S.E.T : A Functional Modeling Approach for Supervision

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Abstract: - The design of supervision systems needs both quantitative and qualitative models, since their interface with human operators is at least as important as their effective algorithmic performances. Human operators need not only clear explanations of past events but also hints on actions they could perform, together with explanations on the impact of such actions. Taking into account simultaneously the functional, qualitative and quantitative representations of a system is thus of great interest as far as cost-effective design of supervision systems is concerned. In this paper, it is shown how the S. E. T. formalism, previously introduced in [Fel-97] [Fel-98], can be used for this purpose.

*Key-Words:*Supervision,Functional models,Bond-Graph theory,Qualitative reasoning. *CSCC'99 Proceedings*, Pages:2461-2467

1. INTRODUCTION

Supervision is concerned with decision making based on the knowledge operators have about the system actual state and the system possible behavior. Operators have to supervise the system, to analyze the current situation and to make decisions if required to prevent drifts and to keep the system as close as possible of its nominal operation.
The ideal supervision system should be able to provide them:

- explanations on past events,
- action plans to correct the system state,
- the impact of those actions on the system state.

Many dedicated systems try to produce such a reasoning. First generation expert systems implement rule-based reasoning while model-based reasoning is the foundamentals of second generation systems. We propose the S.E.T formalization as a theoretical framework for a methodology of cost-effective design of second generation systems. We will consider as a particular application the assistance to operators in control rooms in order to see how it can be implemented.
In section 2, a brief review of model-based reasoning for supervision and of the induced modeling requirements is given. Section 3 is dedicated to the S.E.T formalism and to its different interpretations namely: functional, qualitative and quantitative. Section 4 puts the previous formalization at work on a simple example for a discussion on the implementation of assistance to operators in control rooms.

2 SUPERVISION AND MODEL-BASED REASONING

In a nominal operation context, the control activity consists in keeping the system as close as possible to its nominal state. The operators supervising the system detect possible drifts compared to the specifications of quality of the products and carry out corrections to keep the system tracking desired states or to avoid undesired ones. The combinatory of the possibilities of action and their impact on the state of the system is often uncontrollable by human's brain. Then the operators restrict theirs actions to routine procedures and to those actions that they control. This is not the best cost-effective way (operators tend to produce over-quality to make sure that the products meet the specifications) and the safest one in emergency situations.

2.1 Some supervision systems

Assistance to the operators in their decision-making needs to :

- provide explanations on past events,
- provide action plans to keep the system in its nominal state,
- determine the impact of such actions on the forthcoming state of the system.

Moreover, improving the operators' performances in situation analysis and in decision making calls for information displayed in a historized functional form and expressed in terms of process or physical phenomena. Many systems have been developed with this aim, such as :

- DEVISER, an action plans generator [Ver-85], FORBIN [Mil et al. 85] to plan actions of a robot, OPIS [LePape 87] a task planner. All of them implement temporal reasoning;
- SWITCH [Por.-85] and ESCORT [Sac-86] for real time scheduling,
- DIAMON [Lac-87] for the monitoring and the diagnosis of dynamic systems, or MIMIC [Dvo-89] and QDIAG [Cha-92], based on QSIM models for qualitative simulation [Kui-86],
- DIAPASON [Ley-91] [Mon-92] combines causal reasoning and qualitative simulation and is based on Qualitative Transfer Functions (QTF) [Fer-89],
- ALEXIP [Cau-92] an expert system which puts at work a numerical simulator of the system.

The major disadvantage of these systems is that they are dedicated ones. Their field of expertise is limited and their extremely expensive development limits their generalization in industrial frameworks.

2.2 Supervision systems design

Our objective is to work out a method and to define a theoretical framework for cost-effective design of supervision systems. The first problem that has to be overcome is modeling. Although engineers spend much time and effort formulating a model as a set of mathematical equations or computational procedures one often encounters a lack of quantitative information. In addition, computations such as the resolution of differential equations are sometimes expensive (in time, resources and men). The development of exact models is not always possible : relations connecting different parameters cannot always be mathematically formulated.
The qualitative approach is interesting insofar as it matches the human reasoning, what is called Envisonment by de Kleer [De Kle-77], and as it allows an explicit expression of causal bonds, which a quantitative representation does not. More satisfactory explanation mechanisms can be associated with qualitative approaches. They also make it possible to formalize some expertise easily available from the operators.
In order to increase the operators' analysis and decision-making performances, the information provided to them must be it in a functional way or in terms of process or physical phenomena.
For the design of model-based supervision systems, it appears necessary that these three approaches are combined in order to take advantage of each of them. We intend to use the qualitative model for prediction, the functional model for functional interpretation of the predictions and simulations, and the quantitative one to provide parameter values, state magnitudes, time delays if required.

3 THE S.E.T FORMALISM : A UNIFIED APPROACH

Whatever the formalism used to represent the system, namely functional, qualitative or quantitative, the process at work is the same. Thus, a unified modeling approach can only be based on formalisms which are connected with the expression of physical laws. For example, it can be intuitively understood that the same storage process corresponds to an accumulation function, to an integral relation between variables from a quantitative point of view, to a qualitative variation of the accumulated quantity which depends on the sign of the difference between the input and the output flows. One can also hope to establish simple transformation relations from one formalism to another one. In order to achieve a cost-effective methodology for the design of models, we specify :
- a syntactic approach of functional modeling, which makes it possible to consider computer aided design,
- rules which produce, as systematically as possible, the corresponding qualitative and quantitative models from the functional one.

3.1 SET Functional Process

In [Fel-96] a formal language of physical systems has been presented. It rests on three function classes, namely : Storage, Exchange and Transformation. This typology was first proposed by Le Moigne [LeM-86] and it was claimed that any process could be decomposed into those only three kinds of functions. Considering the class of physical processes, this can be proved using the Bond-Graph approach [Bor-92] [Kar-90] and the tetrahedron of states, derived by Paynter [Pay-61] (fig. 1).
The tetrahedron of states is a system of abstraction that consists of four generalized variables (abstractions of variables among different theories) and five generalized relations between these variables (abstractions of the relations between variables in different physical theories).

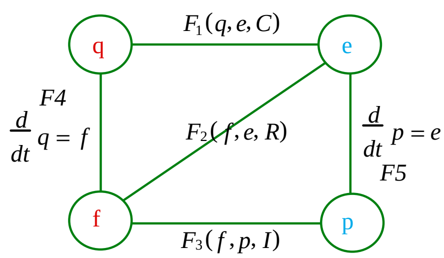

Figure 1: The tetrahedron of states

The four generalized variable are :
- generalized flow (f) : (e.g. mass, volume, charge, entropy flows, etc.)
- generalized effort (e) : (e.g. temperature, electrical potential, etc.), which can be seen as the "forces" associated with flow.
- generalized displacement (q) : defined as the flow integral (e.g. : mass, volume, charge, etc.).
- generalized impulse (p) : defined as the integral of the effort, (e.g. : integral of tension, of pressure, of magnetic flow, angular moment, etc.).

This classification is such that the product of an effort by a flow always has the meaning of power, while the product of a displacement by an effort means potential energy, and the product of an impulse by a flow means kinetic energy. Assuming that the five generalized relations and the four

generalized variables form the minimal system of relations between physical entities, we proved that only three classes of functions could be defined, which correspond to the Storage, Exchange and Transformation processes proposed by Le Moigne. Thus these three classes form a process basis (in the mathematical sense).
Figure 2 shows the functional elementary diagrams when processes deal with power and energy flows. Power inputs and outputs are labeled with a vector of effort and flow variables (e,f), while energies are labeled with a vector of displacement and effort for potential energies (e,q) and with a vector of impulse and flow for kinetic energies (f,p). A Storage acts as an integration of power into energy while an Exchange acts as a derivation of energy into power and a Transformer consumes power it changes into power (dissipation, electrical into mechanical power, ect). This typology is interesting insofar as its understanding is close to our intuition of the phenomena and, as a basis, it ensures that all processes functions can be represented using only these three classes.
Moreover, these functions are constrained by connexion rules. This set of rules constitutes a syntax L(G) that has been shown to be the one of physical phenomena [Fel-97] [Fel-98]. This syntax can be formalized as follows :

$$
\begin{aligned}
w &= S.w_T + E.w_E + T.w_T \\
w_S &= E.w_E + \varepsilon \\
w_E &= T.w_T + \varepsilon \\
w_T &= T.w_T + S.w_T + \varepsilon
\end{aligned}
\qquad (1)
$$

Where w denotes a sequence of functions, « + » is to be read as process parallelization and « . » is to be read as process serialization. So, from syntax (1) :

- a sequence begins with any S or E or T process,
- S processes require E followers or nothing,
- E processes require T followers or nothing,
- T processes require T or S followers or nothing.

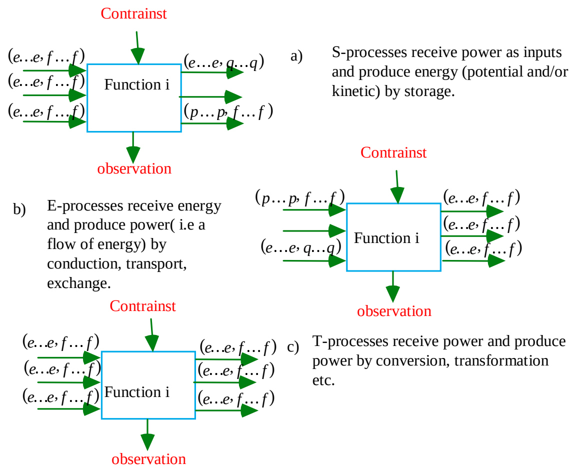

figure 2 : functional diagrams corresponding to a S, E and T, processes.

This syntax is equivalent to the following automata.

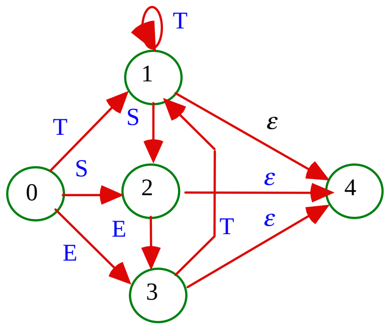

figure 3: The system which recognizes L(G)

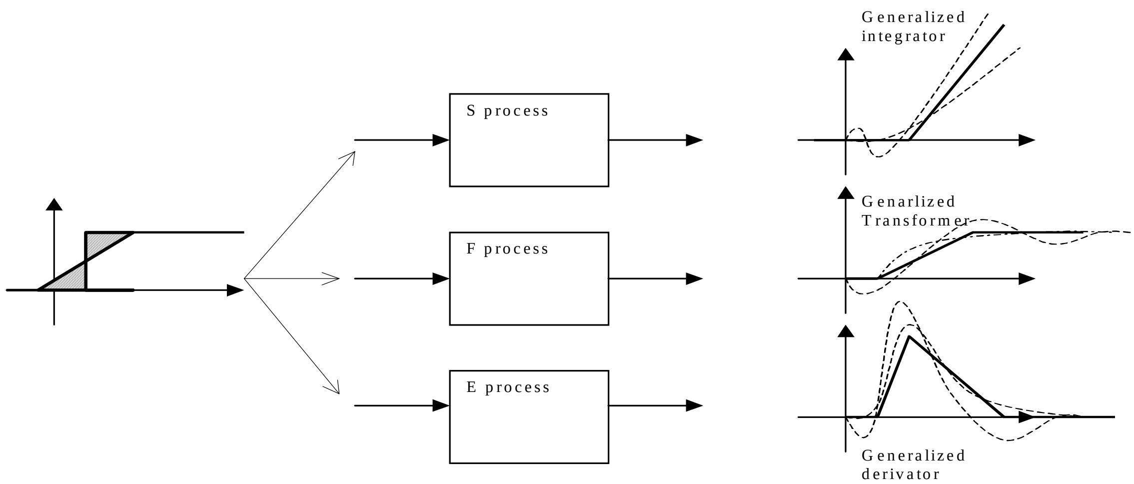

Figure 4 : S, E, T process acts respectively as an integrator of power, a derivator of energy and a tranformer of power.

It is thus possible to calculate the general form of the syntactically valid chains of a functional network, using tools of language theory [Ben-91] [Sal-87]. The generic form of any physical process is:

$$L = (\varepsilon + E.T).(T + S.E.T)^{*}.(S.E + S + \varepsilon) + (S.E + S + E) \quad (2)$$

where:

$$a^{*} = \varepsilon + a + a^{2} + \quad + a^{k} \quad k \to \infty \quad (3)$$

It can also be proven that any syntactically valid process is recursively equivalent to a S or E or T process. So, S, E and T processes form equivalence classes whose general form is :

$$\begin{aligned} &S \leftrightarrow ((T + S.E.T)^{*} + \varepsilon).S \\ &E \leftrightarrow E.T.(T + S.E.T)^{*}.(S.E + \varepsilon) + E \\ &T \leftrightarrow (T + S.E.T).(T + S.E)^{*}.(T.E + \varepsilon) + S.E \end{aligned} \quad (4)$$

S.E.T is a phenomenological approach to functional modeling. Instead of dealing with relations between variables, we first consider which kinds of phenomenon are at work, then we translate those phenomenoa into a network of S, E or T elementary functions. Syntactic rules ensure that the process networks are physically valid, equivalence rules are useful for both process decomposition and abstraction. Finally S.E.T typology leads to a complete algebra of physical phenomena with functional operators, calculation features, formal proof, syntactic validation, abstraction and simplification of functional modeling (for more details see. [Fel-96] [Fel-97] [Fel-98]).

3.2. SET Qualitative process

In S.E.T modeling, each process corresponds to an elementary qualitative behavior. It can be established that S processes correspond to generalized integrators, E processes to generalized derivators and T processes to generalized transformers. Figure 4 shows these relations and classes of qualitative behaviors.

Since the process classes form a basis, those three classes of qualitative responses form a basis of qualitative behaviors. The network introduces a fourth qualitative behavior namely: delay. In fact, connecting processes into à network creates feedbacks which introduce delays (see section 4).

Qualitative behaviors have to respect the same syntactic rules and the same equivalence rules as functional processes. Lets us consider the process sequence of figure 5. The sequence S.E.T (figure 5.a) is equivalent to a T process (figure 5.b), according to rules (4):

$$S.E.T = T \quad (5)$$

It can be seen that the sketch of the qualitative behavior of the S.E.T sequence and the one of the equivalent T process are the same. Rules (1), (2) and (4) are invariant form the phenomenological to the qualitative domain.

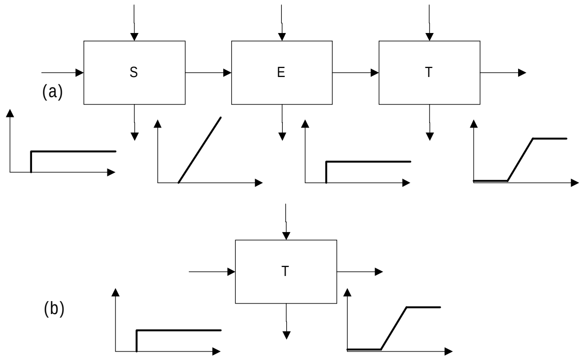

Figure 5 : the qualitative behavior of a sequence of process is the same as the one of the eqsuivalent process.

3.3. SET quantitative point of view

In a similar way, a quantitative generic set of equations corresponds to each class of process or to each class of qualitative behavior [Fel-97] :

$$\begin{pmatrix} d\mathbf{e} \\ d\mathbf{q} \\ \hline d\mathbf{f} \\ d\mathbf{p} \end{pmatrix} = \begin{pmatrix} \pm\alpha & 0 \\ 0 & \pm 1/p \\ \hline 0 & \pm\alpha \\ \pm 1/p & 0 \end{pmatrix} \begin{pmatrix} d\mathbf{e} \\ d\mathbf{f} \end{pmatrix} \quad (6)$$

$$\begin{pmatrix} d\mathbf{e} \\ d\mathbf{q} \\ \hline d\mathbf{f} \\ d\mathbf{p} \end{pmatrix} = \begin{pmatrix} 0 & 1/\mathbf{C} & 0 & 0 \\ \mathbf{c} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/\mathbf{L} \\ 0 & 0 & \mathbf{L} & 0 \end{pmatrix} \begin{pmatrix} d\mathbf{e} \\ d\mathbf{q} \\ \hline d\mathbf{f} \\ d\mathbf{p} \end{pmatrix} \quad (7)$$

Equation (7) is the differential form of the generalized relations F_1 and F_3 of the tetrahedron of states:

$$F_1(\mathbf{q}, \mathbf{e}, \mathbf{C}) = 0, \quad \mathbf{C} = \frac{\partial \mathbf{q}}{\partial \mathbf{e}} \quad (8)$$

$$F_3(\mathbf{f}, \mathbf{p}, \mathbf{L}) = 0, \quad \mathbf{L} = \frac{\partial \mathbf{p}}{\partial \mathbf{f}} \quad (9)$$

Equation (6) is the differential form of the balance equations F_4 and F_5. In the matrix α is a generalized gain, p is the Laplace operator, **C** and **L** are respectively the generalized condensers and generalized inductors of the tetrahedron of states.

$$\begin{pmatrix} d\mathbf{e} \\ d\mathbf{f} \end{pmatrix} = \begin{pmatrix} \pm\alpha & 0 & 0 & p \\ 0 & p & \pm\alpha & 0 \end{pmatrix} \begin{pmatrix} d\mathbf{e} \\ d\mathbf{q} \\ d\mathbf{f} \\ d\mathbf{p} \end{pmatrix} \quad (10)$$

$$\begin{pmatrix} \mathbf{e} \\ \mathbf{f} \end{pmatrix} = \begin{pmatrix} 0 & \mathbf{R} \\ 1/\mathbf{R} & 0 \end{pmatrix} \begin{pmatrix} \mathbf{e} \\ \mathbf{f} \end{pmatrix} \quad (11)$$

Equation (10) and (9) are respectively the generic form of the input/output transfer of E processes and the generic form of the differential equation between its outputs. Equation (10) is the dual form of equation (6). Equation (11) is the differential form of the generalized equation F_2 of the tetrahedron of states :

$$F_2(\mathbf{e},\mathbf{f},\mathbf{R}) = 0, \quad R = \frac{\partial \mathbf{e}}{\partial \mathbf{f}} \tag{12}$$

R is the generalized resistor.

For a F process the generic form of the previous equations becomes:

$$\begin{pmatrix} d\mathbf{e} \\ d\mathbf{f} \end{pmatrix} = \begin{pmatrix} \pm\alpha & 0 \\ 0 & \pm\alpha \end{pmatrix} \begin{pmatrix} d\mathbf{e} \\ d\mathbf{f} \end{pmatrix} \tag{13}$$

$$\begin{pmatrix} \mathbf{e} \\ \mathbf{f} \end{pmatrix} = \begin{pmatrix} 0 & \mathbf{R} \\ 1/\mathbf{R} & 0 \end{pmatrix} \begin{pmatrix} \mathbf{e} \\ \mathbf{f} \end{pmatrix} \tag{14}$$

4. S.E.T AT WORK : A SIMPLE EXAMPLE

Due to space limitation, we consider the very simple system below (figure 6). Suppose we only know the following phenomenological description given by an operator : « it receives a flow, it accumulates a volume and it delivers a flow ». We are going to illustrate how, from this superficial knowledge, the S.E.T formalism helps model formulation, prediction and interpretation.

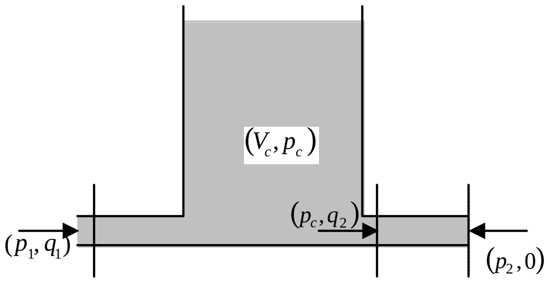

Figure 6: a simple tank example

4.1 Functional representation

First let's identify what kinds of process (S, E or T) are at work. Obviously we have at least one S process due to the accumulation in the tank. So we consider process S1 of figure 7. S1, according to the generic form of S processes, produces energy from power flows. In this case the produced energy is a volume V_c at pressure p_c, from the input and output flows namely : (p_1,q_1) and (p_c,q_2), where p_i is pressure i and q_i is hydraulic flow i. According to rules 1, as a S process, S1 is followed by at least one E process. So, we have to consider process E1 that represents the evacuation from the tank. According to E processes generic form, E1 receives energies as inputs, namely : (V_c, p_c) and (p_2, 0) whose difference creates the output power flow (p_c,q_2). Also according to rules 1, E1 must be followed by a T process.

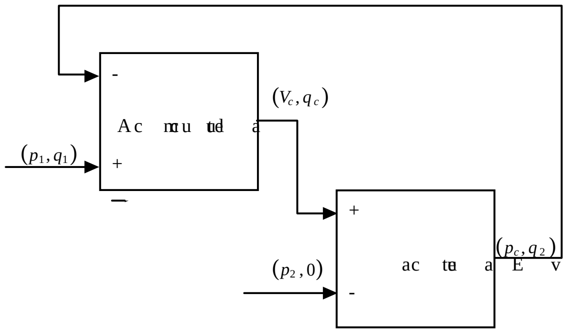

Figure 7: functional representation of the tank

4.2 Qualitative prediction of the system behavior

From section 3.2 we know to which qualitative class the behavior of each process belongs. It is then possible to calculate the qualitative response of the overall network.

Let us suppose an input step on q_1. figure 8 gives the qualitative evolutions of V_c and q_2. Starting from a equilibrium state, (1) a step on q_1 is integrated by S1 creating first a slope on V_c : V_c= S1. q_1. (2) The perturbation on V_c is derivated by E1 giving a step transformed by T1 into another step : q_2= E1.T1 V_c. (3). The perturbation on q_2 is integrated by S1 into a second but negative slope according to : V_c= S1. q_1.- S1. ,q_2= S1. q_1.- (S1.E1.T1)*S1.q_2 , this means that . q_2 influences V_c through a circle relevant to a feedback. So the second negative slope occurs later than the first one. The delay between the two slopes is linked with the time-constant τ of the system. V_c's evolution results of the sum of all the perturbations. So, at time t = τ V_c achieves another equilibrium state and events propagation in the network is stopped.

Let us now suppose that a step occurs on pressure p_2, due for instance to an abrupt obstruction of the output canalization. The behavior of the network is given on figure 9:

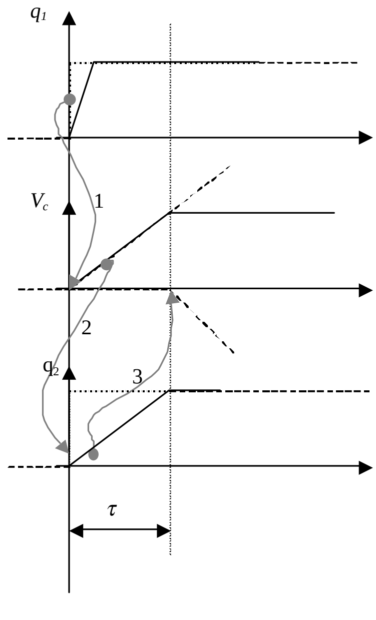

Figure 8 : qualitative response to a step on q_1

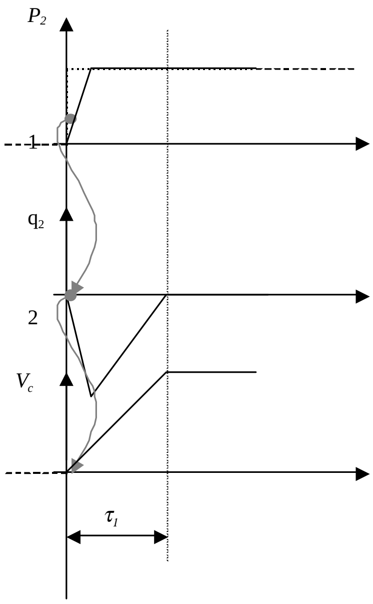

Figure 8 : qualitative response to a step on p_2.

Starting from an equilibrium state, (1) a step on p_2 is derivated by E1 and transformed by T1 into a negative perturbation on q_2. (2) These perturbations are integrated by S1 into V_c , giving a step. Then V_c achieves a new equilibrium state, and the propagation of events in the networks is stopped.

4.3. The structure of the quantitative equations.

From the functional model the analysis of the system can be refined establishing the structure of the quantitative equations that constrain the variables. According to the generic form of the quantitative relation of each class of process (6)(7), (10) (11) and (13) (14) we can establish this structure, only considering the class the variables belong to. We have :

For S1 :

$$dV_c = \frac{1}{p}dq_1 - \frac{1}{p}dq_2 \qquad (15)$$

$$dp_c = \frac{1}{\mathbf{C}}dV_c \qquad (16)$$

For E1.T1 :

$$dq_2 = \mathbf{R}.dp_c - \mathbf{R}.dp_2 \qquad (17)$$

We do not need to know the analytical expression of parameters **C** and **R** which can be linear or not, but only the kind of dependence they establish between the variables of the relation, namely : capacitive, inductive, or resistive. According to these previous equations we deduce:

$$\begin{aligned} dV_c &= \frac{\mathbf{RC}}{1+\mathbf{RC}p}dq_1 + \frac{\mathbf{C}}{1+\mathbf{RC}p}dp_2 \\ dq_2 &= \frac{1}{1+\mathbf{RC}p}dq_1 - \frac{\mathbf{C}p}{1+\mathbf{RC}p}dp_2 \end{aligned} \qquad (18)$$

which confirms the previous qualitative approximation of the system evolution.

5 CONCLUSION

S.E.T formalization ensures that any real process can be represented using three function classes. It helps model simulation and system analysis providing connexion rules and equivalence rules for decomposition. To some extent, these rules tell what should be the process in order to be syntacticaly correct. S.E.T. models provide generic forms of qualitative responses of each class and generic forms of quantitative relations among the variables of the process. The networks build using S, E, and T processes and rules (1) and (4), introduce both causality and, because of the dynamic link introduced by S and E processes, time ordering of events : inputs cause outputs, inputs occur before outputs, loops introduce reaction times and delays. This ordering helps to partially remove ambiguities due to the qualitative nature of events propagated in the network.

REFERENCES

[Ben-91] C. I. Benzaken “Systèmes formels, introduction à la logique et à la théorie des langages”, Masson, Paris, 1991.

[Bor-92] P. Borne, G. Dauphin-Tanguy, J. P Richard, F. Rotella, I. Zambettakis, *“Modélisation et identification des processus”*, Tome 2, Ed TECHNIP, 1992.

[Cha-93] Charles A., Melin C., “QDIAG: a mixed qualitative/quantitative approach to diagnosis of dynamic systems”, *in Proc. International Conference on Fault Diagnosis, Tooldiag,* Toulouse, France, 1993.

[Cau-92] Cauvin S. Braunschwieg B., Galtier P., Glaize Y., «ALEXIP : An Expert system coupled with a dynamic simulator for the supervision of the alphabitol process », Revue de l’Instut français du pétrole, vol.47, n°3, pp 375-382, Mai-Juin, 1992.

[Dvo-89] Dvorak D., Kuiper B.J., «Model-Based monitoring of dynamics systems», in Proc. Internat. Join Conf. On Artitificial Intelligence, IJCAI-89, Detroit, MI, pp 1338-1343.

[Fel-96] Feliot C., Staroswiecki M., "Towards a Formal Language of Physical system", IEEE SMC'96, Beijing, China, 1996.

[Fel-97] Feliot C., *“Modelisation de systèmes complexes: intégration et formalisation de modèles”*, PhD of Université de Lille I, 1997.

[Fel-98] Feliot C., Staroswiecki M., “A Syntactic Approach for Functional Modelling of Physical Systems”, 9th Int. Workshop on Principles of Diagnosis, Dx’ 98, pp. 174-181, Cape Cod, Ma., 1998.

[Fer-89] Feray-Beaumont S., *«Modèle qualitattif de comportement pour un système d’aide à la superision des procédé»*, PhD. of Institut Polytechnique de Grenoble, 1989.

[Kar-90] D. C. Karnop, D.L. Margolis, R.C. Rosenberg, “System dynamics: a unified approach”, John Wiley & sons, 2nd Ed, 1990

[De Kle-87] De Kleer, «Multiple Representation of knowledge in a Mechanics Problem-Solver», *Proc. 5th IJCAI*, Cambridge, Mass., pp.299-304.

[Kui-86] Kuiper B., “Qualitative Simulation”, *Artificial Intelligence*, Vol 29, pp.289-338, 1986.

[Lac-87] Lackinger F., Nejdl W., Haseböck A., «On Model-Based Monitoring and Diagnosis of Dynamics systems», Tech. Report, Université de Technologie de Vienne, Vienne.

[LeM-89] J.L. Lemoigne, “La modélisation des système complexes”, Dunod Bordas, Afcet systèmes, Paris 1989.

[LePape 87] Le Pape C., Smitrh S.F., “Management of temporal constraints for Factory Scheduling”, *proc. Conf. Temporal Aspects in Information Systems*, Sophia-Antipolis, pp. 165-176.

[Ley-91] Leyval L. “*Raisonnement causal pour la simulation de procédés industriels continus”*, PhD of Institut National Polytechnique de Grenoble, 1991.

[Mil et al. 85] Miller D., Firby J., Dean T., “Deadlines, Travels Times and Robot Problem Solving”, *proc. 9th IJCAI*, Los Angeles, Cal., pp. 1052-1054.

[Mon-92] Montmain J., «*Interprétation qualitative de simulation pour le diagnostic en ligne de procédés continus*», PhD of Institut National Polytechnique de Grenoble, 1992.

[Pay-61] H. M. Paynter, “Analysis and design of engeneering systems”, MIT press, Cambridge, 1961.

[Por.-85] Porta H. J., «Dynamic Replannig», *tech. Report (818) 345-8051*, *Jet Propulsion Lab*., California Institute of Technology, Passadena, Cal., 1985.

[Sac-86] Sachs D. A., Paterson A. M. et Turner M. H. M., «ESCORT: An Expert System for Complex Operations in Real Time», *Expert Systems*, Vol. 3, n°1, pp. 22-28.

[Sal-87] A. Salomaa, “Formal languages”, Academic Press, 1987

[Ver-83] Vere.S.A, “Planning in time: Windows duration for activities and Goals”, IEEE PAMI,Vol.5, No.3, 1983, pp. 246-267.