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Rework Impacts Evaluation through System Dynamics Approach in Overlapped Product Development Schedule

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Abstract

This work aims to explore a novel framework to analyze the planning concepts in product development projects employing techniques to reduce the lead-time of activities, such as overlapping of a pair of each. With the System Dynamics methodology, a model to evaluate the rework fraction, needed to accommodate the deviations proportional to the overlapping grade of the activities, is developed. A numerical example is provided to demonstrate the validity of the model. Although problems encountered during the project management are dynamic, they have been treated on a static basis, what has as result, chronic schedules delays, overruns and cost overspent persist in follow the managers' (re)actions. In this work, we have addressed this known problem by introducing and reviewing some characteristics of the concept of rework in overlapped schedules. This consists in observe and capture the relations feedbacks among the original planned project schedule, the overlapping strategy and the inherent uncertainty in a work being done with poor information. To realize this concept, we have faced with many behaviors patterns (e.g. rework, new duration, non-conformity), and analyze the output behavior pattern, produced by the proposed model.

Keywords: activity overlapping; system dynamics; rework; product development projects.

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Introduction

A product development project environment shows itself inherently dynamic, involving multiple feedbacks and complex framework (Sterman 1992), with a variety of interdependent activities and resources, financial and human, being spent. The traditional approaches tend to assume that if each project element can be understood then the whole project may be controlled. However, experience suggests that the interrelationships among the project's components are more complex than is stated by traditional work breakdown structure of project network (Rodrigues & Bowers 1996).

As a response to this feature, rising up the system dynamics methodology, which concentrates efforts on understanding the whole project environment, in this context system dynamics researches on project management provide a general and convincing framework (Lyneis, Cooper & Els 2001), within which to understand reasons behind the chronic managerial problems in project management, as overruns and overspent, and suggests a dynamic approach with a system view on observed management problems, creating a scenario tool to better support management decisions.

Objective

The main objective of this work is to provide a general model utilizing the system dynamics methodology, to estimate the called extended design time, strictly related to the necessary rework fraction, considering overlapped activities.

Overlapping strategy to shorten the project lead-time

The increasing importance of the flexibility and agility of the companies required by the markets, is reflected in an increasing effort to accelerate the development and launch new products or variations of existing products, mainly in make-to-order or engineering-to-order environments, such as, aeronautics, civil, naval and electronics new devices industries.

As Clark & Fujimoto (1991) showed, new product rapid development cycles are characterized by overlapped activities, and the literature concerning on these issue has been increasing since the 1990's. Ahmadi & Roemer (2004) consider the activities overlapping an "essential technique to save development time". For example, we should consider that the conception phase actually is finished before the construction phase starts, hence, with a certain grade of overlapping; the result will be a reduction on the lead-time. Therefore, starting the construction phase before the conception be finished can also, result in an augmented number of changes and accommodations, looseness of productivity, increasing costs and losing time. Furthermore, studies in construction projects have revealed that, when there were more changes due to overlapping, the total number of changes did not be significantly different that others equivalent projects with no overlapping, but the lead-time reduction was worthwhile (Ibbs, Lee & Li 1998).

System dynamics in project management

Basics concepts in system dynamics

System Dynamics (SD) was developed by J. W. Forrester in 1961 (Sterman 2000), when he has developed a theory to approach complex systems, non-linearities, and with several feedback loops of information. The SD main focus concerns on the analyses of system dynamical tendencies. The objective is discovering how the system is stable or unstable, if it oscillates or not, to tend to increase, decreases or tends to equilibrium, i.e., the dynamics behavior that is observed in complex systems is caused by its inherent structure. The principal concept of this methodology is the feedback, where the decisions and the functions pattern behaviors, are derived by the system's information. These decisions results on actions that will change the system as all.

The feedback occurs when the variable *x* affects the variable *y* and, *y* affects *x*, hence, it can not be observed only one of its variables. Only observing the whole feedback system that it can comprehend the system dynamic behavior, which is a consequence of its structure (Sterman 2002). The SD requires that each element and each model relation has non-linear patterns which the feedback loops have different force values (Sengupta & Abdel-Hamid 1993) .

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The Project Management Dynamics

The project management discipline is an important area in management theory and is poorly studied with complex models that represent its complexity, where delays and cost overruns are most common than exception (Sterman 1992), what lead us to use tools and methodologies that support the decision makers to act under a high degree of uncertainty and complexity. These ones are motivated by frequent changes in scope or budget, actually due by feedback of what is being performed (Hendrickson & Au 1998). To solve such problems and to develop a continuous learning environment that arose the system dynamics methodology applied to project management.

Some key features of the SD modeling tool are: multiple actors involved, feedback processes, non-linearities, flows of information and goods. These models are largely utilized in large-scale projects in naval shipbuilding, aerospace projects, software, and hydro power plants (Abdel-Hamid & Madnick 1991) and (Rodrigues & Bowers 1996).

Large-scale projects become complex dynamical systems because they:

- Are extremely complex, consisting of multiple interdependent components;
- Are highly dynamics, i.e., changing over time;
- Involve multiple feedback processes;
- Involve non-linear relationships;
- Handle with soft and hard data and information.

As Rodrigues & Bowers (1996), the applications of SD in project management has been motivated by various factors:

1. a concern to consider the whole project rather than a sum of individual elements, called as holistic approach;

2. the need to examine major non-linear aspects typically described by balancing or reinforcing feedback loops;

3. a needed for a flexible project model which offers a laboratory for experiments with management's options; and

4. the failure of traditional analytic tools to solve all project management problems and the desire to experiment with something new.

Overlapping strategy of shortening project lead-time

The overlapping strategy of activities with a view to reducing the project lead time has been studied in the context of project scheduling and new product development. Browning, Frickle & Negele (2006) provide a review of work on modeling product development process (see also (Ahmadi, Roemer & Wang 2001)). Krishnan (1993) provides a framework to help designers or managers to decide when and how to overlap the activities reducing product development lead time while ensuring that the adverse effects on product quality and development effort are minimized, and presents an way to determine how to disaggregate design information and overlap consecutive stages based on the evolution and sensitivity properties of the information exchanged (Krishnan 1996).

The information dependencies between development tasks constitute the information processing view of the development processes, and can be modeled as a Markov chain (Chakravarty 2001) and arranged into a Design Structure Matrix (Cho & Eppinger 2005). The overlapping strategy differs from the sequential approach in that it allows downstream project stages to start before preceding upstream stages have finalized their works (Roemer, Ahmadi & Wang 2000). In way to belong project faster and cheaper, the managers have noticed big advances in project management, and the one of the most useful and popular, is the overlapping. As a result, the duration of individual activities actually increases through overlapping, while the total project lead-time decreases because working concurrently on different activities. Thereby, overlapping utilizes incomplete information; it requires that project stages start their work assuming a certain grade of work done with a quality less than the specified, forcing the system need the rework, which is often needed to accommodate unforeseen upstream stages. Time-cost trade-offs are

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extensively discussed in the project schedule literature, where activities can be shortened (crashed) at additional costs. Because both crashing of activities and overlapping aim reducing completion times, they can be considered alter nativities or complements to each other.

Nicoletti & Nicoló (1998) develop a linear programming model with a view to maximizing information flow in concurrent engineering projects. Chakravarty (2001) makes analysis of single and multiple overlaps properties and its impacts on cost functions.

Ford & Sterman (2003) state that concurrent development not only increases the vulnerability of projects to changes and errors requiring rework, but also increases the fraction of work released that will require changes. Ahmadi & Roemer (2004) present a cost minimization model for the simultaneous crashing and overlapping of activities in a project consisting of activities in series, analyzing the impact of different evolution/sensitivity parameters. Zhang, Qiu & Zhang (2006) establish a method to measure the coupled strength of tasks and to calculate the gross workload, determining the best sequence of coupled tasks based on task output influence ratio, parameter change ratio and parameter feedback.

Gerk & Qassim (2008) provide a mixed integer nonlinear programming model for the acceleration of projects, employing the simultaneous crashing, overlapping, and substitution of project activities, with the assumption that the rework fraction caused by overlapping rates is previously known.

The Dynamic Model for Evaluate Rework Impacts

Project Scheduling with Overlapping

Let be a project with n+1 sequenced activities, where two activities, i-1 (upstream) and i (downstream) with precedence relationships, as shown in Figure 1.

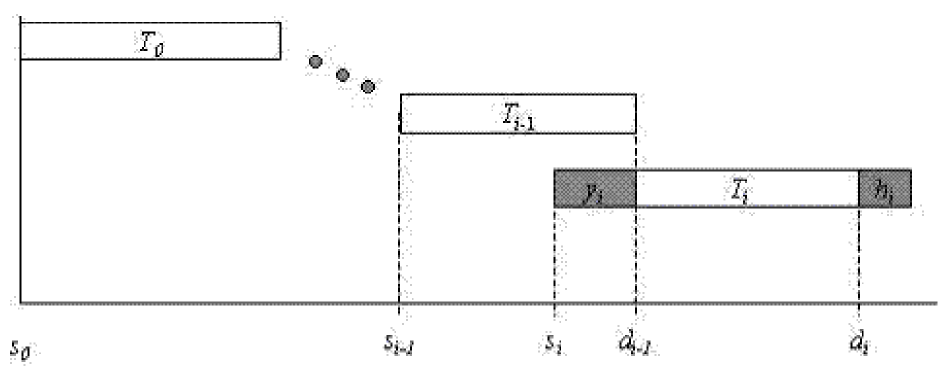

Figure 1. Activity scheduling.

Denoting T_{i-1} is the estimated duration for activity i-1, and T'_i is the estimated duration for activity i, and there is a overlapping between i and i-1 with a certain amount of hours denoted by y_i, we shall determine T which represents the summation of durations of both activities, as:

$$T_{\lambda} = T_{i-1} + T_i^{'} \qquad (1)$$

The first consideration that must to be made is that the overlapping is expressed as:

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$$y_i = d_{i-1} - s_i \,, \tag{1}$$

denoting the comprehended time between the anticipated start of the downstream activity and the finish of the upstream activity, being a function of

$$h_i(t) = \int_{s_i}^{d_{i-1}} p_i(t)dt \tag{2}$$

By the fact of the precedent activity starts with less information than it actually has, a additional work should be necessary, in order to accommodate developments unperceived in the upstream activity, such as

$$T'_i = T_i - y_i + h_i \tag{3}$$

which is calculated with the original value T_i, and h_i which denotes the total rework needed in function to overlapping.

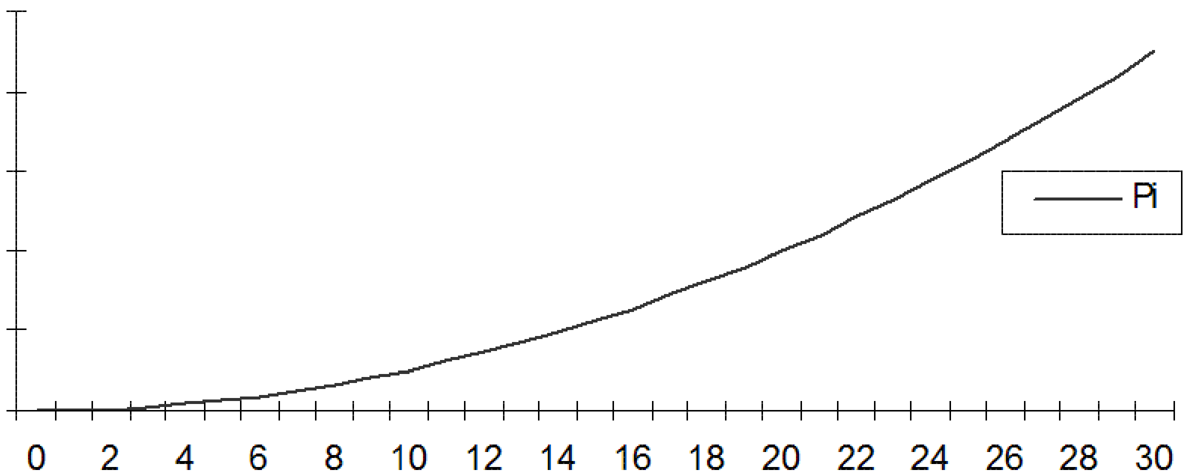

Figure 2. Probability function $p_i(y_i)$.

The probability density function, as Figure 2, that represents the overlap incidence on stage *i*, is

$$p_i(y_i) = \int_0^{y_i} y_i dy_i \tag{4}$$

However, is the activity *i* runs *dt* units of time, the rework probability is a concave function, if the information ratio is high, and convex, otherwise (Krishnan, Eppinger & Whitney 1997) and (Ha & Porteus 1995), as

$$p_i(\tau) = 1 - e^{-1/(\tau)} \text{, where } \tau \in [s_i, d_{i-1}] \tag{5}$$

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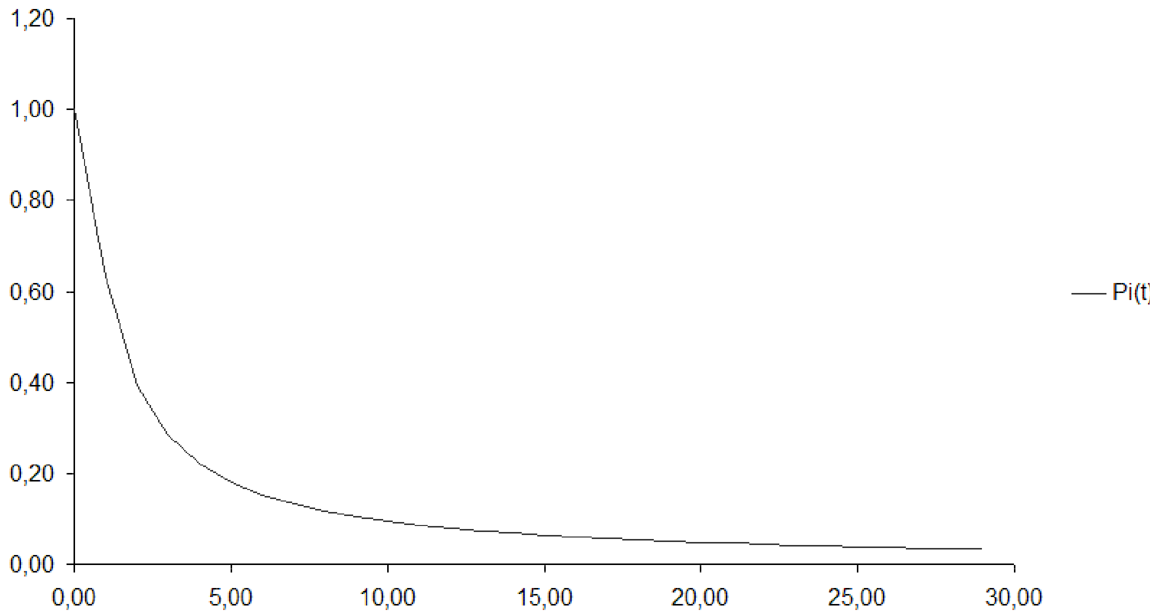

Figure 3. Rework probability function.

Hence, the probabilty $p_i(\tau)$ becomes a function of y_i (Loch & Terwiesh 1998). As explicited by Lyneis, Cooper & Els (2001) the project environment is highly dynamic, and a "learning system" arises as a consequence of experiences and previous models.

As proposed by Zangwill & Kantor (1998), the learning curve can be formulated as a differential relation, which concerns the rework and the learning fraction, $L_i(t)$, in a derived relation of the existing dynamics of "predator-prey", that follows the expression:

$$\frac{dh_i(t)}{dt} = -\alpha L_i(t) h_i(t) \qquad (6)$$

where is a proportionality coefficient ($\alpha \in (0,1)$). On the other hand, the fraction of learning concerns two main factors, that is a auto-inhibition factor, and of mutual inhibition. Therefore,

$$\frac{dL_i(t)}{dt} = \beta L_i(t) - \gamma (L_i(t) h_i(t)) \qquad (7)$$

, and

$$L_i(t) = \int_{s_i}^{d_{i-1}} \frac{dL_i(t)}{dt} dt \qquad (8)$$

So the equation (7) can be rewirtten as

$$\frac{dh_i(t)}{dt} = -\alpha L_i(t) \int_{s_i}^{d_{i-1}} p_i(t) dt \qquad (9)$$

where $-\frac{dh_i(t)}{dt}$ is the learning ratio into the *overlapping* time windown.

For equations (8) and (10) the parameters and depend on the observations made into the project environment, and may be related with the workforce experience, quality and quantity of training, inspections frequency, complexity of the project and information exchange between stages. By convenience, a resolution schema is described,

begin

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$$T_{i-1}$$
$$T_i$$
$$s_i, d_{i-1}$$
$$y_i = d_{i-1} - s_i$$
$$T_\lambda = T_{i-1} + T'_i$$

$$p / t = s_i \rightarrow d_{i-1}$$
$$T_i' = T_i - y_i + h_i$$

$$p_i(t)$$
$$dh_i / dt$$
$$dL_i / dt$$

GO to T until $t = d_{i-1}$

The initial conditions are $t_0 = s_i$, $t_f = d_{i-1}$, T_{i-1} and T_i are known and $\in \left]0,1\right]$.

Through the equation system described above is possible to determinate the total time between two sequential activities, with overlapping, and the learning effect, as Figure 4.

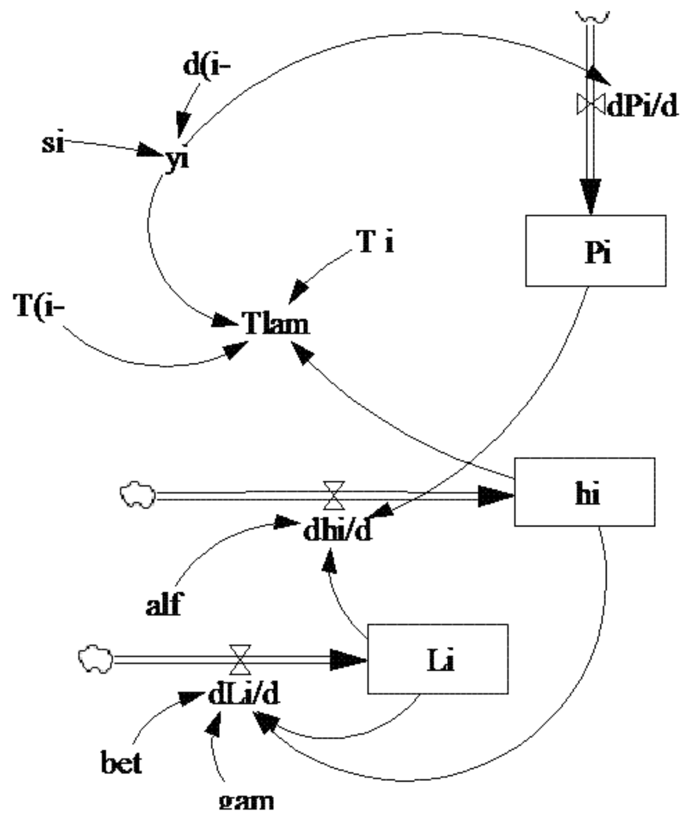

Figure 4. Causal loop diagram.

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Results

In this section a numerical example extracted from the industry will carried out to illustrate the model applicability. The example consists on a product development project with a estimated time of duration of each activity and a rule to overlap a pair of activities with an estimated rework fraction due to overlapping. Hence, the model will be applied to re-estimate these rework fraction on an analytical basis, instead of an empirical one, with the aim to evaluate the rework fraction that arose from each activity pair overlapping.

The Table 1 contains the activities description, precedence relations and the actual time for each activity. In the Table 2 the overlapping times and activities pair are considered and a rework fraction of each pair. The Figure 5 describes the project network, as indicated by Table 1.

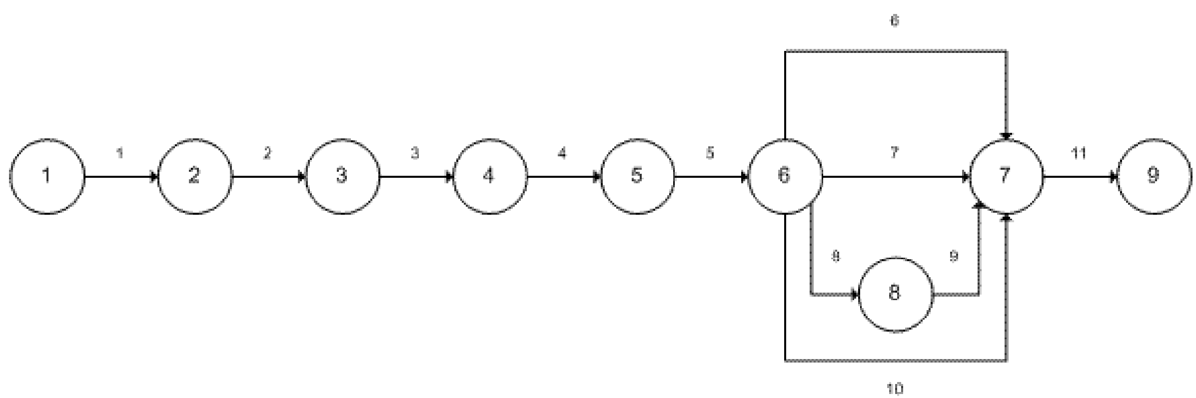

Figure 5. Network diagram of the product development project.

Activities	Description	Precedent Activ.	Actual Time (weeks)
1	Product Conception	0	8
2	Materials selection	1	10
3	Process conception	2	8
4	Production Systems Design	3	5
5	Prototype tests	4	3
6	Procurement	5	4
7	Production planning	5	3
8	Tools and machine acquisition	5	2
9	Equipment installation and set-up	8	1,5
10	Personal hire	5	4,5
11	Plant commissioning	6,7,9,10	1

Table 1 - *Description of the activities and product development project parameters.*

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Activ. Overlapping (*i*-1 - *i*)	*T*(*i*-1)	*Ti*	*si*	*d*(*i*-1)	Overlapping duration (*yi*)	Empirical Rework fraction (*hi*)
1 - 2	8,0	10,0	5,0	8,0	3,0	0,10
2 - 3	10,0	8,0	8,0	10,0	2,0	0,20
3 - 4	8,0	5,0	6,0	8,0	2,0	0,25
4 - 5	5,0	3,0	3,0	5,0	2,0	0,25
5 - 6	3,0	4,0	2,0	3,0	1,0	0,20
5 - 7	3,0	3,0	2,0	3,0	1,0	0,15
5 - 8	3,0	2,0	2,0	3,0	1,0	0,15
5 - 10	3,0	4,5	2,0	3,0	1,0	0,25
8 - 9	2,0	1,5	1,5	2,0	0,5	0,10
6 - 11	4,0	1,0	3,0	4,0	1,0	0,20
7 - 11	3,0	1,0	2,0	3,0	1,0	0,10
9 - 11	1,5	1,0	0,5	1,5	1,0	0,20
10 - 11	4,5	1,0	3,5	4,5	1,0	0,20

Table 2 - *Activities overlapping data (time in week basis).*

With the data displayed on Tables 1 and 2, the total time behavior have been calculated and analyzed for each pair of activities and the calculated rework fraction according to expressions shown on previous section. To solve this system of equations a software specific to System Dynamics models has been used, the VENSIM PLE®, available at www.vensim.com; it utilizes a differential equations solver with the Euler method, with time step determined by the modeler. In this work a time step of 0.03125 was used.

Activ. Overlapping (*i*-1 - *i*)	*T*(*i*-1)	*Ti*	*si*	*d*(*i*-1)	Overlapping duration (*yi*)	Total time of the pair of activ.	Empirical Rework fraction (*hi*)	Calculated Rework fraction (*hi*)
1 - 2	8,0	10,0	5,0	8,0	3,0	15,86	0,10	0,09
2 - 3	10,0	8,0	8,0	10,0	2,0	17,19	0,20	0,15
3 - 4	8,0	5,0	6,0	8,0	2,0	12,19	0,25	0,24
4 - 5	5,0	3,0	3,0	5,0	2,0	7,19	0,25	0,40
5 - 6	3,0	4,0	2,0	3,0	1,0	7,72	0,20	0,43
5 - 7	3,0	3,0	2,0	3,0	1,0	6,72	0,15	0,57
5 - 8	3,0	2,0	2,0	3,0	1,0	5,71	0,15	0,86
5 - 10	3,0	4,5	2,0	3,0	1,0	8,22	0,25	0,38
8 - 9	2,0	1,5	1,5	2,0	0,5	5,08	0,10	1,39
6 - 11	4,0	1,0	3,0	4,0	1,0	5,71	0,20	1,71
7 - 11	3,0	1,0	2,0	3,0	1,0	4,72	0,10	1,72
9 - 11	1,5	1,0	0,5	1,5	1,0	3,22	0,20	1,72
10 - 11	4,5	1,0	3,5	4,5	1,0	6,22	0,20	1,72

Table 3 - *Activities overlapping data (time in week basis).*

Based on the obtained results, in Table 3 we can observe for greater duration time values for each activity and for overlapping times, the model is good enough, i.e., it is adherent to empirical data, with initial conditions equal to = 1, = 0.3 e = 0.2. To further works the value could be changed to test the adherence of

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model results.

In Figure 6 an existed correlation between ${dh_i}/{dt}$ and ${dL_i}/{dt}$ is described by its phase diagram. Furthermore, in Figure 7 it can be observed that when the overlapping fraction increases, ${y_i}/{T_i}$, to values upper to 40% for the activity duration, the model outputs for rework fraction, ${h_i}/{T_i}$, is greater than those provided by the literature (Gerk 2005), because the probability of rework is a direct function of the overlapping fraction.

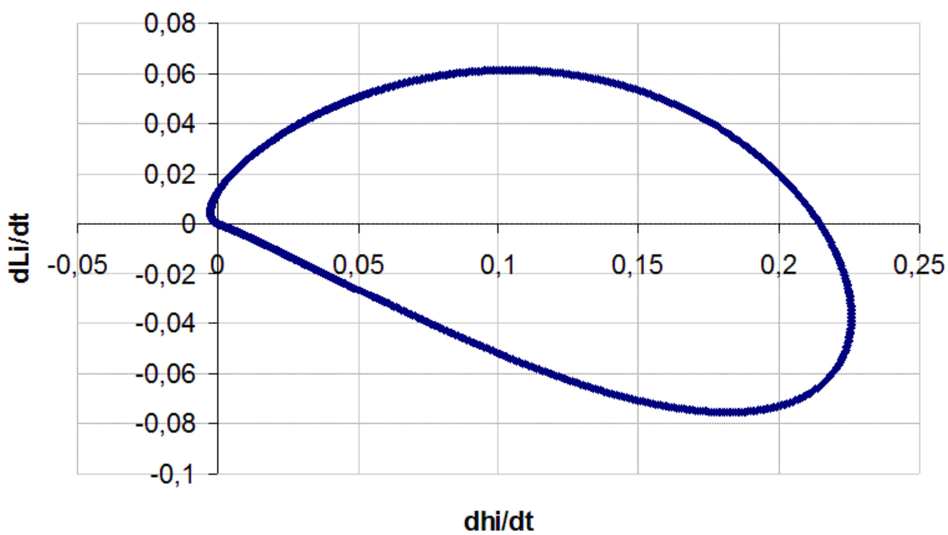

Figure 6. Phase diagram for learning and rework for 200 weeks.

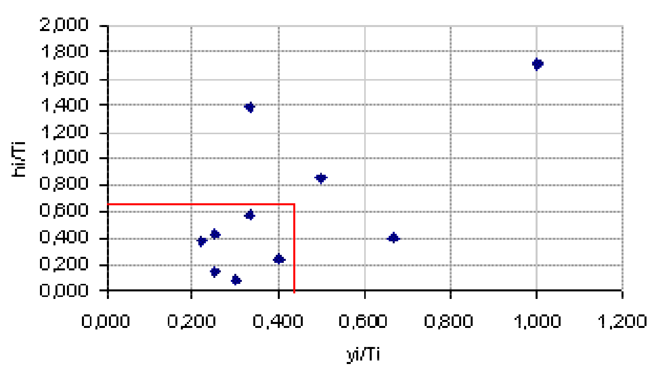

Figure 7. Correlation between *yi/Ti* and *hi/Ti*.

Discussion

Although problems encountered during the project management are dynamic, they have been treated on a static basis, what has as result, chronic schedules delays, overruns and cost overspent persist in follow the managers' (re)actions.

In this article, we have addressed this known problem by introducing and reviewing some characteristics of the concept of rework in overlapped schedules. This consists in observe and capture the relations of feedbacks among the original planned project schedule, the overlapping strategy and the inherent uncertainty in a work being done with poor information. To realize this con-

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cept, we have faced with many behaviors patterns (e.g. rework, new duration, non-conformity), and analyze the output behavior pattern, produced by the proposed model.

Although the research results discussed need to be further refined and developed, in order to clarify the necessity of auxiliary variables and to establish the detailed sense of feedbacks and loops, they revealed that a dynamic approach to evaluate the impact of rework in an overlapped schedule, can be measured and analyzed in quantitative terms, not only in intangible terms.

As a possible application of the model, evaluating a high complexity environment as a product development model, it could be applied in a collaborative work scenario, where the work and rework hours should be estimated after periodic meetings and carrying out information uncertainty.

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