# TEACHING SYSTEM DYNAMICS IN A FRENCH SCHOOL OF ENGINEERING

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## 1 - INTRODUCTION

We shall describe here the development of the System Dynamics teaching content at ECP (Ecole Centrale Paris), following some 25 years of teaching this subject in various French Universities, Institutes of Technology and Business Schools. The ideas and experience accumulated in previous years have been applied at ECP, one of the top French engineering schools, and will be described in this chapter.

This course was created three years ago, at the same time as, and within a new specialization program in Industrial Engineering whose aim is to give a global but in depth view of Industrial Processes. System Dynamics was considered as particularly suited to take into consideration all the numerous closed loop Processes.

The Industrial Engineering specialization, with some 60 students, deals with three subjects :
- Design Processes
- Logistic Processes
- Economic Processes

As it stands now, System Dynamics is an optional course within the Design Processes sector.

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## 2 - A SHORT PRESENTATION OF ECOLE CENTRALE P ARIS (ECP)

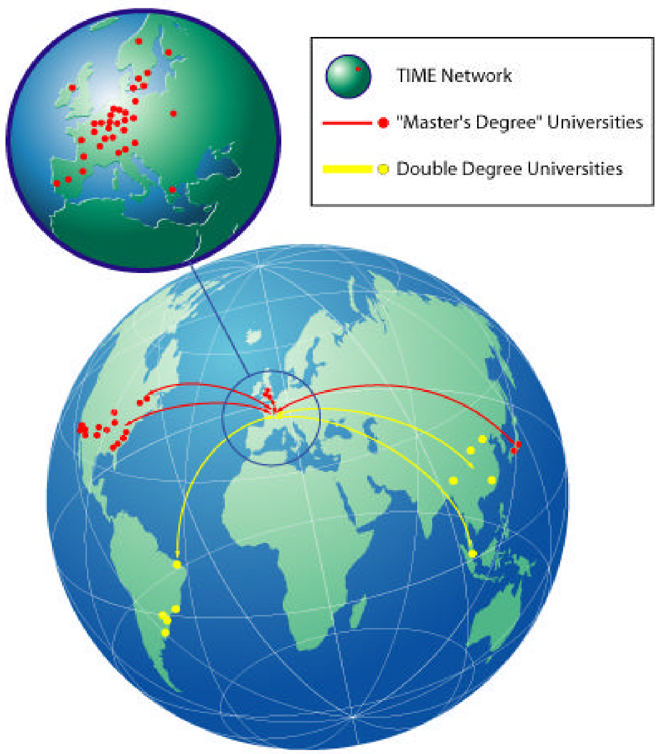
### GENERAL :

Ecole Centrale Paris is one of the most prestigious engineering school in France.
Founded in 1829 to train multidisciplinary engineers for industry, ECP is considered as one of the leading engineering "*Grandes Écoles*" in Europe.
It is accessed through a very selective competitive process, at least 2, generally three years after high school. 400 students enter each year, of whom 100 coming from European Universities.

### Educational project :

First two years : Basic scientific and technical education.
3rd year :"Area of specialization" in a specific field, chosen amongst 8 scientific or industry-related sectors : Civil & Environnemental Engineering, **Industrial Engineering**, Information technology, Applied mathematics, Mecanical & Aerospace Engineering, Applied Physics, Process & environemental Engineering, Electrical Engineering.

**<u>Partnership</u>** : ECP is in partnership with prestigious technological Universities in Europe creating the “TIME NETWORK”, and it has developed a "Master's Degree" Network involving American Universities like Harvard University, MIT, Stanford University, Georgia Tech….



## 3 - <u>Teaching System Dynamics</u>

How to teach System Dynamics ?

When faced with students in their early twenties, eager to learn, full of imagination, with a strong desire to change the world, but disorderly, impulsive, often lacking method in their approach to problems, what meaning should be given, and how should one teach System Dynamics so that these students become and remain interested in this approach, while "keeping their feet on the ground" ?

A tentative answer to this question leads to defining several aspects of the teaching approach :

1 – System Dynamics is to be considered as both a <u>philosophical approach</u> to complex dynamic problems, but also as a <u>practical quantitative method</u> without which any analysis remains of little use.

2 – students are often <u>imaginative</u> – and it is a quality which we must develop rather than quelch – but they are also required, particularly as future scientists, engineers, managers – to be <u>practical</u>, to obtain, show and analyze <u>meaningful results</u>.

Hence we try to develop four complementary aspects of our teaching :

1 – **The <u>philosophical</u> aspects of SD**, which we feel are twofold :

**Feedback Loops**

- SD deals with – and only with – system s which contain feedback loops. This is hardly a limitation, since most systems contain feedback loops which are the essential cause of the complexity of their dynamic modes of behavior. On the other hand, this sets SD apart from other modelling and simulation techniques which deal with and are applicable to structures without feedback loops. This is an important initial criterion for choosing the system which the students will study, model and simulate. Although the students at ECP have had courses in feedback systems and have no difficulty with the concept, we unfortunately find, again and again, that they often have difficulties in recognizing the presence of feedback loops in "soft" systems, or on the contrary realizing the absence of such loops.

It is one of our aims, and main tasks to have them look systematically for feedback loops in whatever system they want to study and analyze.

**Causality**

- we repeatedly insist on the necessity to explain the <u>cause</u>(s) of results obtained through simulation, that "why" is at least as important as the "how" of future behavior. Explaining results, behaviors, proposing intelligent changes should be more important than predicting uncertain (even if likely) future developments, and these causal explanations should be based on the complementary and interacting notions of state vector which caracterizes a system and the vector of force which cause change in that same system.
Here again, the natural tendency of many students, which we systematically try to correct, is to present simulation results, whether normal or surprising and

counterintuitive, without much effort to explain the internal (system) reasons for such behaviors, and without searching for policy changes or even new policies which could modify these results.

In order to favor the search for causes and develop the awareness of the effects and importance of closed loops, we systematically ask students to start – and finish, we'll see later why – by drawing a causal diagram of the problem they chose to tackle. In our experience, we have seen that starting analyzing a problem by means of a causal diagram, has many advantages :

- it gives a global view of the system, and avoids jumping immediately into details,
- it brings out very quickly at least some feedback loops within the system, thus justifying the u se of SD, or on the contrary, showing that the latter is not the appropriate approach,
- it allows a better immediate dialog with the client, in this case the professor,
- it gives a good start for the next step, namely the construction of a dynamic quantitative model.

We shall also develop later in this paper the notion of "a posteriori" causal diagrams, drawn after the model has been developed, thoroughly studied and used. The idea is to help develop tools for showing dynamic behaviors of complex systems in a way that can be easily understood by managers and policy makers, without having to get into lengthy and detailed explanations about the model. But showing only the main causal feedback loops, those which act in the long term, whose effects are not evident to understand, nor to forecast, requires a deep knowledge of the system, a knowledge based on an extensive use of the model.

The philosophical aspects of System Dynamics are introduced right at the begining of our course. But we have come to realize, again and again, that these concepts are quickly forgotten, and we must come back to them throughout our teaching, whether it be theoretical – main concepts and examples of SD – or practical – models developed by students or large models realized outside the course -.

## 2 – The practical aspect of SD

As mentioned earlier, we consider that beyond its philosophical aspects, SD is a practical quantitative tool meant for the analysis of complex time evolving systems, and this attitude does suit scientifically minded future engineers and managers.
Hence we pass very quickly to the practical aspects of SD :

- separation of variables into levels, rates and information - decision - influence variables, explaining with a few very simple examples, the reason and the need for this decomposition,
- delays, non-linearities, graphs and mathematical or logical functions, etc.,
- the use of some specific softwares such as **ithink** or **Stella**, **Vensim**, **Powersim** (not yet much in use in France).

At the Ecole Centrale Paris, where most students are bright, fast and highly scientifically oriented, all these elements pose no problem. There remains, however, one recurring question more or less openly asked by most students : how to start a dynamic model on the basis of the causal diagram built previously ? We try to show that in principle, the answer to this question is simple and quite general. We suggest looking within the causal diagram for a few level variables (don't try to be exhaustive, a few such levels will do, to start with) which can be characterized as follows : if and when everything stops brutally (vacation period, for example, when the company closes, with neither sales, nor production nor ordering taking place), level variables are the only ones not to vary at all, to remain fixed at the last evolving value. All other variables will either fall to zero or become inexistant and/or useless. This has proven to be an effective way to start modelling, whatever the problem, choosing level variables according to this criterion, the the flows which fill or empty the levels, finally all variables, parameters and constants which influence flows.

Introducing the principles of System Dynamics and some practical notions about SD modelling, with a few relatively simple examples, takes relatively little time, about 9 to 10 hours. The next step consists in having the students develop a practical model and use the resulting simulator to analyze and get to know better the system under study.

We have always felt that learning SD must imply the creation, development and use of some real model, if only to teach students how to obtain and explain results, whether interesting and curious and even counterintuitive, or on the contrary banal, expected and with no new informational content (the latter being a result by itself).

The question then arises, as to what type of system should students analyze. Should we impose or at least propose certain problems, certain areas of analysis, such as logistics, production problems, company management, directly connected to their main subjects of study ? Or is it possible to give total freedom of choice, with the only restriction that the proposed problem (system) shows complex time behavior, a complexity certainly due to feedback loops within the system ?

These questions are linked to two seemingly contradictory aspects we mentioned above, namely the "youthful imagination" of most students and "down to earth" attitude required from them. Which of these aspects should be favored ? Can they be combined ?

## 3 - **Developing <u>Imagination</u>**

Since SD can be applied to practically every domain involving either nature or man, or both, we feel that giving students a freedom of choice is one way of letting them develop their imagination. It is also a good way to let them realize – through some hard to accept and bear, but healthy failures – the limits of wild topics, wildly imaginative suggestions, unrealistic ideas.

As examples of such "wild" topics analyzed by students using SD, let us mention :

- succesful development of a music group (a topic often proposed by students, which shows a frequent interest in music),
- competition between two ant colonies,
- management of a football club, or of a pizzeria,
-happiness within a couple.

4 – **Obtaining and showing <u>practical</u> results**

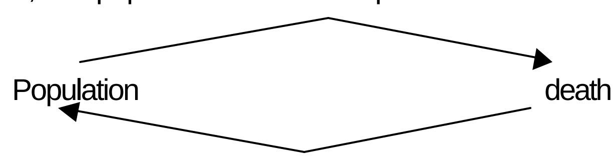
Whatever the subject, we have always insisted on the practical and quantitative aspect of SD, hence on the need to develop a realistic simulator which could show useful results and lead to a better understanding of the dynamics of the system being analyzed.

Rather than developing at length the aspects of practicality upon which we insist mostly when working with students, we shall discuss the main difficulties or shortcomings students encounter when dealing with SD as applied to whatever problem they chose to study. Obviously, creating an interface using the corresponding possibilities of the available softwares, does not generate problems (it tends, in fact, to become one of the easiest aspects of modelling, and we have to insist that the content is more important than the showcase). On the other hand, we insist again and again on the notion of feedback loops, a notion students should keep in mind from start to the end of the course (and hopefully all their life !) and in particular when presenting and explaining results.

5 – **<u>Loops</u>**

But all loops are not of equal interest, and we try to develop in students the capacity to realize that, and to be able to show these differences.

1 - "hardware" loops are evident, unavoidable and not modifiable. For example, the "population – death" loop



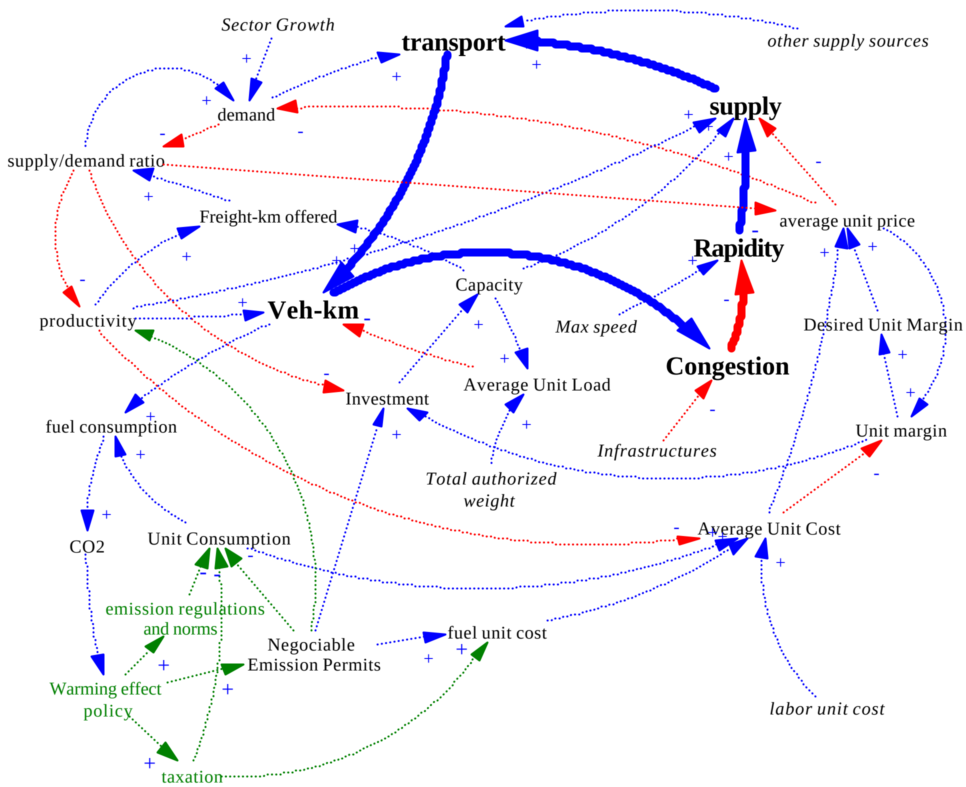

is automatically taken into account by everyone, even if totally ignorant of SD, of modelling, of simulation, of abstract thinking. Such loops must not, and generally are not omitted by students, but they generate little new information as to the behavior of the system.

2 - "policy" loops which involve policy and decision variables, whose effect can be short term or relatively long term, but which are in both cases well known and recognized, their individual dynamics corresponding to expected behavior. The analysis of such loops is useful because the corresponding effects are generally a mix of many loop behavior types, and a loop by loop decomposition helps understand what was possibly expected, hoped for or forecast through intuition, but was too complex to be rationally and simply analyzed and explained. These are the feedback loops one can expect students to show, to analyze and to explain.

Here is an example of such a long term loop whose existence and effects are quite evident. It comes from a study[3] which was done on freight transport, and

[3] Patrice SALINI (INRETS, France), Michel KARSKY (KBS, France) (2002), « SIMTRANS (Freight Transportation Simulation Model)", *System Dynamics International Conference,* July 2002, Palermo

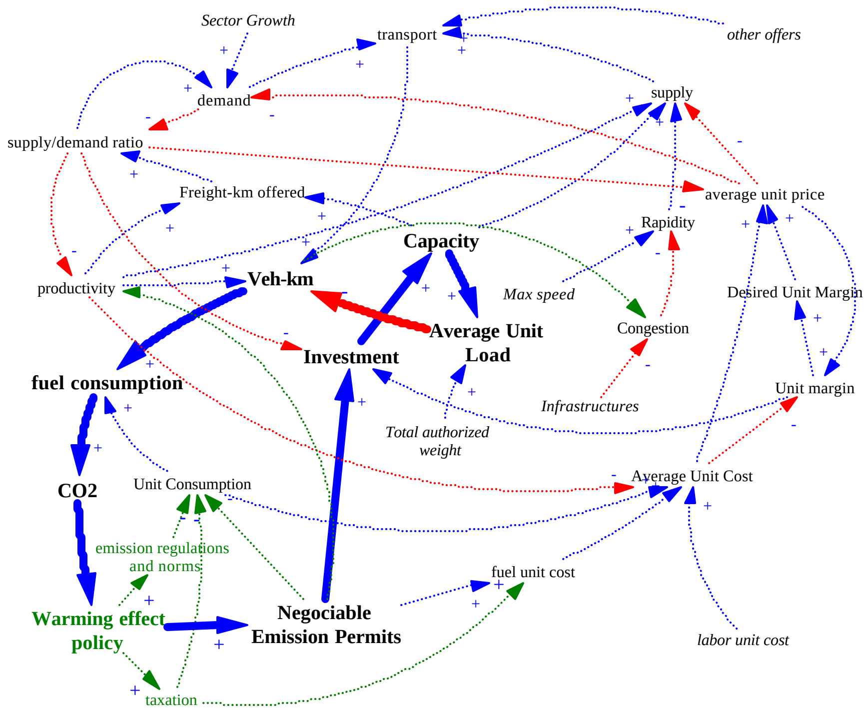
the possible effects (or lack of effects) of emission permit policies. The following causal diagram drawn after the model was developed, simulated and analyzed showed a multitude of "policy" type feedback loops. Here is an example of a long term loop whose existence and effects are to be expected and are not surprising. This loop brings no surprising information, but forgetting to take it into account could lead to trouble in the long term.



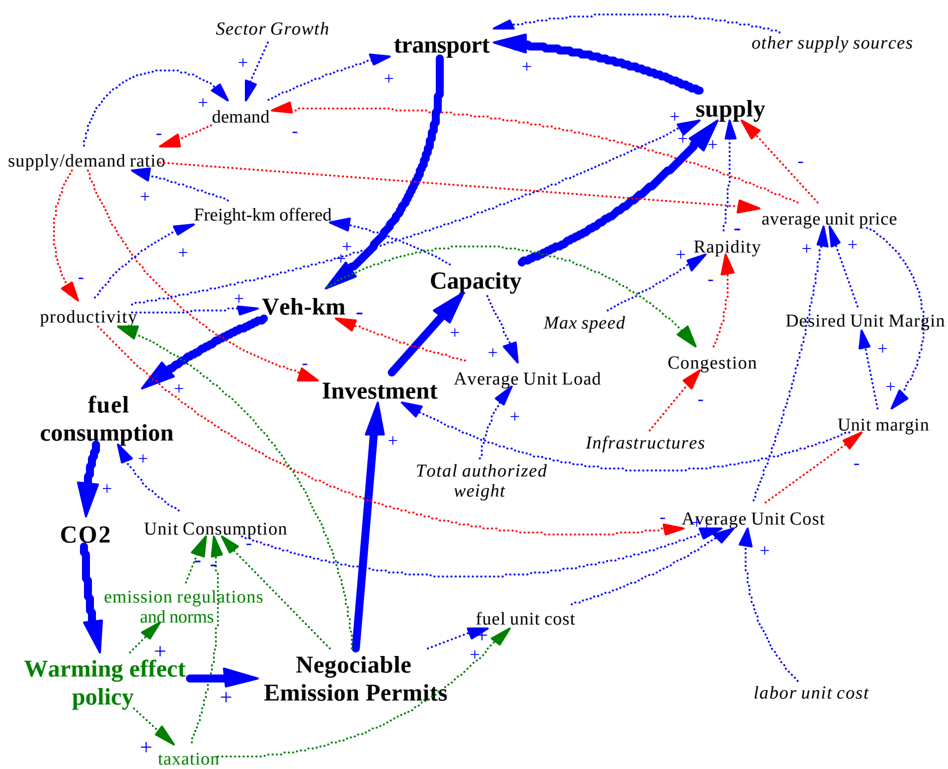

**A long-term « evident » feedback loop**

3 – Most eften, when modelling some real complex problem, one finds loops often involving quite a few variables, with long term and sometimes counterintuitive effects, but whose existence is ill perceived, or ignored or forgotten. To show and analyze these loops one by one, showing also how they can combine effects, has proven to be very effective in the process of convincing users, experts and clients, that their problem is in effect a complex one and that long term consequences of decisions can be forecast and can be taken into account. It is rare for students to succeed in finding and analyzing such loops, if only because this requires experience (the presence of experts for the field) and time.

Taken from the same freight transport model, here are two long term loops which may contradict each other, and must therefore be analyzed carefully.




**A slow stabilizing and favorable loop**




**A slow acting loop whose effect would contradict that of the previous loop**

For both types of “policy” loops, whether evident or not, whether short or long term, we insist in our teaching on the necessity to bring them out by redrawing a causal diagram at the end of the study, after having become well versed in the system being analyzed. This “a posteriori” causal diagram should be an important part of the whole exercise, it shows how well the student has mastered the problem and, not less important, how he/she can pass this understanding to others.
To conclude this chapter, let us make a resume of the steps we find important when teaching System Dynamics, and the main difficulties students seem to have when learning this discipline :

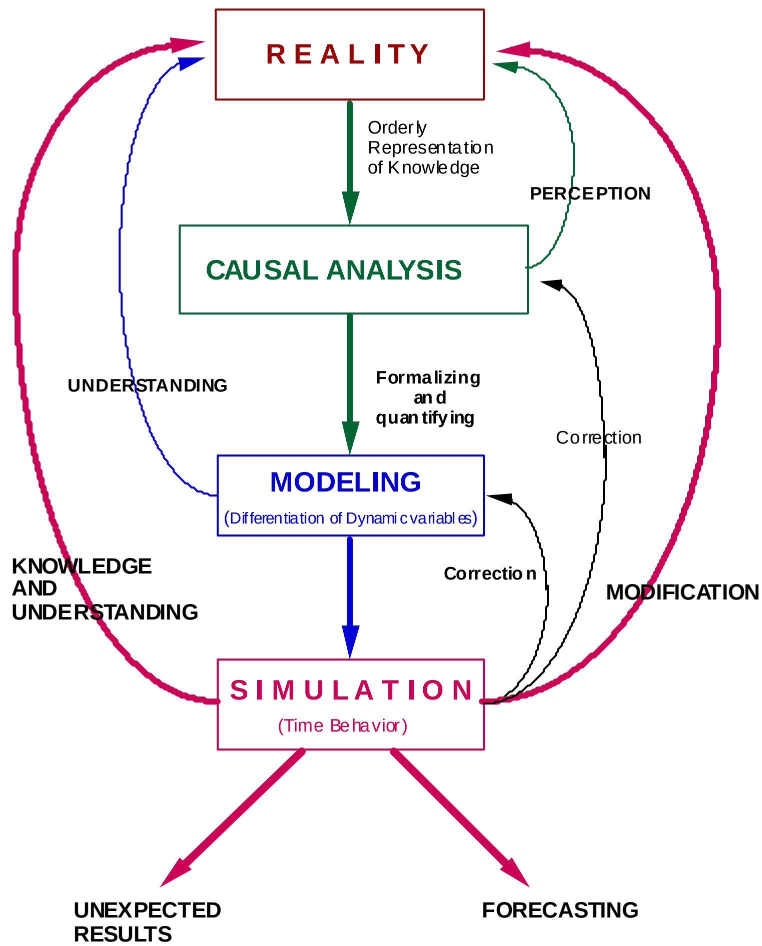
- the basic concepts, which give a quasi-philosophical view of our approach to systems :
1 - **feedback loops**, a universal concept - though often overlooked -, responsible for most of the complexity of dynamic behaviors of systems.

At ECP, students have no problem with the concept and effects of loops, but they still have difficulties transposing their knowledge onto “soft” systems, so as to recognize in the latter at first sight the presence or absence of such loops. Unfortunately, students less versed in feedback theory (business schools, some economists, etc.) have even more difficulties with the concept.

2 – complementary and mutually interacting notions of **state** which characterizes a system, and of **force** which causes change.

Questioning and analysing the reasons for some behavior, whether normal or unexpected, is not in the habit of most students in their early twenties. Although the softwares available allow easy causal analyses, we must constantly remind students to use these cause- searching tools, rather than developing a paralyzed type of attitude when faced with a seemingly unusual model behavior (we repeatedly have to remind them that such unusual behavior is most likely due to an error in the model, rather than the fault of the computer, of the real system being analyzed...or even of the tutor !)

- But SD is a pragmatic, quantitative approach to complex systems, hence practical tools are needed, and exist, to model and simulate. The successive steps, both theoretical and practical, in the analysis of dynamic systems, the possible consequences and conclusions that can develop from such studies, can be summarized in the diagram on the next page.
Most students at ECP have no problem with the use of the available softwares, with mathematical, logical or graphical functions. Rather, they tend to use too much mathematics, with three or four line long equations, but this youthful defect is easily overcome.




THE MODELLING AND SIMULATION PROCESS

- Because of the variety of systems around us, and the applicability of SD to most of them, we feel it worthwhile to let students use their imagination, however wild it seems to be – as long as it remains realistic and practical -,in their choice of the system they want to analyze using SD. We must add that we have been seldom disapointed with the subjects which were chosen, modeled and simulated.

Here again, we have observed, that students have difficulties in differentiating between problems which can be tackled by means of SD (because of the presence of feedback loops) and those where no loops exist or are effective.

- It is extremely important to learn how to show and explain results as clearly as possible. Most softwares used for SD analyses have interface possibilities which help in this final task, and we require that the final presentation use these facilities. This poses no problem, whether at ECP or elsewhere, and it is in fact the prefered and easiest part of the project.

In addition, we ask - and shall develop this aspect of the final phase of the project – that students analyze the problem and explain possible short or long term developments with the help of a causal diagram drawn after the model has been developed and used. Students who succeed in this final task, really benefit fully from our course and will have understood in depth, and hopefully for a very long time, the System Dynamics approach.

## 4 - Some examples of students projects

### Types of projects proposed by our students:

**Management/Finance**

- Management of a supermarket
- Management of an investment company in office real estate
- Management of a soccer stadium

**Model of companies**

- Ski ressort
- Restaurant managing
- Manufacturing plant

**Organisation**

- Management of a French university
- Management of a small town
- Management of a soccer team

**Miscellaneous**

- The development of an Ant's Nest
- Evolution of a butterfly specie
- Happiness of a couple
- Development of a music band

# Example 1 : Cohabitation between two Ant's Nests

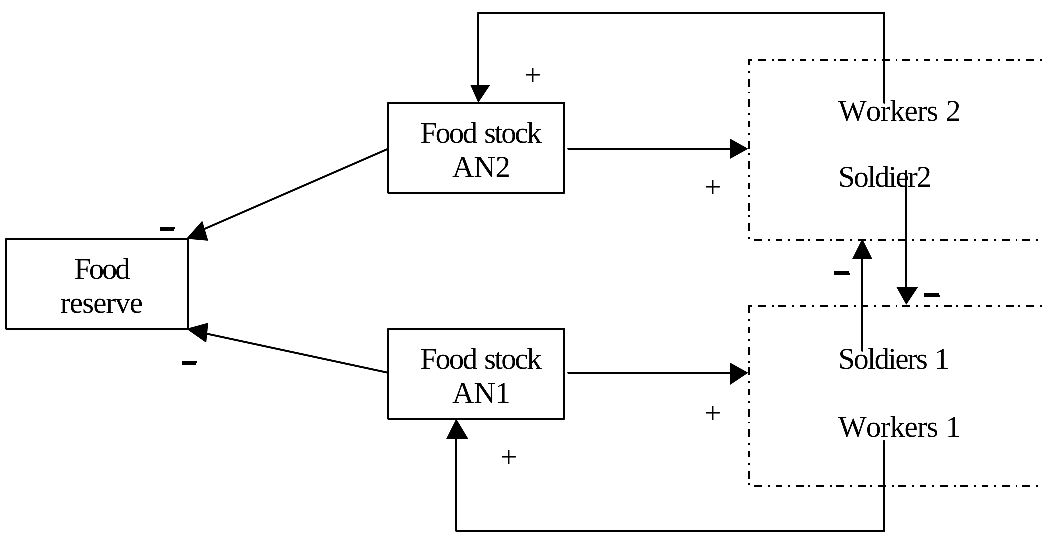
## Definition of the problem

▪Some information about Ant's Nests

- 1 queen per nest
- two sort of ants :
  - soldiers
  - workers
- Population of a nest : from 100 000 to 1 million
- Ants are agressive
- Two nest can't exist on the same territory

## Modelling through Stella®

General behavior of the system




Food is brought by workers while soldiers try to eliminate the whole population of the other nest (workers, soldiers and queen).

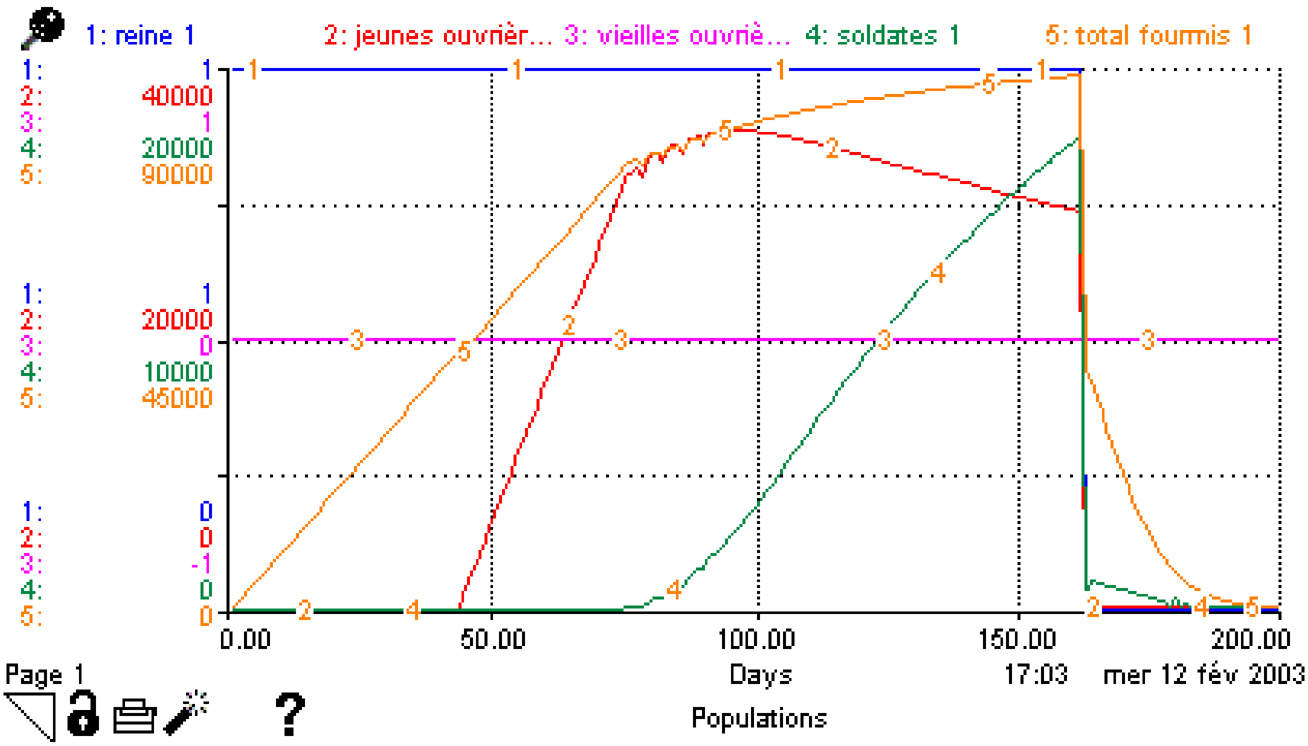
The food stocks of both nests can deplete the total food reserve.
A queen lays eggs which become nympheas which in turn become soldiers or workers depending on the rate of stress of the nest: the higher the stress due, for example, to some danger, the more soldiers are created at the expense of workers, thus diminishing the input to the food stock of the nest.

**Results**

1 - A single nest stabilises its population around 150 000.

2 – When two similar nests coexist, the stress becomes important, the number of soldiers strongly increases at the expense of workers, insufficient food is brought to each nest and borth of them disappear.

Evolution of nest 1




3 – It is not surprising to find that a nest disappears sooner if it is weaker than its competitor ( scenario parameter : strengh$_{i}$ < strengh$_{ij}$)

4 – A counter-intuitive result : nest 1 has a birth rate 50 times less than that of nest 2, hence a much lower population. When competing with each other, and contrary to expectations, it is nest 2, the bigest one, which suffers and disappears. This is because the stress rate of nest 1 increases much faster than that of nest 2 (population of nest 1 seems too small to appear dangerous to nest 2, hence the coresponding danger is overlooked). Soldiers of nest 1 attack and kill the population (soldiers and workers) of nest 2. When the latter begin to realize the danger, it is too late.

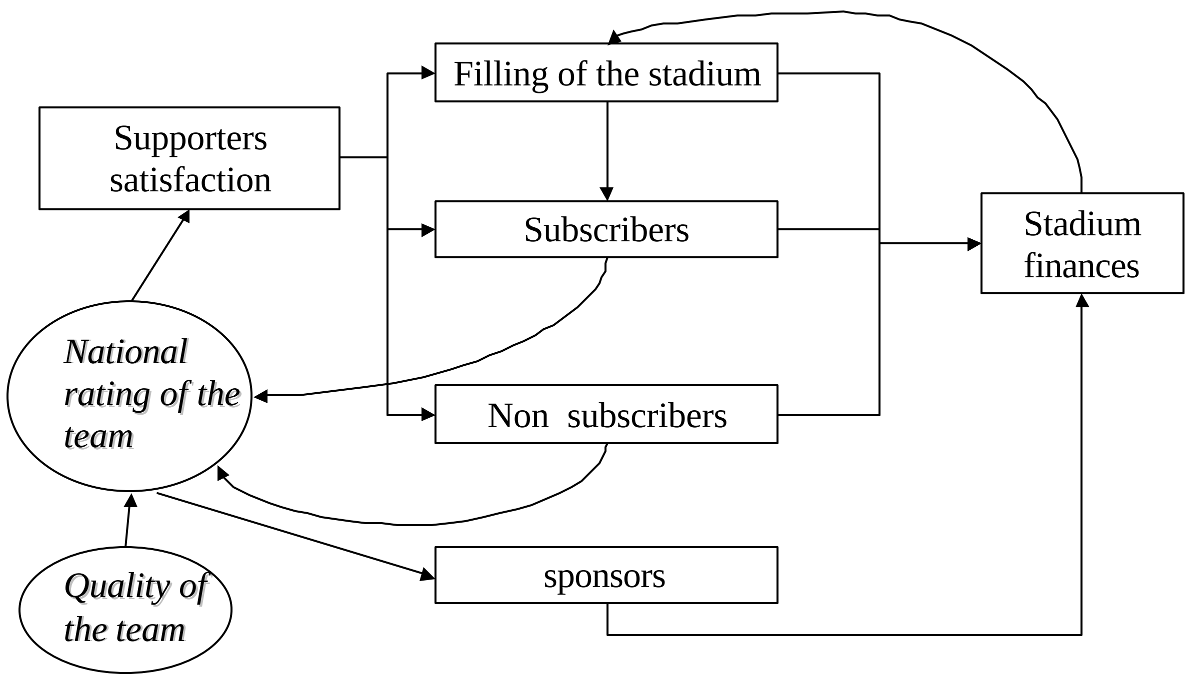
Let us add that this example was very well presented, both in written and oral form, the variables and results were well documented.

# <u>Example 2 : Management of a soccer stadium</u>

**Definition of the problem**

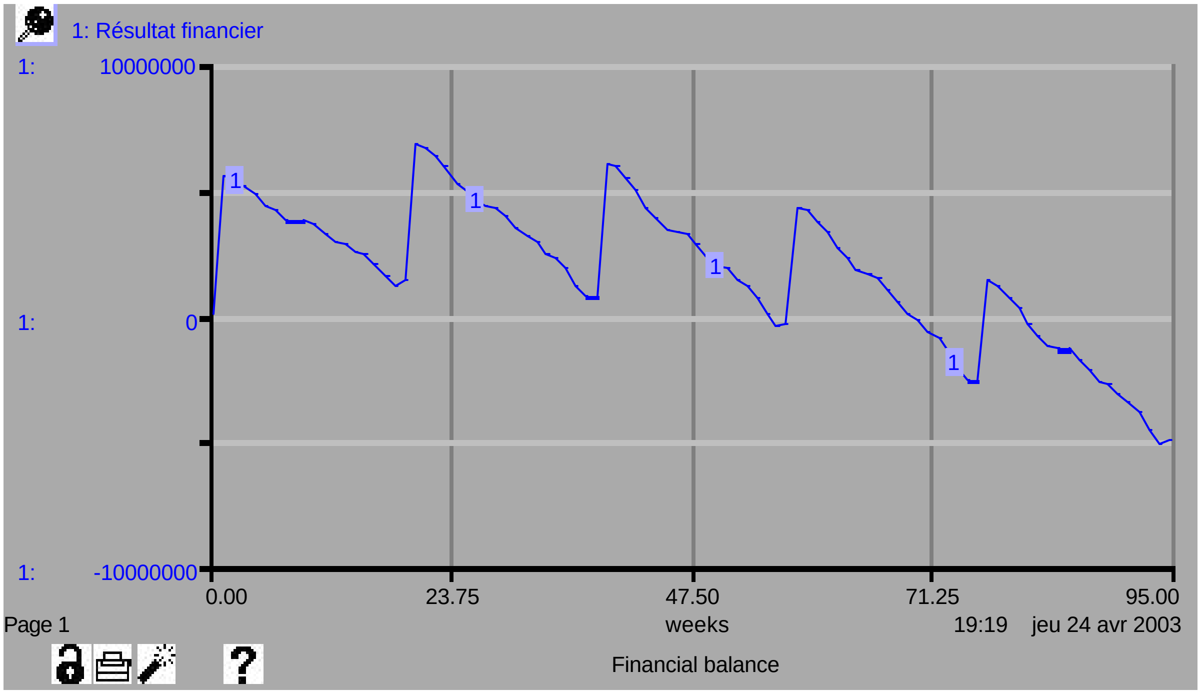
- Management model of a soccer stadium.
- Simulation over five championship seasons (95 weeks).
- If money is gained, it can be invested into the extension of the stadium.
- Supporters satisfaction depends on the results of the team, and influences the number of subscribers.

**Model Structure**



**Results**

1 – A Weak team causes the financial balance of the stadium to progressively deteriorate.




On the contrary, and not surprinsingly, good results lead to an improvement of the financial balance of the stadium, which can be offset by a tendency to overinvest.

Among other results, this work allowed students to confront their mental model and the corresponding model of a system, with reality.

## 5 – <u>Conclusion</u>

This topic interests students whose attendance to the course has more than doubled from year to next. They seem to be particularly attracted by :

- the novelty of approach to systems, an approach they were not used to in their previous training,
- the freedom to apply a scientific and quantitative method to problems considered as “non-scientific”,
- the freedom we give them in the choice of the subject, thus developing their imaginative approach to topics of very different kinds,
- the use of new software (ithink, stella, vensim) which require rigorous thinking and modeling.

We believe it essential that young engineers and future managers develop their sense of system approach in order for them to improve their ability to make as right a decision as possible, realizing that feedback loops exist not only in machines but all over the soft systems that surround them.Beyond the year to year requirements of teaching System Dynamics, there is also within ECP a desire and an ambition to develop a center of competency in this subject, with seminars, conferences, and master and doctoral projects and theses.

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