, as shown in Figure 12. The state space representation of the closed loop complex PBL process can be written as follow:

$$\dot{X} = A\,X + BU \qquad (7)$$
$$Y = C\,X + DU \qquad (8)$$

Where A is the system matrix, B is the input matrix, C is the output matrix, D represents direct coupling between input and output. We can write (7) and (8) by considering the structure shown in Figure 12 as follow:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \cdots \\ \dot{x}_5 \end{bmatrix} = \begin{bmatrix} \frac{-1}{a_1} & 0 & \cdots & 0 \\ 1 & \frac{-1}{a_2} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & \frac{-1}{a_5} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_5 \end{bmatrix} + \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \\ \cdots \\ r_5 \end{bmatrix} \qquad (9)$$

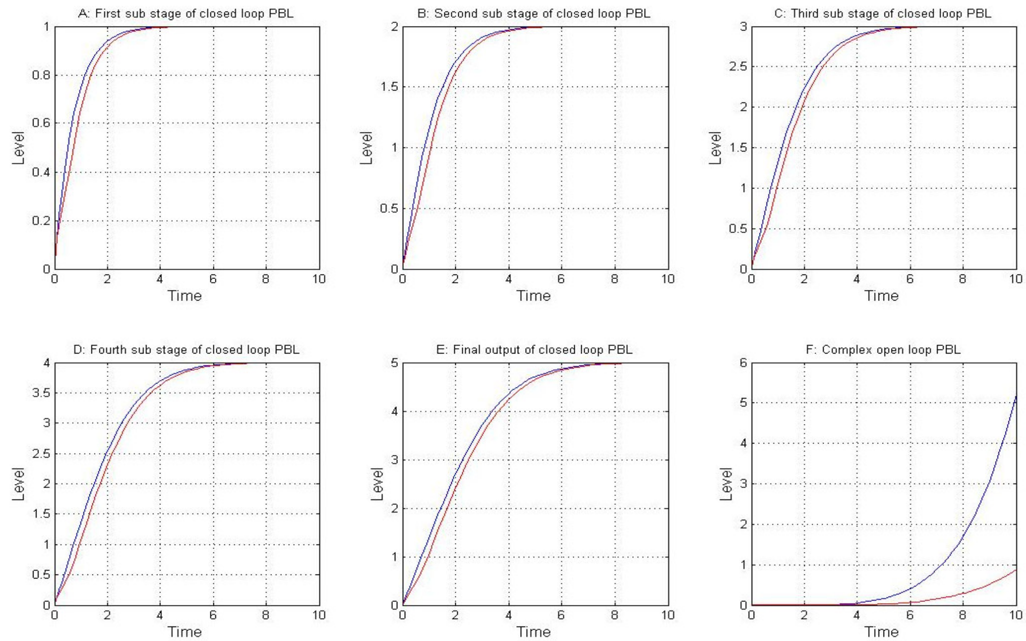


FIGURE 13
FIVE STAGES CLOSED AND OPEN LOOP PBL, BLUE IS NOMINAL, RED IS 30% WEAKER STUDENT

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_5 \end{bmatrix} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_5 \end{bmatrix} \qquad (10)$$

Where x_i for i=1, 2, 3, 4, 5 are internal states that represents the advancement level for each sub process; r_i for i=1, 2, 3, 4, 5 is the reference signals for each sub process and represents the required implementation level by the end of each sub process by its end, y is the actual output, a_i. are the sub process constants. We notice here that A is lower triangular, its Eigen values are then represented by the main diameter:

$\lambda_i = \frac{-1}{a_i}$ where $i=1,2,3,4,5$.

All Eigen values are strictly negative which means the proposed closed loop model of a complex PBL is stable and able to bring the output to the desired set goals [11].

In deriving the model (9) and (10), we considered that effective feedback is continuously practiced, and the teacher has access to control parameters that gives the student a utility for improving performance, in the case of weaker learning capabilities compared with the average student's peers, i.e. by introducing the control parameter K as in (5). This control parameter is an aggregation of student's self esteem, motivation, ability to accept increased workload, etc. We call here for further research in psychology and cognitive science on developing effective algorithms for tuning this parameter, i.e. recommended effective advice the teacher can provide for his students for an enhanced amplifying factor K.

Let us now consider simulating the model (9) for the normal student case, i.e. $K=1$, in comparison with 30% weaker student. The simulation shows very close dynamic of both nominal and 30% weaker student. This enhanced dynamic progress of the weaker student in comparison with the nominal students is related to the feedback practice. Such encouraging results may lead us to propose the following hypothesis:

Hypothesis

- Feedback practice is an effective pedagogical methodology for conducting constructivist PBL learning courses.

- Feedback can bring student performance to the assigned desired implementation task set by the teacher despite considerable differences in a student's knowledge constructing model.

- Feedback will accommodate uncertainty in a student's ability to commence PBL and could lead all students to meaningful learning.

- Feedback is also effective for compensating the extra load efforts needed by students alongside the PBL work.

5. CONCLUSION

The cybernetic tool, “Feedback control systems” has been successfully used in the engineering domain. There has been recent active research in embedding this tool in the economic field. However, the use for modeling and analysis of pedagogical processes is a new phenomenon.

There have been many calls in the pedagogical literature to shift towards constructivist teaching and learning methodologies. One of these is the project based learning approach which is only about one decade old. In this work, we proposed generic mathematical models of PBL, and we derived models of so called open and closed PBL.

Dynamical analysis and simulations of these models showed many superior characters of closed loop PBL over the open loop PBL. They revealed that closed loop PBL is a stable process. In other words, students drift off the assigned project objectives is much more difficult than in the case in open loop PBL. Adapting feedback in the closed loop model may lead to compensating differences among students in achieving the assigned learning outcomes.

We argue that feedback control systems can be used as effective cybernetics tool for modeling, dynamical analysis, and furthermore controlling pedagogical processes as it has been used in the engineering sciences.

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