Application of system dynamics to simulations of product development process management activities

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Abstract: This article proposes a model for applying System Dynamics to the simulation of product development process (PDP) management. System dynamics is an approach that enables one to analyze the behavior complex systems may display over time. The model is structured based on the "Activities" dimension in PDP management; the allocation of resources to carry out these activities; and the effects of this allocation on the performance measurement factor of "development timing". The structure of activities adopted in this model is APQP (Advanced Planning of Quality Product), which is included in the QS 9000 Manual. In these activities, what is considered is mainly the allocation of staff (human resources) to the project teams, based on capabilities and team size. The model's behavior was evaluated under specific external conditions.

Keywords: system dynamics, product development, product development process management, human resources in product development

1. Introduction

First of all, reaching excellence in product development process (PDP) management implies firstly, knowing the factors that affect this process' performance, and afterwards, taking actions that lead to the expected performance. From the managerial point of view, this task has become more complex as market dynamics grow, increasing competitiveness between companies and the complexity of economical and managerial factors that interfere in PDP. There are a number of factors that may influence performance in the product development process and, in spite of the cognitive capability of some managers, evaluating the interaction between these factors and the result this interaction will produce in the development process is not an easy task. The performance of a product development process can be assessed by criteria such as design quality, development cost and the timing to conclude the project.

Following these presuppositions, the aim of this article is to present a model, applying System Dynamics, which represents the structure of PDP, in order to understand (by dynamic simulation) how the actions taken to allocate human resources in this process would affect development timing.

The structure of the product development process, drawn up for the intended simulation, was based on APQP (Advanced Planning of Quality Product), from QS 9000, 1994.

An important factor which influences the results, i.e., PDP performance, is the structure of this process. The level of importance of this factor in relation to other management factors in PDP is not clearly definable. However, it is possible to observe that the professionals involved in PDP understand and value the definition of a structure in terms of product development in their companies, involving stages and activities. The importance of this factor for the companies, mainly in the automotive sector, can be seen in the demands for processes that are formally structured into stages and activities concerning the development of new products. The best example of this is the wide use of the reference manual for product development known as APQP by the companies which apply QS-9000, as well as the indirect demands for other standards in management systems.

Therefore, the model to be simulated is described in flow and stock diagrams which represent the product development structure adopted in APQP. This makes it possible to analyze how some management factors influence product development timing, by analyzing the timing in which the required activities in each stage of APQP are carried out.

There is a number of factors which influence the timing that development activities take to be concluded, such as: training of staff that are part of the development team, how experienced the team is, availability of technological resources, time spent to re-work the project, as well as integration and simultaneity among activities.

In the model, only some of these factors are considered: 1) The allocation of resources during the development stages, particularly the ones related to the availability of human and technological resources and to the capability or competence of those resources to carry out the required activities efficiently; and 2) The activities related to re-work during the development process. The issues related to training and allocation of human resources and their importance for PDP are highlighted by CLARK & FUJIMOTO (1991). According to REPENNING (2000), if the capability and quantity of human resources effectively working in the project from the beginning of the development is ignored, this would increase re-work in the development stages afterwards. During the description of the model, the assumptions adopted for each variable are described in detail.

In companies, several projects compete for the same available resources. Allocating these resources among the development projects so as to do out all the important activities within the established deadline, with the required quality and within the budget, are tasks that go beyond the cognitive capabilities of managers. (COOPER et al. (1998), STERMAN (1992)).

System dynamics has been applied for designing models to understand and solve problems in a variety of areas such as industrial planning (FORRESTER (1961)), economy (STERMAN et al. (1983)), administration and definition of public policies (HOMER & ST. CLAIR (1991)), biology and medicine (HANSEN & BIE (1987)), as well as product development projects (REPENNING (2000), FORD & STERMAN (1998), ABDEL-HAMID (1984)). The variety of application areas of this tool is an indicator of its importance in designing models to support decision-making. However, according to STERMAN (2000), all the models are incomplete, i.e. they can not represent reality as it is, but just draw closer to it.

This is an important assumption, as it allows us to consider that there is more than one possibility of modeling the "reality" when we face socio-economic systems. Modeling and simulating the movement of a pendulum will certainly be simpler and the result closer to the real one than to modeling complex systems, with innumerous possibilities and variations that involve quantitative and qualitative data, as is the case in the product development process. Therefore, it is not an easy task to start the product development process from mental models and design a structured model as stock, flow, converters and connector models which represent PDP.

2. APQP – Advanced Planning of Quality Product

In APQP, there is a structure that clearly defines which stages and activities should be carried out in the PDP. As APQP is widely known, not only in the automotive sector, it will be used as a reference for the design of a simulation model according to the approach of System Dynamics. Figure 1 shows the stages in APQP.

The stages and activities which comprise APQP are:

2.1. Stages

Stage 1: planning

This stage consists of determining the clients' needs and expectations, aiming at planning the product development program. This stage of PDP should always consider the customer first, i.e., the activities done at this stage aim to ensure that the customer's needs have been understood before the project actually starts. The activities are as follows:

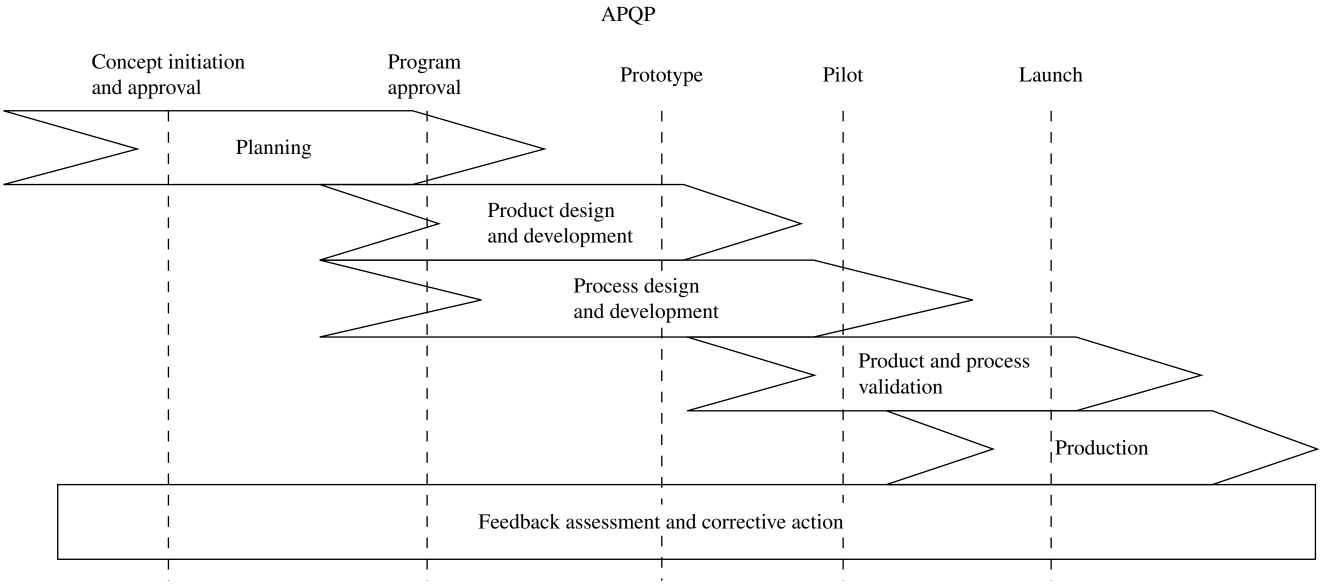

Figure 1. PDP model structure. Source: APQP (1994).

1. Research the "Voice of the Customer" (market research, historical warranty and quality information);
2. Design the business plan;
3. Carry out product and process benchmarking;
4. Survey product and process assumptions;
5. Estimate rates of product reliability;
6. Survey customer inputs;
7. Define design goals;
8. Define reliability and quality goals;
9. Prepare preliminary bill of material;
10. Prepare process flow chart;
11. Define preliminary listing of special product and process characteristics;
12. Define product assurance plan; and
13. Critically analyze the development plan with management support.

Stage 2: product design and development

In this stage the project characteristics are better specified, and building the prototype starts, in order to check whether the product meets customer expectations and whether the design follows the customer's requirements. The activities to be carried out are the following:

1. Draw up the Design Failure Mode and Effects Analysis (DFMEA);
2. Draw up the DFA (Design for Assembling) and DFM (Design for Manufacturing);
3. Design verification;
4. Design reviews;
5. Build the prototype and define the prototype control plan;
6. Draw up engineering drawings
7. Define engineering specifications;
8. Define material specifications;
9. Drawings and specifications changes;
10. Define new equipment, tooling and facilities requirements;
11. Define special product and process characteristics;
12. Define gauges/testing equipment requirements; and
13. Analyze team feasibility commitment and management support.

Stage 3: process design and development

This stage involves developing a productive process that ensures that customer's requirements and needs are met. In order for this to occur, the following activities should be carried out:

1. Define packaging standards;
2. Review product/process quality system;
3. Conclude process flow chart;
4. Define floor plan layout ;
5. Define characteristics matrix;
6. Carry out PFMEA;
7. Draw up Pre-launch control plan;
8. Draw up process instructions;
9. Define measurement systems analysis plan;
10. Define preliminary process capability study plan;
11. Define packaging specifications; and
12. Critically analyze management support.

Stage 4: product and process validation

In this stage manufacturing process validation is carried out by producing a trial run. The aim is to ensure that all the previous activities have been carried out according to the plan, supplying products that meet the customer's requirements, (specifications, production volume, etc.). During this stage, the following activities are carried out:

1. Draw up trial run;
2. Evaluate measurement systems;
3. Evaluate preliminary process capability;
4. Production part approval;
5. Carry out production validation testing;
6. Evaluate packaging;
7. Production control plan; and
8 Critically analyze management support and quality planning sign-off.

Stage 5: feedback, assessment and corrective action

After validating and implementing the product process, the effectiveness of the product quality plan is assessed, based on the production control plan. This stage aims to reduce process variation, ensuring problem-solving and continuous improvement, and acting as PDP feedback. The following activities should be carried out at this stage:

1. Analyze and reduce process variation;
2. Analyze and correct product performance (customer satisfaction); and
3. Analyze services and delivery.

We can therefore observe that the timing quality of carrying out the activities in each stage directly influence the PDP results, i.e., it can be asserted that productivity in each stage determines PDP performance.

2.2. Precedence relationship between stages and APQP activities

The APQP manual defines a precedence relationship for the activities to be carried out and shows that, as one stage's activities are finished, subsequent stage activities can be started. In order to simplify understanding, Figure 2 shows the precedence relationship among the APQP stages and activities.

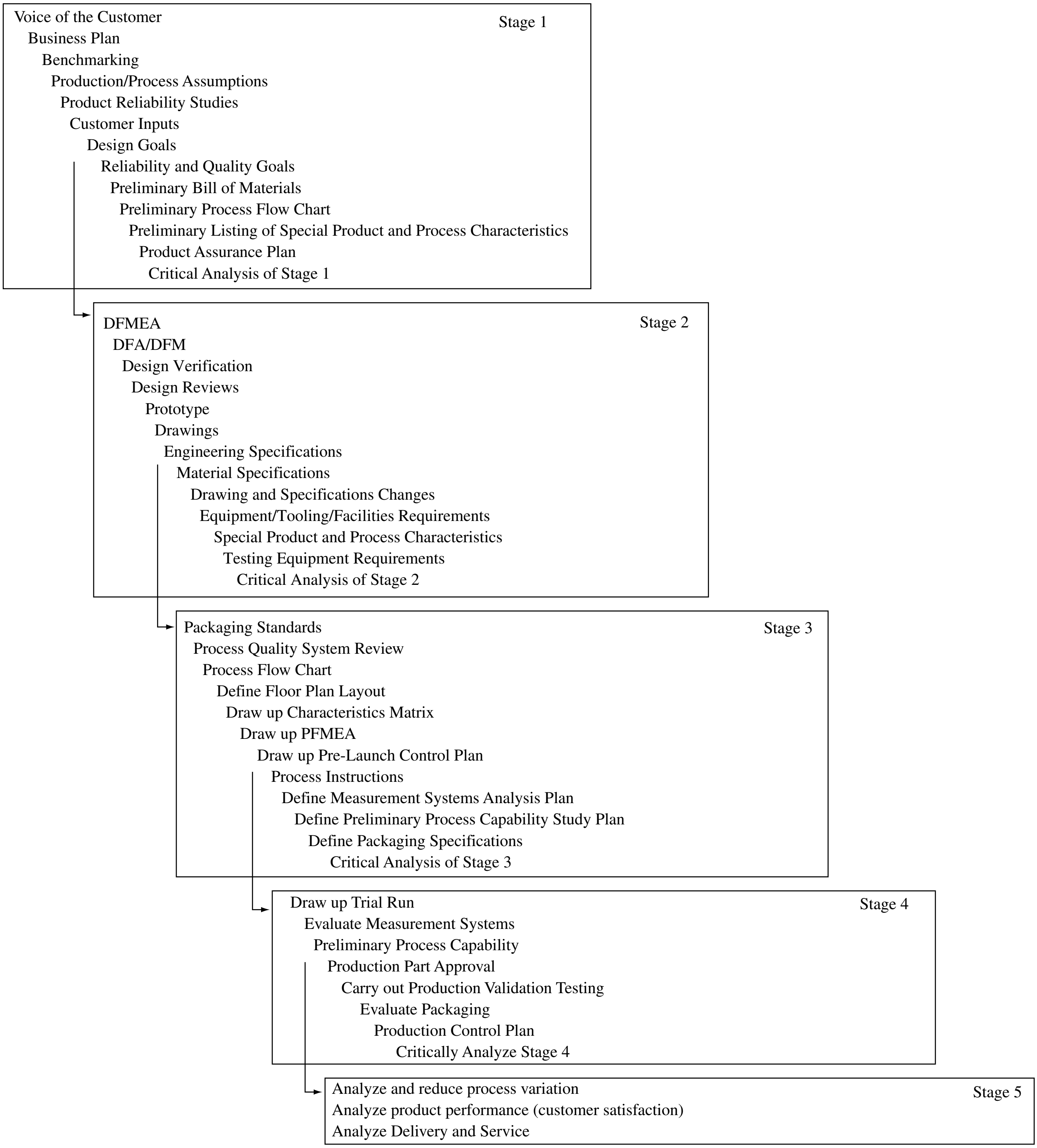

Figure 2. Precedence relationship among APQP stages and activities.

In Figure 2 it is possible to visualize how activities from one stage "feed" the execution of the following ones, which is an important factor to consider in the model, since it conditions the simultaneity degree among stages and defines the probability of re-work to happen at each stage, which could have been carried out in the previous stages. It can also be observed in Figure 2 that in order to start the first activity in Stage 2 (DFMEA), all the activities previous to "Reliability and Quality Goals" should have been concluded in Stage 1, i.e., eight activities should be concluded in stage 1 so that Stage 2 can start.

3. Causal diagram associated to PDP

The structure known as Causal Diagram (FORRESTER,1961; STERMAN et al., 1983) enables one to visualize the existing inter-relationship between the effects and their causes within a system. For the proposed model, a generic causal diagram related to PDP was drawn up, considering the following factors that affect its process:

- The Competitive Corporative Strategy adopted by the company for products and markets;
- The Product Development Strategy and the inter-relationship between product design;
- The stages and activities involved in the Product Development Process;
- The organizational structure of the development teams;
- The methods and tools used in product development; and
- Technical and managerial capability for Product Development.

Figure 3 relates these factors in a thorough way. The objective is to understand how the casual diagram, which is specific to the PDP structure, was developed from this macro diagram, as shown in Figure 4.

It is important to differentiate the objectives in the two causal diagrams drawn up. In the first one, there is an overview of the way in which the factors are related and affect PDP.

The analysis could start with CORPORATE STRATEGY, by addressing the following issue: How is strategy defined by the corporation, which will influence the internal strategy of product development? It is clear that, as this issue is understood, it is possible to proceed to analyze the element/dimension INVESTIMENTS IN PD, and so on.

In Figure 4, the causal diagram shown represents a part of the first diagram, with added element/dimensions of interest to analyze the Product Development Process Structure. In the diagram, the element/dimensions are focused on the system related to the structure, which aims to evaluate how the allocated human and technological resources affect execution timing of each activity of APQP and PDP as a whole.

The analysis can begin with the element/dimension PDP STAGES/ACTIVITIES, which will define how many and which activities should be carried out in PDP. Next, the analysis continues, trying to understand how HUMAN RESOURCES and TECHNOLOGICAL RESOURCES capability and availability interfere in the execution timing of the activities and in the quantity of activities that will require re-work, which will also affect the DEADLINE FOR EACH STAGE AND THE PDP.

This kind of analysis facilitates the drawing-up of a simulation software model. The causal diagram is not a pre-requirement, but it enables the analyst to maintain the focus on the breadth of the model, as well as noticing which are the existing relationships between the element/dimensions of the system that is being analyzed.

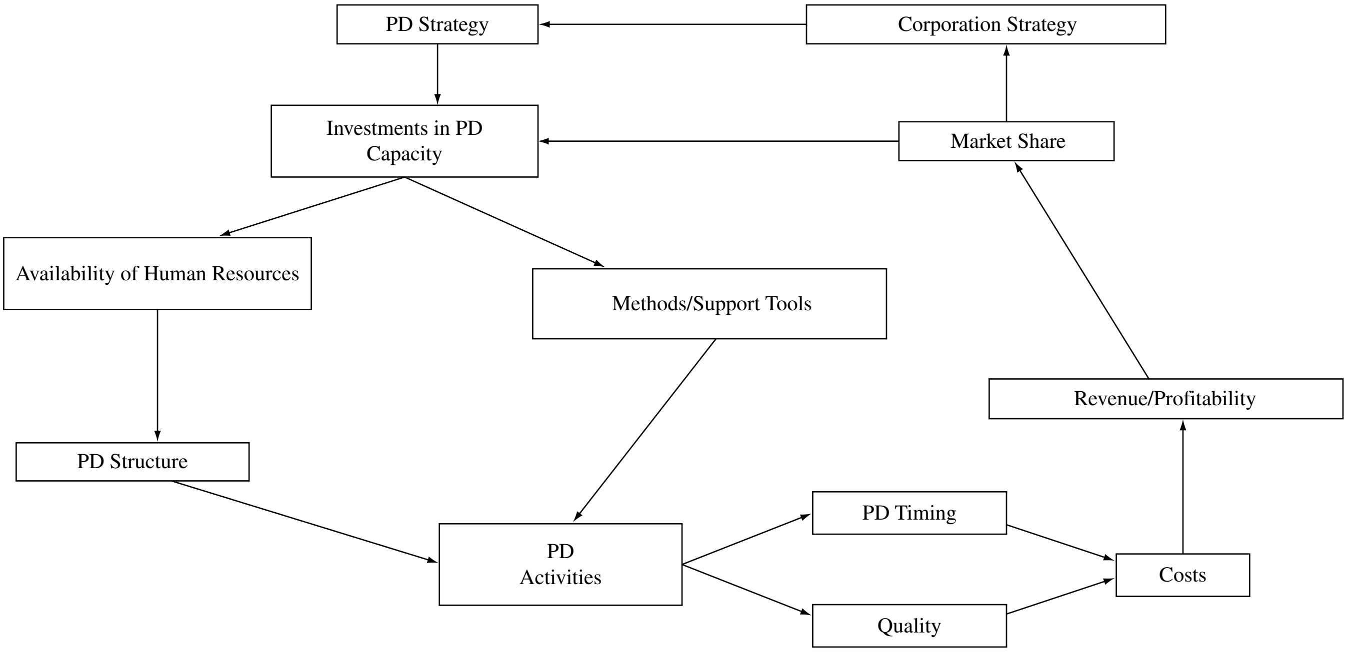

Figure 3. General causal diagram with factors that influence PDP.

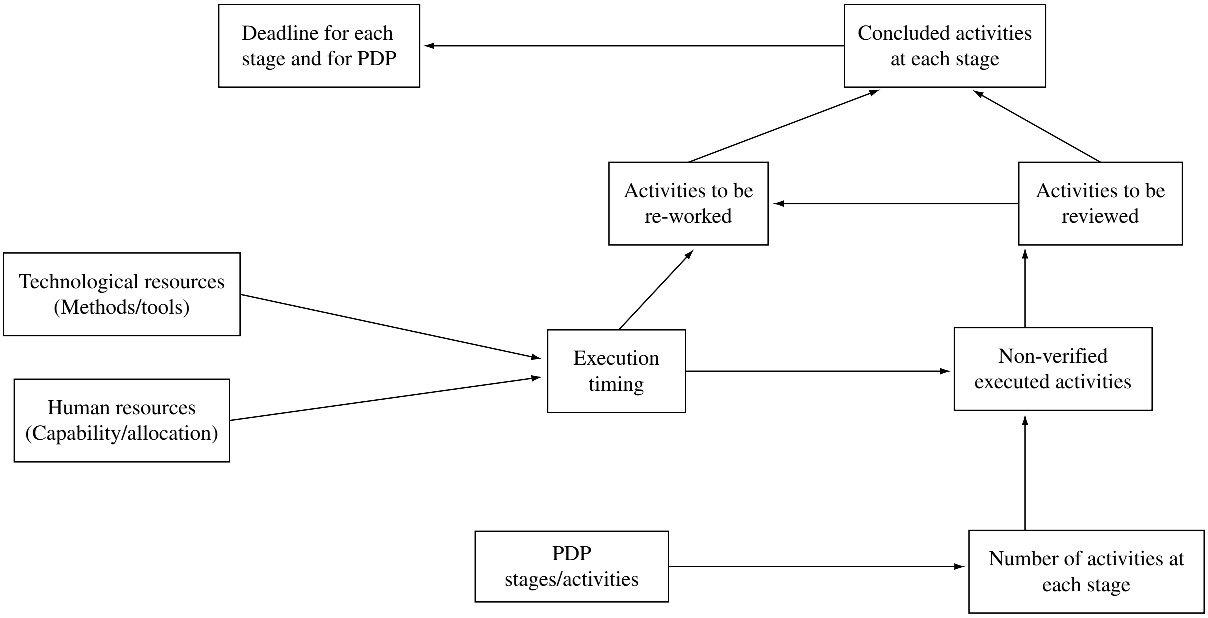

Figure 4. Specific causal diagram for the PDP structure.

4. The proposed model of flow and stock diagrams

The design of the model and its adopted assumptions were based on mental models and concepts associated to the product development process, which was obtained from professionals in companies and from academics who work in PDP management. They were consulted according to what was described in SOUZA JR (2003). The simulation was carried out using the STELLA software, version 6.01.

4.1. The model for an APQP generic stage

Figure 5 shows the generic structure adopted for each APQP stage.

The first stock of the “n_verified_exec_activ” corresponds to the required activities in the stage which were carried out, but not yet verified, either completely or partially. This stock shows how many activities were done in a determined period of time. It is believed that the average time it took to do the activities and the number of activities to be carried out influence the timing or the execution rate it of these activities in a determined stage. In Figure 5, these variables are represented by converters that are linked to the “exec rate” flow and to the stock described previously. As the required activities in the stage are being done using determined timing, they are checked later in relation to the execution timing.

The second part of the structure, which is represented by an output flow of the “n_verified_exec_activ” stock linked to the “verif_activ”, represents the activities which are being analyzed and which will be defined as: “are concluded satisfactory” or “should be re-worked or improved before being considered concluded”. The timing used to verify the activities is influenced by the average time of checking these activities, which is usually shorter than the time spent to do them, and by the availability of the activities already carried out, and is represented by the “verif rate” flow, which determines the relation between performing – verifying – testing the stage. The adopted assumption in this part of the structure is that verifying is a process that may occur

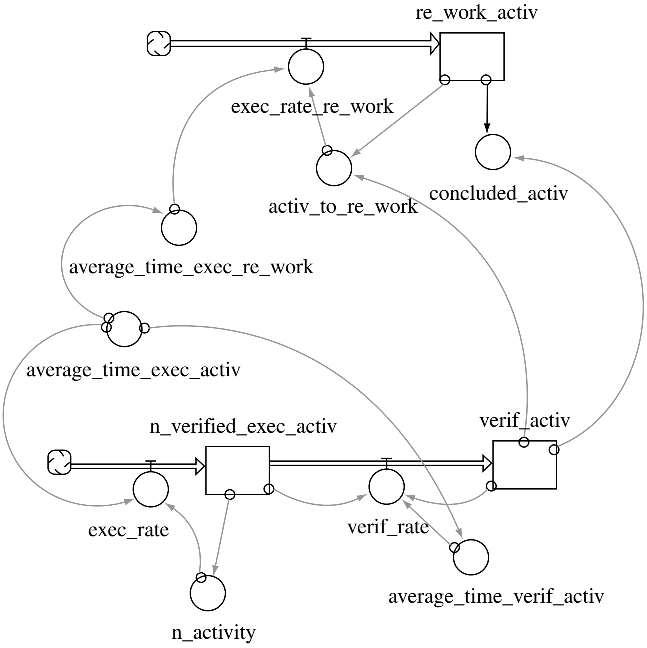

Figure 5. Generic structure of the APQP stages.

at the same time as the activity or may demand a longer period of time. For example: the preparation of a process flow is fast and checked instantly, but the preparation of the pro-types may take more time and require longer post evaluations. For this reason, the average time to do and verify the activities is adopted.

The third part of the structure represents the re-work in the APQP stage. The quantity of activities to be re-worked in a stage depends on the available capability to do the activities required in the stage. It means that the higher the level of capability of the company or the development teams, the less probability these activities will have to go through re-work or improvement. The "Re work Activ" stock demonstrates how many activities were re-worked in a determined stage. The timing used to re-work these activities is defined by the average time to accomplish the re-work, which is considered in the model always below the time spent to do the activities.

As soon as the activities of a stage are considered satisfactorily concluded, the next stage of the APQP starts. The "concluded activ" converter must have the same number as the quantity of activities to be carried out in the stage. We should highlight the correlation between Figure 2 and this part of the model. The preceding relations may be built into the model so as to check the level of simultaneousness between the stages and the PDP activities. Whenever it is necessary to conclude all the activities of a stage to start the next one, there is little simultaneousness in the development. On the other hand, considering that the model has a certain number of activities which are satisfactorily concluded, the next stage can be started. It is important to have in mind that every company checks a specific PDP simultaneousness level.

The Equations associated to the stocks of the PDP generic structure are:

$$\text{n\_verified\_exec\_activ}(t) = \text{n\_verified\_exec\_activ}(t - dt) + (\text{exec\_rate} - \text{verif\_rate}) * dt \quad (1)$$

$$\text{verif\_activ}(t) = \text{verif\_activ}(t - dt) + (\text{verif\_rate}) * dt \quad (2)$$

$$\text{re\_work\_Activ}(t) = \text{re\_work\_activ}(t - dt) + (\text{exec\_rate\_re\_work}) * dt \quad (3)$$

These differential equations demonstrate the relation of input and output activities in different situations. In other words, the number of activities which were done, verified, re-worked and concluded satisfactorily at each stage is evaluated at different moments of the development process.

The converters, which are variables that influence the execution timing of the activities in every flow of the generic structure, are:

$$\text{n\_activity}(t) = \text{parameter } 1 - \text{n\_verified\_exec\_activ} \quad (4)$$

The above equation specifies the number of activities to be carried out in the APQP stage. At t = 0, the number of activities is the same as the one defined in parameter 1, which varies according to the one required at the stage. As time passes by, the activities are done and the number of activities to be carried out in the stage must decrease.

$$\text{average\_time\_exec\_activ} = 1 / \text{level capacity develop} \quad (5)$$

The average time of doing the activities is influenced by the capacity level of developing the products, which may range from 0 to 1. When the level is maximum, the average time will be estimated, which is defined in the STELLA software (menu Run: time specification). As the capacity level lowers, the average time to carry out the activities will increase.

$$\text{average\_time\_verif\_activ} = \text{average\_time\_exec\_activ} / \text{parameter } 2 \quad (6)$$

Similarly to what is found in Equation 5, the average time to verify the activities depends on the capability of human resources and the availability of the technological resources. However, it is believed that the average time to verify the activities is correlated to the execution timing of the activities based on a parameter that can be defined for each case. In case parameter 2 is equal to 3, it means that the average time to verify the activities corresponds to 1/3 of how the execution timing.

$$\text{activ\_to\_re\_work} = (\text{parameter } 3 * \text{verif\_activ} - \text{re\_work\_activ}) \quad (7)$$

The number of activities to be re-worked or improved depends on the probability of possible activities to be re-worked, according to parameter 3, which is associated to the allocation and experience of the resources in the stage mentioned.

$$\text{average\_time\_exec\_re\_work} = \text{average\_time\_exec\_activ} / \text{parameter } 4 \quad (8)$$

The average time of the re-work to be done is defined as it is in Equation 6, i.e., parameter 4 will define the relation between the average timing of the activities and the average time of the re-work to be done whenever it is needed in the activities.

$$\text{concluded\_activ} = (\text{verif\_activ} - \text{verif\_activ} * \text{parameter } 3) - \text{re\_work\_activ} \quad (9)$$

The number of the concluded activities is a result of the number of the satisfactorily concluded activities (which have been verified and with no need of re-work) and the number of the re-worked activities, which are represented by parameter 3. By the end of the simulation, the converser must accept the number of activities required to be carried out in the APQP stage.

4.2. The aggregation of human and technological resources to the model

In the previously described model the aim was to join important variables to the how the project was led and what strongly influenced the results regarding development timing. As mentioned before, the importance of the competence and availability of the resources involved in the PDP to fulfill the requirements in the activities at each stage of the development is evident. The adopted assumptions, when including these aspects into the model, are:

- The development teams have people from different fields therefore the more experienced they are concerning the project in progress, the higher the level of capability of human resources to carry out the required activities in the stage;
- The people of the development team do not have the same level of experience in the project and can be classified as having: little experience, average experience and a lot of experience;
- At every level of experience, some people are not linked to the project (completely or partially) for a number of reasons (dismissal, dedication to other projects, new functions, etc);
- Even though people leave the project, there must be new people joining the project, who will have little experience in the project;
- There is continuous learning throughout the product development, which takes a certain amount of time and involves people from work placement students with not much experience to very experienced people in the project; and
- The required technological resources to carry out the activities are included in the model in such a way as to be evaluated regarding their availability, no matter what the reason for their unavailability (absence, in use and usage conditions).

Figure 6 shows the modeled structure that comprehends the capability and availability of the technological and human resources, which will aggregate the model in the development stages.

The aim of the structure is to model the way human resources in the PDP are available and the way they learn

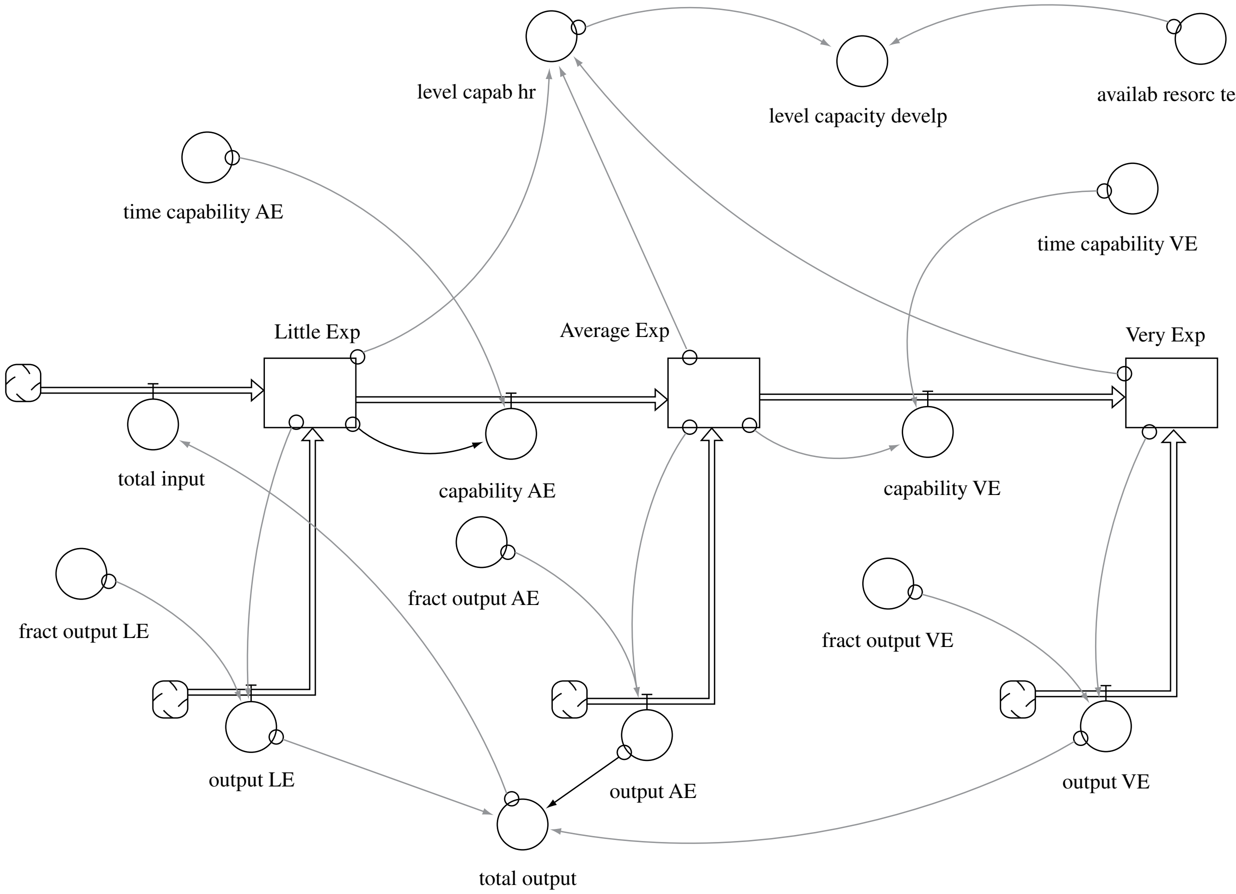

Figure 6. Structure of the model regarding the technological and human resources.

about the project during the development of a specific product. It also shows the interaction of these resources with the availability of technological resources to carry out the activities of each APQP stage.

The first stock of the structure "Little Exp" (LE) represents the number of professionals involved in the PDP who are acquiring know how in the development project. This happens for different reasons and they have been previously described in the assumptions of the structure of the model. This work will not discuss the reasons why there are people who are not very experienced and who belong to the project team. The point is that this takes place due to dismissals, transference of people to other projects, etc. This stock is fed by an input flow called "total_input", which is the "total" number of new professionals that must be replaced and that will need some time to learn about the project. As they learn about the project, they go through the "average_exp" (AE) and "very_exp" (VE) stocks. It is important to consider that at any learning moment throughout the development process, some of the professionals (engineers, technicians and administrators) leave the project and will be replaced by new ones with little experience.

The relation in human resources classified as little, average and very experienced in the PDP will define the capability of people to develop new products represented in the model by the "level capab hr" converter, which will be described as follows.

The "availab resorc techn" converter refers to what is available, at a determined moment, regarding the technological resources to carry out the required activities at each stage. Generally, if 100% of the technological resources (software, hardware, standards of tests, etc) are available at the necessary moment to carry out the activities, the converter will receive value 1. When there is not this availability, the value must be between 0 and 0,99.

The relation between the "level_capab_hr" and "availab_resorc_techn" converters determines the capacity level of the company in developing new products, especially considering how a project is carried out, which is represented in the model by the "level capacity develp" converter. This converter has values that range from 0 to 1, and are connected to the first structure shown before (Generic Stage, Figure 5), aiming to influence the execution timing of each APQP activity.

The most important equations of the referred structure to the technological and human resources of the model are described as follows:

$$little\_exp(t) = little\_exp(t - dt) + (total\_input + output\_LE - capability\_AE) * dt \qquad (10)$$

$$average\_exp(t) = average\_exp(t - dt) + (output\_AE + capability\_AE - capability\_VE) * dt \qquad (11)$$

$$very\_exp(t) = very\_exp(t - dt) + (output\_VE + capability\_VE) * dt \qquad (12)$$

These equations show (at a determined PDP moment) the capability level of the professionals involved in a specific development project to carry out the required development activities at a stage.

It is important to highlight the fact that each company has its own norms when classifying the human resource competences to develop a new project. This competence level may be related to the type of project developed by the company (radical, platform or derivate).

The converters (the variables that determine the flow parameters), the information of the technological resource availability and the capability level to carry out the activities are described as follows:

$$fract\_output\_LE = parameter\ 5 \qquad (13)$$

$$fract\_output\_AE = parameter\ 6 \qquad (14)$$

$$fract\_output\_VE = parameter\ 7 \qquad (15)$$

These three equations determine the percentage of the little experienced (LE), average experienced (AE) and very experienced (VE) professionals in the project who are not linked to the referred development. Practically, it means that there are losses of time and knowledge in the PDP due to people who are involved in the project leaving at the beginning. The parameters 5, 6 and 7 can be estimated for each company. The ideal situation is that they are 0, which means that the same group that started the development will be part of it up to the end of the life span of the product.

$$time\_capability\_AE = parameter\ 8 \qquad (16)$$

$$time\_capability\_VE = parameter\ 9 \qquad (17)$$

The equations refer to the necessary time to turn professionals with little experience (LE) into very experienced (VE) professionals, as well as the average experienced (AE) professionals into very experienced (VE) ones regarding the project. Furthermore, in this case parameters 8 and 9 are specific for each company and can be defined in months or even in years. An example of the previous statement is the fact that in developing products of the derivate type, it may occur that the time spent in terms of the capability of human resources may be shorter in relation to the development of new platforms, i.e., each type of project has a specific characteristic.

$$total\_output = output\_LE + output\_AE + output\_VE \qquad (18)$$

This equation refers to the number of professionals that are not linked to the PDP and can be used as a source of information for people to be replaced. At this moment, there is a positive causal loop in the system. If the number of people leaving is 0, no change will occur in the capability level of the human resources.

level_capab_hr = ((little_exp / (little_exp + very_exp + average_exp)) * parameter 10) + ((average_exp / (little_exp + very_exp + average_exp)) * parameter 11) + ((very_exp / (little_exp + very_exp + average_exp)) * parameter 12) (19)

This equation determines the capability level of human resources based on the following:

- Parameter 10 represents the effect, in terms of importance, that the little experienced professionals have considering the capability level of human resources to carry out the required activities at each stage;
- Parameter 11 represents the importance that the average experienced professionals have considering the capability level of human resources to carry out the required activities at each stage, seeing that each of these weights must be higher than the previous one (parameter 12 > parameter 11 > parameter 10);
- Parameter 12 represents the importance that the very experienced professionals have considering the capability level of human resources to carry out the required activities at each stage; and
- Each of these weights must be higher than the previous one (parameter 12 > parameter 11 > parameter 10).

Equation 19 shows that if only very experienced professionals are involved in the PDP, theoretically the capacity level to do the activities required by the APQP stages would be higher than when there are professionals of different levels. However, there may be limitations concerning the number of available people, or the company may consider it interesting to mix levels of competence as a way to stimulate learning in the PDP.

availab_resorc_techn = parameter 13 (20)

This converter has values between 0 and 1, where the extremes represent the lack or the total availability of technological resources of the required activities at each stage of the product development process.

level_capacity_develp = level_capab_hr * availab_resorc_techn (21)

The relation of the converters referring to the capacity of human resources and the availability of the technological resources determines the development capacity of new products, i.e., the capacity to carry out all the required activities in the APQD. This converter will be connected to the “average_time_exec_activ” converter in the generic stage of the APQP, where there is an inter-relation between the technological and human resources and the timing of the required activities in each APQP stage.

Figure 7 shows the combined structure for the PDP considering the capacity of the human resources, the availability of the technological resources and the APQP represented by one generic stage.

After the explanations shown concerning a model that takes into account technological and human resources joined to a model of the generic stage of a development process, it is possible to reapply this generic stage and make appropriate links to obtain the representation of all the APQP stages, making up five stages, according to the Systems Dynamic approach.

5. The validation of the model

An illustration of the model is shown in this topic using the attribution of extreme values to the parameters. The objective is to evaluate how the model responds to these values. This test is known as the extreme condition verification test and enables us to evaluate if the proposed structure is suitable and also if the model will achieve the expected behavior. The structure of the model was discussed with the company professionals and illustrations and tests were carried out in two automotive companies (SOUZA JR, 2003), with the aim of finding a suitable model for the reality of the organization in order to be more reliable.

5.1. Attribution of extreme values to the parameters of the model

Among the possible tests to evaluate the model, the extreme condition verification test can be done separately from the others, which basically deals with the attribution of extreme values for the parameters of the model. The expected result with these tests is a predictable behavior from the model, which is graphically demonstrated in the interface environment of the software. In order to simplify the analyses in this article, the results will only be shown graphically. One should have in mind that the number of activities to be carried out in each of the APQP stage is: Stages 1 and 2: 13 activities each; Stage 3: 12; Stage 4: 8; and Stage 5: 3 activities, making up 49 activities. The attribution to the extreme values for parameters of the model is analyzed as follows in 5 different situations.

Situation 1: Number of little experienced (LE), average experienced (AE) and very experienced (VE) professionals available to carry out the APQP activities and stages is equal to zero.

In this situation, it is expected that no activities would be started in the APQP, since this parameter shows that there are no available professionals to carry them out. Figure 8 shows the obtained result.

Graphically speaking, it is possible to observe that no activity starts. The graph shows the development time in months in the x **axis**, and the number of activities at each stage in the y **axis**. For example, in the case where activities

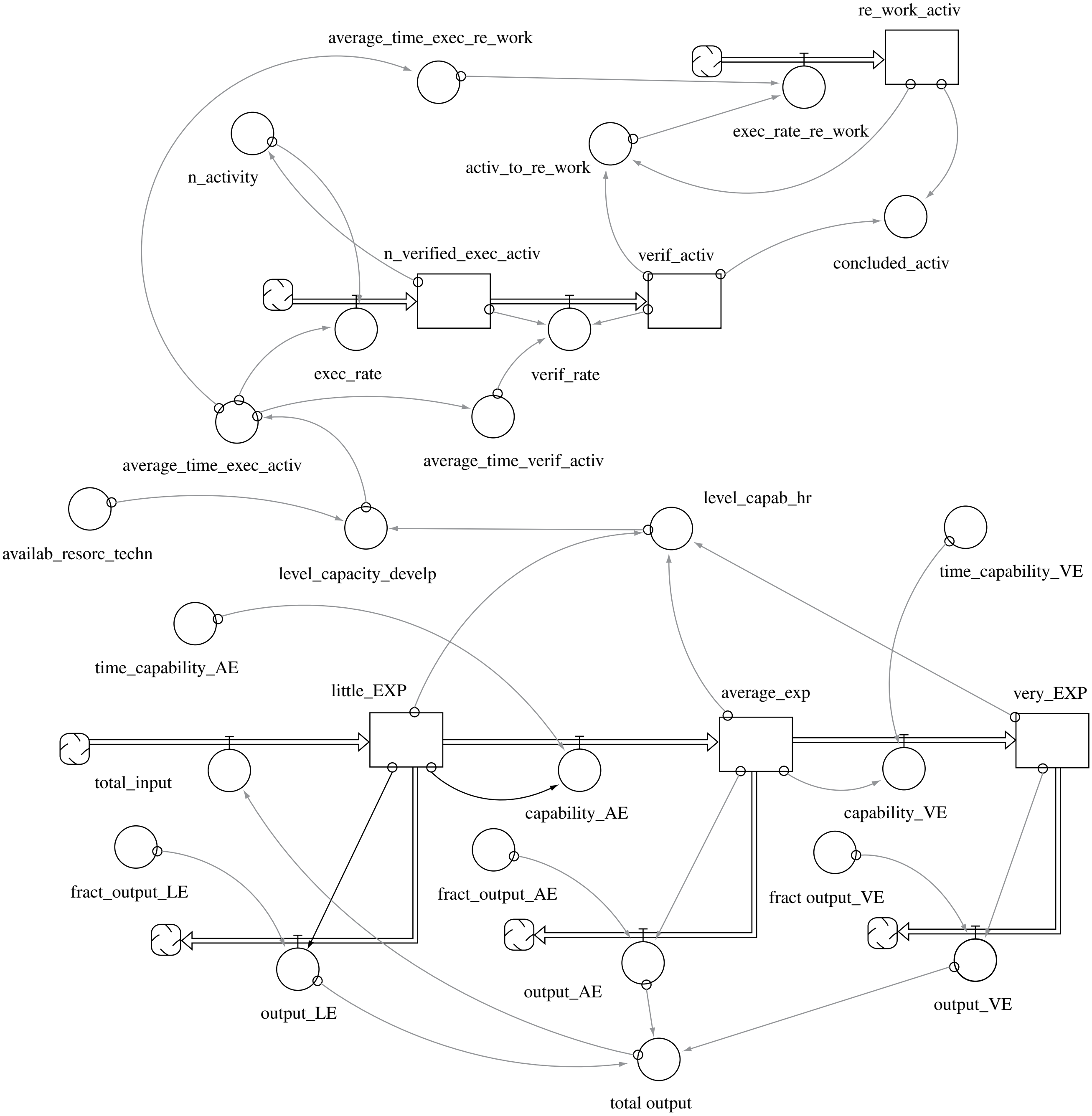

Figure 7. Combined structure for PDP according to the system dynamics approach.

are carried out in Stage 1, the number of activities carried out would come under "1: Concluded Activ 1" and so on. Therefore, at each moment of the development (x axis), it is possible to visualize how many activities were completed at each stage. In this case, no activity was carried out.

Situation 2: Considering that: a) only experienced professionals in the project are performing the activities, b) the percentage of the re-work of the activities at each stage is **90%**, and c) the re-work time is equal to the usual timing of the activity.

Situation 3: considering that: a) only experienced professionals are performing the project activities, b) the percentage of re-work at each stage is **10%**, and c) the re-work time is 5 times shorter than the usual timing of the activity.

The expected results in Situation 2 must show a longer execution timing of activities at each stage, while in Situation 3 the development time, i.e., the conclusion of the activities must be much shorter. Figure 9 represents Situation 2 and Figure 10 represents Situation 3.

In Figure 9, the **upper display** indicates the number of activities carried out for each stage and which corresponds to the total number of activities while the **lower display** indicates 24 months. This means that in Situation 2, the development time would be 24 months.

Figure 10 shows that the activities are concluded considering Situation 3 parameters in an 18 month development period of time, as shown in the **lower display**. There is also a change in the trends, which shows that in Situation 2 the number of activities carried out and satisfactorily concluded takes longer than in situation 3.

Situation 4: considering that there are no restrictions regarding the **precedence relationship** among the activities, i.e., the level of simultaneousness is the **maximum** in the development. Therefore, all the activities at each stage start at the same time when t = 0. Figure 11 shows this hypothetical situation.

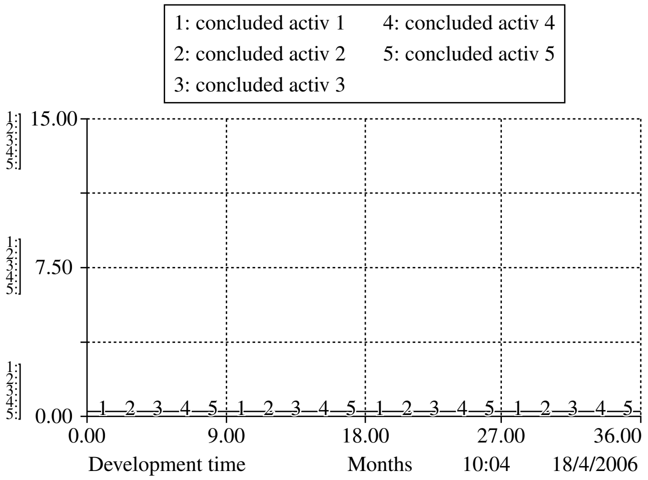

Figure 8. Simulation Result when there are no human resources available to carry out the activities.

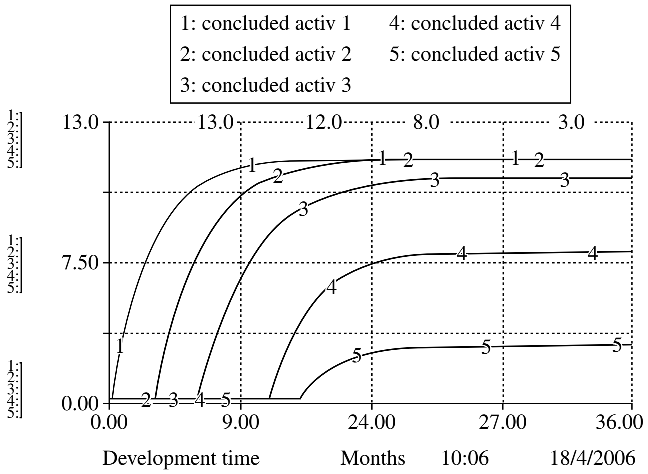

Figure 9. Simulation results considering that 90% of the activities are re-worked at each stage in a period of time similar to the execution timing.

Figure 11 shows that, considering a hypothetical average period of time of the activities execution and that the level of simultaneousness is the maximum possible, all the stages start and finish almost together, which in this example the development time takes 13 months.

Situation 5: When the activities in the subsequent stage can only start at the moment in which the activities from the previous stage are concluded, i.e., there is no simultaneousness when the development process of the products is taking place. Figure 12 represents this hypothetical situation.

Figure 12 shows that the activities in Stage 2 only start when the activities in Stage 1 are concluded. The same occurs to the other stages. There is an increase in terms of time in the development process of the product. This example shows that Stage 5 only starts after 48 months from the beginning of the development.

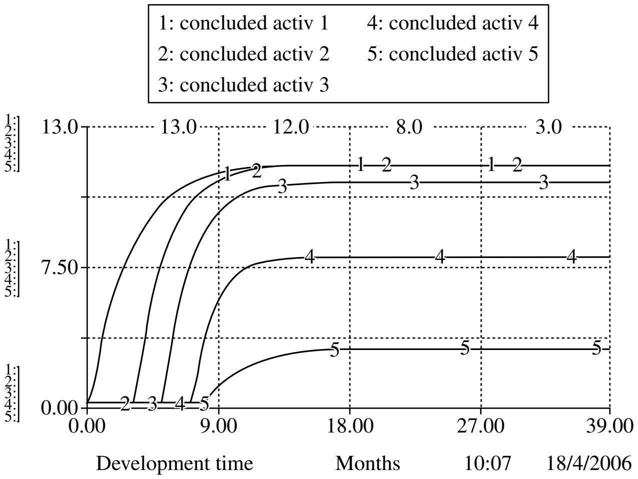

Figure 10. Simulation results considering that 10% of the activities are re-worked in a period of time five times shorter than the timing.

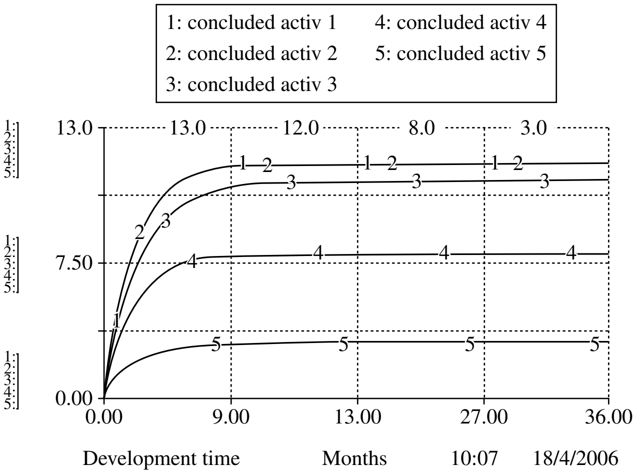

Figure 11. Simulation results considering that there are no **precedence relationships** among the stages and activities of the APQP.

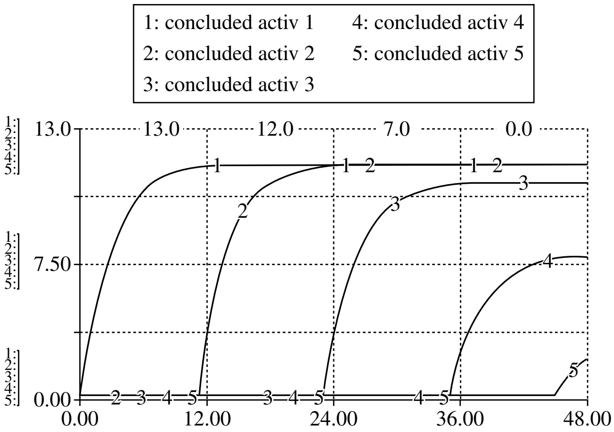

Figure 12. Simulation results considering that the stages in the activities are carried out in a sequential way.

The previous described situations are useful to show the way the model responds to the chosen parameters and to the variation of their values. It is possible to see that the model presents the expected behavior with parameters having hypothetical and extreme values.

6. Conclusion

The aim of this work was to draw up a model, making use of the System Dynamics, which is a supporting tool for the management of the product development process, and to evaluate, by simulation means, the effects of the allocation actions of human resources throughout this process.

As a follow up to this work, the model is being applied in real situations with all the presented parameters having real values. Afterwards, the other validation tests of the model will be able to be carried out. Besides testing the viability of the model in several real situations, the intention is to broaden its scope, incorporating other management aspects, making the necessary adjustments and making the model and its applications known as a supporting tool to the APQP management.

As an immediate application, the proposed model can be used in training. It is a simple tool that has a "friendly" user interface. After drawing up the flight management simulator (display where the user determines the parameters of the model using control buttons), the simulation becomes a training complement related to the PDP management.

The evaluation of the impact on the allocation decisions of the resources regarding the costs of the product development (i.e., to take into account the corresponding costs for the decisions taken) can be also included in the model.

Another important point to be considered in future studies is the allocation of human, financial, laboratory and test resources among the projects that will be developed. This makes it possible to evaluate at which moment the projects will compete with these resources. This model should be able to identify the different project types and estimate the quantity of resources that should be necessary for them, besides pointing out the "bottle necks" when performing the development stages of the project due to the shortage of the resources for all projects. Applications of dynamic models that combine theories of restrictions to a generic manufacture environment are described by REID & KOLJONEM (1999).

Some facts that occur in the PDP such as delays at subsequent stages caused by delays at the beginning of the projects could be predicted and analyzed by the use of the proposed dynamic modeling. This would be a way to try to understand the consequences that events which take place in the present may bring for the future. Therefore, experience, feeling and assimilation could be used together when taking decisions. The role of the dynamic simulation would be an important supporting tool for the decisions that must be taken in the product development process.

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