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The roles of System Dynamics in environmental problem solving

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Abstract

The present Technical Report has as its main content (from section 1 to section 11) the homonymous paper accepted as a poster at the 2008 International System Dynamics Conference, Athens, Greece, July 20 - 24, 2008. We made some very small additions mainly to clarify some minor points. It moreover contains:

1. in section 12, a few notes on System Dynamics and System Thinking;
2. in appendix A, some hints for a research project about the use of System Dynamics as a consensus fostering tool;
3. in appendix B, some hints for an ongoing research project that is at the root of the content of sections from 1 to 11.

As a concluding remark, we note how this Technical Report is not an introduction to System Dynamics and therefore all the basic concepts of the field are taken for granted.
Reports of errors and inaccuracies are gratefully appreciated.

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1 Introduction

The present paper aims at examining some of the various meanings and scopes[1] of System Dynamics (SD) within the entangled arena of human affairs and particularly in the arena of **environmental problem solving** (Cioni (AIRO 2006 Cesena 12-15 September 2006)).
In those arenas interest groups make use of formal models to dress their opinions, interests and stands with the chrism of objectivity. From this perspective, SD can either be a help to unmask such tricks and to reveal the true positions at stake but can also be a hindrance since its "objectivity" can present a very partial solution as a definite and immutable one.
The paper has a sequential structure that forces us to present the topics in a given order though they should be examined in parallel. This is true for what concerns actor, experts and stakeholders, on one hand, and problems and solutions on the other hand but is true also for the various role of SD since it is very hard and rare to find in practice pure roles. Such roles are indeed often mixed with all the other ingredients in an often confusing patchwork.
One of the aims of this paper is, therefore, that of presenting SD as a meta tool to unravel such a skein and clarify from time to time who is using SD and to what purpose.
The paper, therefore, presents the main features of SD, who can use it, how, when and why. A section on the various roles of SD follows. Then we present the various arenas where SD is used and a discussion of the hamlet's dilemma "help or hinder" to close, traditionally, with a section devoted to partial and tentative conclusions.

2 The main keywords

The paper is centred on the following keywords:

1. role,
2. environment,
3. problem,
4. solution,

and on the uses of SD. SD represents a paradigm in Kuhn's sense (Kuhn (1978)) since it undoubtedly represents a change in the conception of the world, from a reductionistic to a holistic view[2], but it can also turn into a set of engi-

[1] The **scope** of an activity, topic or piece of work is the whole area which it deals with or include.

[2] From an holistic point of view a system is more than the sum of its parts so that the parts have no meaning without the whole whereas from a reductionist point of view a system can be reduced to its parts and their interactions and each part can be examined in isolation from the others. It is intuitively clear how a purely holistic view is not practical and that in all cases we are forced to isolate a system from the rest of the world still maintaining the fact that all its parts are meaningful for the functioning of the remaining parts (see section 3).

neering techniques up to losing its theoretical autonomy and become a sub field of the nobler art of *System Thinking* (Richmond (2001)). A deeper analysis of this sort of a cognitive paradox is among the aims of the present paper and will be started in section 4. In this section we aim at examining the afore mentioned key words.

A **role**[3], in the context we are interested in, can be defined (Biswas (2007)) in a dynamic way as a collection of responsibilities where a responsibility is a task that must be carried out to fulfil at least in part a role. In this way we embody *SD* within a perspective similar to that of actors, experts and stakeholders (see section 5).

The word **environment** is overloaded of meanings since almost in every scientific discipline this word assumes a particular meaning with its own nuances. It is therefore necessary to make some considerations so that phrases such as "the environment of a system that is modelled through a model whose environment accounts for some features of the environment" may have some sense.

In the present paper we start from the basic meanings of the word "environment" that denote:

1. a nature related concept as "the complex of physical, chemical, and biotic factors (as climate, soil, and living things) that act upon an organism or an ecological community and ultimately determine its form and survival" (the Merriam-Webster Online Dictionary);

2. a social related concept as "the aggregate of social and cultural conditions that influence the life of an individual or community" (the Merriam-Webster Online Dictionary);

3. a linguistic or systemic related concept as "the position or characteristic position of a linguistic element in a sequence" (the Merriam-Webster Online Dictionary).

We aim, on one hand, at mixing the first and the second meaning to account for the interactions of human societies with the nature, from which the environmental problems originate, and, on the other hand, to use the third meaning as a way to characterize the context of our systems. We therefore can understand the aforesaid phrase if we interpret the second occurrence of the word "environment" as "context".

The last meaning moreover allows us to recover an holistic perspective by linking our models to an outer world that makes them integral part of the reality (see section 3).

[3]The Merriam-Webster Online Dictionary gives the following definitions of this word: **1 a** (1) a character assigned or assumed ("had to take on the role of both father and mother"); (2) a socially expected behaviour pattern usually determined by an individual's status in a particular society **b**: a part played by an actor or singer; **(2)** a function or part performed especially in a particular operation or process ("played a major role in the negotiations"). We are essentially interested in the last meaning, at least for what concerns *SD*, whereas for actors, experts and stakeholder we will consider mainly the socially related definition.

A **problem**[4], at this level, can be seen as a sort of a question that someone makes and that begs for an answer. With this we mean that a problem can be formulated as a question but, what is more important, it has a poser, someone who believes that a certain situation is a problem and that may be seen as the owner of the problem (Daellenbach (1994)). The main point is that whenever a question is posed by a single person in many cases it is biased in the sense that it contains in itself the answer. To escape from this trap a question must become a collective one so that any potential bias is blurred and loses any efficacy.
Last but not least a **solution**[5] represents an answer to the question that is represented by the corresponding problem. Unfortunately, for what concerns the answers, in many cases we have no guarantee neither of existence nor of uniqueness. If the former event can be dramatic the later can be even worse since the plurality of answers mixed with the urgency of a problem can impose a sub-optimal solution as the best possible solution. This essentially because a deep analysis of all the possible answers would be too time consuming and those affected by the problem have no such an amount of time at their disposal.
There is also another family of problems that we try to address in this paper, at least from the point of view of environmental problems. This family is centred on the observation that not all the questions are sensible questions and not all the sensible questions have an answer. With this we mean that not all claimed problems are really problems, and so deserve the efforts of finding a solution, and not all real problems can be solved but, in many cases, the status quo or letting things follow their course are the best policies we can adopt.
To solve this problem, so to understand which are the real problems, we can appeal to *SD* as either a descriptive (see section 7.2) or a cognitive tool (see section 7.4).

3 From reality to representations

The starting point is **reality**[6]. Reality is the place where we spend our life and where we experience situations that may range from pleasant and enjoyable to unsatisfactory and disturbing.
Usually no much effort is devoted to the management of situations at the former end of the range[7] whereas those at the latter end of the range are termed as

[4]From a linguistic point of view (Cobuild (1988)) a problem is "a situation that is unsatisfactory and causes difficulties for people."

[5]From a linguistic point of view (Cobuild (1988)) a solution is "a way of dealing with a difficult situation so that the difficulty is removed" but is also an answer to a riddle or a puzzle.

[6]The problem of defining what is meant with reality, if a reality exists or we have a plurality of realities and how can such realities be known and communicated is far beyond the scope of this paper and the possibilities of its author. For our purposes with reality we mean a subjective shared knowledge whose construction is one of the objectives of a process that uses *SD* as one of its tools. One of the aims of this paper is the explanation of what this, more or less exactly, means.

[7]So to make this pleasant and enjoyable experience the more long lasting and shared that it is possible.

problematic and are thought as being worth of every effort to find a solution. The first step is therefore, see Figure 1[8], the starting abstraction from reality

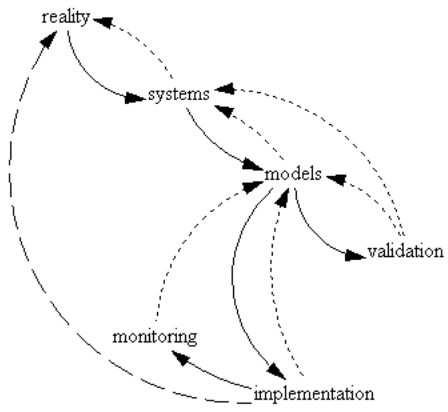

Figure 1: *Abstracting and modelling*

as the "social product of the open interaction of a wide variety of individual subjectivities" (Daellenbach (1994), page 26) to the identification of systems. This first step has no chrism of having either an unique definition or an unique feature since, on one hand, Daellenbach (1994), page 23, asserts that "systems are recognized as human conceptualizations" that do not "exist per se" whereas, on the other hand, Forrester (1994), page 9, asserts that systems are "the nature of the real world".

We think that whenever we deal with the environment (see section 2) the correct approach is the former though in some cases even the latter can be used. We can account for this position with an example from Ford (1999). Let us suppose we want to describe the dynamics of a deer population within a limited area on the basis of a reference pattern of the recorded number of deers along a given time horizon. We want to understand what may have caused such a pattern to understand which policies we can adopt to intervene in what we believe is a problematic situation.

We can decide that for our purposes reality is made of deers (preys), wolves (predators) and the deers' food (biomass) and that these are the ingredients of our system. In this way we are supposing that the only cause of death for the deers is an encounter with a wolf or the lack of food and that wolves depend only on deers for their survival. It is easy to see how this kind of system has no

[8]In Figure 1 with the solid lines we define a feed forward chain of relations from reality to model implementation and monitoring whereas the dotted lines form the feedback loops that allow local or global revisions and the dashed lines denote an effective influence from the element at the tail to that at the head. We note that the graph of Figure 1 does not represent a CLD (sse section 4), since its arcs are not signed, but rather an influence graph where if we have $A \longrightarrow B$ we mean that A influences B. In this case we do not know if between A and B there is a relation of direct or indirect proportionality.

existence per se but depends on the beliefs of a system designer since another system designer may claim that also livestock (that reduce the area available to the deers) and human hunters (that invade the deers' area and disturb their way of living) must be seen as a part of the system and yet another system designer may claim that other factors must be taken into account. Anyway we decide to go on and describe formally our first system. In this way we obtain a model of the system. Such a model can take many forms that range from verbal description to mathematical formulations.
These forms however are almost never in concurrence among themselves since a mathematical formulation (see section 4) is the last step of a second abstraction process that starts with a verbal description and continues with a qualitative analysis. The variable elements are what we do mean with qualitative analysis and what we do mean with a mathematical formulation.
In our prey-predator example we can describe the interactions amongst deers, wolves and biomass (verbal description), identify the relations amongst these elements and the meaningful parameters (qualitative analysis) and derive, for instance, the Volterra's differential equations that describe that system and represents one of its models.
As it is shown in Figure 1, during the definition of a model we may feel the need to revise the definition of the system we are building up and from there widen or shrink the portion of reality we are describing, depending also on the available data (time series or behaviour patterns for instance).
Once the model has been devised we must **validate** it and, if it is the case, both **implement** and **monitor** it.
The validation phase (Ford (1999), page 283) is an art since it is not grounded on any uniform procedure. Since every model is by design (Ford (1999), page 283) a simplification of the system under study it is not possible to validate it. What we can do is either to test a model to invalidate it (Ford (1999), page 284) or to see if it generates god testable hypotheses that are relevant to important problems. Our aim is gaining a confidence in a model and in its results. To do so Ford (1999), page 285, suggests five tests to increase the confidence in a model: verification (or the model runs as intended), face validity (or its structure makes sense), historical behaviour (or its historical input data reproduce historical output data) and detailed model check (comparison with other concurrently available models).
When we have a model that has been validated or proven to be valid (in the sense of Ford (1999), pages $283 - 288$) we want to use it or implement it as a set of policies that, in their turn, influence reality (see the dashed line of Figure 1). We cannot avoid this feedback since if it is absent this would mean that our policies are non influential. Since our policies have no guarantee to be the sole policies acting on reality, however, this feedback may be the cause of failures. Our policies, indeed, act on non deterministic environments (Wooldridge (2002)) that are the product of many concurrent policies whose effects in many cases cannot be coordinated in any way. This lack of coordination is caused by the presence of different and a-priori unpredictable delays and, what is even more important, by possible undesired interactions among the various policies.

This means that policy P_1 may interfere with its effects in an undesired and unpredicted way with another policy P_2 that usually has been designed so to work alone or without any consideration on the presence of P_1 and vice versa. This mean that we can devise a transportation policy that unexpectedly impacts on land use policies for agricultural production and so, in an indirect way, an food production and prices so interfering with other policies in those fields whose design may have been carried out without taking this effect into consideration.
A possible solution is a continuous monitoring of reality that turns in continuous revision of the models with the risk that possible policies are never implemented. This is a real difference since we do not have cognitive feedbacks (such as those represented by solid and dotted lines connected to form closed loops) but "effectoric" feedbacks[9] that alter (in many cases in an irreversible way) the reality from which we extract the systems that we model.
As to our deer-wolves example if we wish to improve the quality and quantity of the vegetation by reducing the deers population we can intervene in many ways with many policies (from selective slaughters to an increase in wolves population) that show their effects with delays that may mask the irreversibility of their effects that can prove to be completely different form what we expected. We can find similar problems whenever we try to model (Gallo (2007)) the diffusion of pollutants (such as DDT or PCB) in the environment, their effects on ground waters and food chain as well as the possible policies we can plan to implement to reduce such effects. If we do not behave carefully whenever we step from policies implemented on models to the same policies on real systems and, for instance, discard or do not appreciate well delays we can miss the target. Our policies fail to attain a reduction of those effects because our understanding of the real phenomena that we embedded in our models was faulty.

4 The main features of *System Dynamics*

4.1 Introduction

The term **System Dynamics** contains two terms that define the scope of the subject: **system** and **dynamics**. A **system** is an organized assembly of components with a global behaviour where each component "contributes towards the behaviour of the system and is affected by being in the system. No component has an independent effect on the system. The behaviour of the system is changed if any component is removed or leaves."(Daellenbach (1994), page 27)
Any system, moreover, has an outside environment (Daellenbach (1994), page 27) that influences its behaviour (through input variables) and that is influenced by the system behaviour (through output variables).

[9] With this term we denote a feedback that directly and physically exert an effect on reality so to leave a permanent print on it with possible irreversible effects. We contrast this type of feedback with information feedbacks that do not necessarily exert an effective and permanent influence on reality.

This definition of a system underline a certain arbitrariness of its definition since we can imagine further links between input and output variables that turn those variables into system state variables and, at the same time, require the definition of a new set of input and output variables. In this way, from a purely holistic point of view, we would turn the whole reality in a single system.
It is necessary therefore to identify a boundary between a system and its environment by discarding as non influential a certain number of feedbacks and, at the same time, define the concept of subsystems as a set of components that have the same properties of the system itself so that they can be isolated from the original system. Formally, if S is a system with environment E and we define a subsystem $S' \subset S$ we obtain $E' = E \cup S \setminus S'$ where the set operations are executed on the sets of components and their interrelations.
When we speak of **dynamics** we mean that we are interested not only in behaviours that change over time but in behaviour that are determined by feedback loops or closed chains of cause and effect. From this perspective we discard problems that are intrinsically static even if they may have dynamic consequences (such as the choice between two routes for a proposed highway, Forrester (1994), page 8) and concentrate only on problems that are inherently dynamics or that can be described by models with feedback loops[10].
Usually the word system is used in conjunction with a specifying word (Cuena and Ossowski (2001)) so that we can speak of **natural systems**, **social systems** and **artificial or man made systems**.
Natural systems obey essentially to physical and biological laws over which little control may be exerted. Such systems tend to show typical behaviours, patterns of behaviour, resilience, inertia and delays and do not admit short cuts that in many cases cause disastrous consequences.
Social systems tend to behave in the same way but for the presence of norms and social laws (Wooldridge (2002), chapter 9) that can dictate and enforce behaviours.
Artificial or man made systems can be more easily tractable since they can be seen as models at different (generally lower) levels of abstraction.
Given a system firstly we want to describe it and secondly we want to know which are the proper questions we can pose about it.
To formally describe systems we aim at identifying both state variables and control variables: the former can undergo only indirect changes whereas the latter can be directly controlled. Such variables define the so called set of world states[11] S with ideal states $S^+ \subset S$ that are almost never achievable (since, generally, environments of the systems are non-deterministic[12]) and undesired states $S^- \subset S$ that the system must avoid in its dynamical evolution.
As to the proper questions (Cuena and Ossowski (2001)) we may wish to ask

[10] Feedback loops are one way of describing such problems but surely are not the only way. Another way could be recurrence equations.

[11] The set S in general may be either countably or uncountably infinite.

[12] We say that an environment is non deterministic whenever the system behaviour depends on it in such a way that the same action in apparently the same conditions can result in completely different outcomes, Wooldridge (2002), page 16.

"what is happening?" (so to analyse a situation and identify either problematic or advantageous aspects), "what may happen?" (so to identify possible evolutions in absence of any intervention towards an undesirable future), "what may happen if ..." (so to identify possible scenarios, see further on) or "what should be done?" (so to define possible policies for the improvement of a system operation).
If we are able to identify problematic features[13] or symptoms that something is going wrong in the system we are describing we can use SD to put in evidence such symptoms and SD models to execute a diagnosis as an explanation of the causes of the undesirable behaviour (Cuena and Ossowski (2001)). In this way (Cuena and Ossowski (2001)) we can define a **prediction task** (that determines the evolution of the model through the control variables), an **option generation task** (that may overcome the problem) and an **action selection task** that allows the definition of possible interventions.

4.2 The SD perspective

SD looks at reality from an holistic point of view so that reality is seen as a complex web of interrelated components that influence each other and also themselves through causal closed chains or loops. From this perspective, SD aims at defining **models** of **systems** as abstract representations of portions of reality.
A given portion of reality reveals itself through phenomena that can be described and that can represent problems that must be someway solved.
Within this framework, SD tries to identify some entities that can be used to describe the phenomena of interest and their interactions through causal chains. The real explanatory power of SD resides in the shift from linear causal chains to closed chains of both positive and negative feedback loops.
In this way SD defines the so called **causal loop diagrams** (CLDs) as models of systems that are abstract and simplified representations of portions of reality.
The next step involves the definition of the relations between our portion of reality, that we are trying to describe as a system through a model, and its external world and a characterization of the various entities we want to use to describe the model.
For this purpose we define the types of the needed variables in order to characterize conservative material flows and non conservative information flows in graphical models that represent graphically differential equations by using level variables as well as flow, auxiliary and constant types variables.
In this way we can define **stock-flow diagrams** (SFDs) representing systems where external world exerts its influence on the model through either exogenous variables or levels' initial values as opposed to endogenous variables that form the heart of the model.

[13]We do not enter in details neither on the fact that this requires that we know the right or proper behaviour nor on the definition of for whom the behaviour is problematic, why and at which extent.

SFDs can be used to model differential equations of any order that are simulated continuous time with difference equations by fixing an initial/final time and a time step.
In this way we can obtain the characteristic time trajectories of all endogenous variables, trajectories that can be compared with available data, measured on the portion of reality we are trying to model and that represent our reference patterns: if our variables succeed in reproducing such patterns within a small error we can validate the model otherwise a more or less deep revision process of the model is required up to a full redesign of the model itself and of its interactions with its outer world (see section 4.3).

4.3 The model building process

Once a system has been identified it is necessary to build a model of it. We can find a sort of recipe of the model building process in Forrester (1994), page 4. The starting point[14] is an undesirable system behaviour that must be understood and corrected. To do so we must describe the relevant system and convert that description in a SFD with the necessary equations. The next step is the model simulation followed by the design of policy alternatives and structures that form the base for an education and deliberation phase until a consensus is reached on the policies to be implemented. As a last step the chosen policies are implemented. This process is not linear from the start to the end and is characterized by a lot of feedback loops from almost every step to any other so that it is necessary to fix either a time bound or some strict performance measure[15] to prevent it from being endless.
Another more environment oriented recipe can be found in Ford (1999), pages 171-178. The recipe proposed by Ford (1999) starts from the necessity for the model builders to get acquainted with the system since a model must be the product of cooperative efforts[16]. It is therefore important to be specific about the dynamic problem by drawing graphs over time of the important variables and summarize why people are dissatisfied with the system performance[17]. Then the process goes on with the definition of SFDs and CLDs in this order (or in the opposite, depending on builders' tastes) followed by the estimation of meaningful parameters[18], possibly with the help of some experts. The last steps are the simulation of the model, so to verify that it is able to reproduce

[14]We cannot criticize such a recipe point by point so we only describe it. It should be interesting to understand for whom a behaviour is undesirable and why, so to start.

[15]Both these features tend to introduce some arbitrary constraints in the process. Who fixes the time bound? How? Who fixes the threshold value of the performance measure and how? And so on.

[16]We think that in this case what is missing is the first abstraction step from a reality to the corresponding system.

[17]Again we find here some missing abstraction steps regarding the definition of performance measures, the meaning of bad and who, why and how perceives something as bad.

[18]The step of parameters definition is not explicitly mentioned and it may be supposed to occur in the diagrams definition phase.

the reference mode[19], and the sensitivity analysis to see if the model is enough robust to produce the reference mode even with variations of the values of the parameters. The final step is the test of the policies through variations of the policy variables (that have been defined in this way at the level of problem definition) so to see if the designed policies cause the desired variations in the problematic behaviour. Sensitivity analysis and policies testing differ since in the former case we modify the values of uncontrollable parameters whereas in the latter we modify the values of controllable policy related parameters. Again the process is iterative in nature and to be sure it comes to an end we again must impose outer constraints in time or performance measures.

4.4 Qualitative and quantitative analysis

Though Forrester (1994), page 10, affirms that "all systems have the same fundamental structure of level and rates (accumulation and flows)" qualitative analysis under the form of *CLD*s may represent the best starting point whenever the model building process involves stakeholders and actors that have no training or expertise in *SD*. Again Forrester (1994), page 12, state that *CLD*s

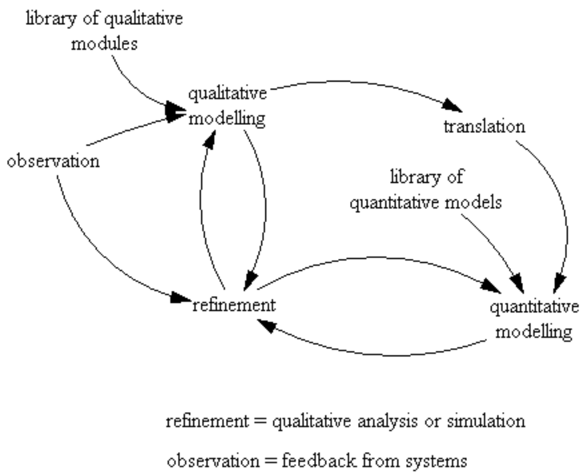

Figure 2: *Qualitative and quantitative analysis*

can be useful only after the model has been built so the the builders can explain it but that, from the beginning of model conceptualization, it is necessary to start with the identification of system levels and then the rates that cause those levels to change.
Other authors (Binder et al. (2001)) propose *CLD*s as good starting point for system modelling and tools for detailed system description or as ways to contain

[19]We can see the reference mode as representing the whole set of recorded data that identify the problem at stake.

verbal descriptions of people's understanding of a problem or a process (Burns (1979?)) and, at the same time, propose tools for their translation into SFDs (Binder et al. (2001) and Burns (1979?)) as a necessary step for their simulation. In this way (see Figure[20] 2) it is possible to bridge the gap from qualitative modelling (the basis of qualitative analysis) to quantitative modelling (the basis for quantitative analysis). In Figure 2 we put in evidence the roles of **observation** of systems evolution over time and of **refinement** through either simulation (quantitative modelling) or qualitative modelling. Refinement is a two way link between the two types of modelling but translation is the necessary step to effectively pass from a qualitative model to a quantitative one.
Last but not least in Figure 2 we have introduced the use of library of off-the-shelf modules (to be used in the design of qualitative models to implement typical behaviours such as exponential growth, exponential decay, oscillating behaviours and sigma-shaped behaviours.) and models (to automatically translate the aforesaid modules into quantitative terms).

5 Actors, experts and stakeholders

Since we aim at presenting a critical analysis of SD we start from a somewhat distant perspective. Using Biswas (2007) we can define an **actor**[21] as an entity that performs some **actions** (as fundamental units of behaviour) based on some perceptions. An **activity** is a task that an actor, that can play one or more roles, needs to perform to fulfil one of his roles. An activity is generally composed by a set of actions. Activities can be executed either in sequence or, if they are independent, in parallel. Once actors and activities have been defined we can define a **scenario** as the specification of a set of activities performed by interacting actors.
Actors (Biswas (2007), page 5) can be seen in scenarios and endowed with roles and responsibilities. We note that each role is defined in terms of the composing responsibilities and that in the environment we can imagine a set of roles and responsibilities that can be arranged and assigned in the proper ways. From this arrangements and assignments we can derive a certain number of behaviours.
Within this framework actors are the outcome of a process of abstraction that allows their characterization only on the basis of meaningful roles and activities. We therefore see actors as entities that work within a context (determined by the actions of the other actors). Actors can:

1. collaborate or work together for a common effort;
2. cooperate or work together for a common purpose;
3. coordinate or bring into common action, movement, or condition;
4. negotiate or discuss the terms of an arrangement;

[20] The links of Figure 2 represent influence relations.

[21] In many cases we are going to use the word decider (decision maker) as a synonym of actor.

5. compete to gain a personal advantage at the expense of others.

We note that the actors we have defined in this way either keep this role or assume one of two other roles: **expert** or **stakeholder**. In this way we have three non disjoint categories that may be even embodied in the same person. A decider (see further on) may be an expert in some field and a stakeholder living in a certain area. On the other hand if we restrict the scope of a decision process every stakeholder may be a decider and if we widen the scope of a decision process an expert may see his expertise boil down to one of the many expertises in the playground.
Each actor, in the simplest case, acts on the basis of a certain number of generally private data (Biswas (2007), page 5) such as:

1. beliefs or facts;

2. desires or what each one want to reach (his goals);

3. intentions (or how each actor wants to reach his goals).

Such data represent the input of a SD model building process and must be, at least partially, shared if that process is to produce a model that is approved by all involved actors.
A more classical SD oriented perspective can be found in Daellenbach (1994), page 87. Daellenbach (1994) focuses his attention on a certain number of problem-centred categories such as **problem owner**, **problem user**, **problem customers** and **problem solver**. A problem owner (usually a decider) has control over certain aspects of a problem situation and over the choice of the action to be taken. According to Daellenbach (1994) there may be hierarchies of problem owners that are delegated to perform some choices and to control some subsystems. A problem user is who uses a solution and/or executes the decision approved by the problem owner. Problem customers are either the beneficiaries or the victims of the consequences of using a solution. Within this model they have no possibility to oppose but they can only complain. Last but not least a problem solver has the duty to analyse the problem and develop a solution that must be approved by the problem owner. In this way we have a strict hierarchy where the stakeholders (or problem customer) have almost no real power. Moreover Daellenbach (1994), page 88, states that who are the relevant stakeholders become clear only after the relevant system has been defined. In this way it could possible to properly define the set of stakeholders so to obtain a wide group of supporters that approve the proposed solution. Last but not least Daellenbach (1994), page 91, states that "for a problem to exists there must be an individual (or group of individuals), referred to as decision maker, who is dissatisfied with the current state of affairs", has some goals or objectives, knows how to measure if such goals have been achieved and how and can control "aspects of the problem situation that affects the extent to which goals or objectives can be achieved". Again we have a top down approach and no possibility that problems are raised directly by stakeholders that must follow an indirect path.

Another approach has been proposed by Richardson and Andersen (1994?) that propose the definition (page 1) "of five roles or functions" for the support of "effective group model building efforts". Such roles are the **facilitator**, the **modeller/reflector**, the **process coach**, the **recorder** and the **gatekeeper** and should be embodied by people that support members of a group for a rapid and effective model building process. We think that these roles can play an important role in helping a group of actors to build a model for the solution of a problem. From this perspective we can imagine actors, in the broader sense of the word, playing such roles. What we think is missing from that approach is what comes before a model building process starts and what comes after, when the model has been built and political decisions must be taken by the deciders, validated by the experts and accepted by stakeholders.
In this paper, therefore, we present a somewhat different perspective since we do not want to limit ourself to the modelling phase (Richardson and Andersen (1994?)) or to adopt a hierarchic problem-centred approach (Daellenbach (1994)). In the spirit of SD we indeed propose a holistic approach where we cannot discard any point of view or any perspective or any role and, moreover, proceed both bottom up (from stakeholders to deciders) and top down (from deciders to stakeholders).
Environmental problems[22] involve people at various decision levels and timings (van den Belt (2004)) both as individual and as groups. At each of these levels people involved can belong to one or more of the following (non disjoint) categories:

1. actors A,
2. experts E,
3. stakeholders S.

Actors represent people that has the political and/or economical responsibility of taking decisions in all the phases, from the design to the implementation to, maybe, monitoring and evaluation. Such decisions tend to influence the lives and interests of **stakeholders**, since they cause a change in the status quo, and are taken with support of the **experts** (see further on in this same section) from various fields. Among the actors there may be some of them that benefit from the "privilege" of having the real power over the decisions to be undertaken, we call them **real actors**.
Actors are usually part of hierarchical structures so that they have natural timings and levels of involvement in a decision process. Stakeholders involvement, on the other hand, can occur at various levels and timings of a decision process (van den Belt (2004)).
Actors and stakeholders tend to form coalitions of proponents and opponents in a decision process and such coalitions involve experts as possibly biased opinion makers that, in this role, may be more a hindrance than a help since they may act as unquestionable authorities that hinder the creative search of solutions

[22] See section 6 for a discussion of the terms problem and solution.

from both actors and stakeholders. Experts, see Gordon (1994) Dalkey (1969) and Kluver et al. (2000) among the many, indeed should be involved in a neutral and possibly anonymous way so to provide the technical ground on which the search for solutions should move.
We note how **experts** (Cuena and Ossowski (2001)) usually elicit different and even contradictory knowledge and reasoning methods. They use ontologies[23] (Wooldridge (2002), page 180) that may subtly conflict among themselves and confuse stakeholders that, generally, do not posses any of those ontologies but make use a common sense empirical knowledge base. This can belittle the power of SD as a cognitive tool since the opinions of the experts are no more a shared base of knowledge but a source of confusion.

6 Problems and solutions

A problem is usually seen (Daellenbach (1994)) as an undesirable performance behaviour pattern. Within our framework a problem is, more properly, a perceived bad situation. We can say that if there is no perception of a situation as being bad there is no problem and no need to devise a solution so that the status quo is guaranteed to go on with possibly minor adaptations and redistributions. In this sense a problem is either a failure of the status quo or an evolution of the status quo in a direction that is perceived as negative with respect to a desirable outcome. In both cases an alignment process is needed with more or less urgency. The [not only] key point is **perception**. Perception can be from either a subset of actors or a subset of stakeholders or even from a set of experts. Problems are, indeed, characterized by:

1. their level of perception,
2. their level of urgency,
3. their scope both in time and space.

Once perceived, problems must be defined more or less formally. At this point, problems claim for solutions. **Solutions** are represented by policies that guide the evolution of a system toward a desired goal. This guidance can be either top-down or bottom-up directed (Elliot et al. (2005), van den Belt (2004), Pareglio et al. (1999)). Here we have one of the many trade-off of any decision process: quicker decision processes usually turn into longer implementation phases owing to resistances posed from those stakeholders that feel to have been unduly excluded from the process, whereas longer decision processes might be followed by quicker implementation phases because all stakeholders agree on the undertaken decisions and perceive them as fair and envy-free (Brams and Taylor (1996)).
As to the **level of perception**, we denote the perception from either [some of] the actors or from [some of] the stakeholders or from both. Such types of

[23] An ontology (Wooldridge (2002), page 180) is a formalized definition of a body of knowledge and a set of methodologies.

perception do not weigh the same and are guided by distinct goals and time-scales. Anyway for a problem to be perceived as such, a "pain threshold" must be exceeded, where such a threshold is usually problem-dependent and can be manipulated at various levels.
The **level of urgency** defines the possibility of real planning. If this level is high no participative and consensual planned solution (Butler and Rothstein (2004)) is usually possible but authoritative and top-down solutions are imposed by the **real actors**. The main issue is that, in many cases, mainly when the perception level of a problem is low, the situation is let free to evolve uncontrolled until the crisis is so near that the urgency level is raised, the perception is favoured and a last minute emergency solution is imposed.
We can mention as examples the oil crisis and the policy of biofuels development, the methane crisis and the project and implementation of re gasifying plants, the problem of traffic jams and the construction of new highways, the environmental pollution caused by trucks traffic and the need to build new high capacity railway lines and so on.
Last but not least the **temporal or spatial scopes** contribute to the definition of the proper actors and stakeholders. It is obvious that, with respect to a problem and its potential solutions, not all stakeholders have the same benefits and suffer the same costs and, in a similar way, not all the actors can exert the same decisional power and influence.
Discarding emergency driven solutions, given a perceived problem where a planning process may be carried out usually a more or less wide succession of sets of solutions can be devised[24]. At this point all these solutions must be ranked according to the many different criteria that have been proposed until when one is chosen to be implemented[25]. This is the true hard part since both tangible and intangible goods enter into play and multiple criteria may be advocated (Vincke (1989)).
At his level the question of the feasibility of each solution is posed as well as the comparison between bad and good solutions (with respect to what? or to whom?) and between rigid and flexible solutions (Collingridge (1979), Collingridge (1983)). Both flexibility and rigidity must indeed be seen as referring to the costs that are caused by an abandoning or a radical change of a solution that proves highly negative according to commonly recognized criteria or to the perception of those who have posed the problem.

[24] The whole process, if we include also the monitoring and evaluation phases, spans generally over more or less long periods of time ranging from some weeks to months and even years. During these periods many solutions may rise and fall many times, others may evolve and be modified and so on. We therefore speak of a succession of sets of solutions.

[25] Criteria can depend on social, legal or technical norms but can also be designed, implemented and agreed on by all those involved in a decision process so to filter out the invalid solutions or those solutions that do not satisfy the agreed on criteria.

7 The various roles of SD

SD can play various and different roles in the interactions among actors, experts and stakeholders for both the definition of the problems and the search for solutions. The usual role is that of a faithful and neutral representation of reality in the hands of the experts that claim, in this way, to have the only real knowledge of a problem and the only right solution so that all the others involved subjects can only approve without any dissent. Fortunately this is very seldom the case and there is a wide area of manoeuvres for the design and implementation of consensually defined solutions (Elliot et al. (2005), Butler and Rothstein (2004)). As a basic form of knowledge, in the following subsections we are going to examine such roles so to start a discussion on each of them.

7.1 SD as a normative tool

The distinction[26] between **normative** and **descriptive** decision theory has been posed in Rapoport (1989) as a distinction between "what ought to be" in a normed world and "what it is" in the real world. We use such a distinction here between SD as a normative tool and SD from other perspectives among which we pose a descriptive role.
Sometimes SD is indeed used as a normative way to approach reality. As it is shown in books such as Roberts et al. (1983), Kirkwood (1998) and others in this stream of thinking, it is tempting to say that reality behaves as it is imposed by a model so that, obviously, if we modify some parameters of a model a necessary set of consequences will occur and reality will submissively bend. This attitude derives from hard sciences such as physics, mathematics and engineering, very apt at working with complicatedness more than with complexity[27], but it is out of place with regard to environmental problems that require a multidimensional and multidisciplinary approach.
This point of view may be legitimated both from the use of hydraulic metaphors of levels and flows within our SFDs and by the fact that our SFDs represent graphically differential equations.
Given that the outer world is correctly represented by a set of manageable variables whose influence can make the system behave in some predictable ways and given that these ways are governed by well posed differential equations it

[26] We also refer to Merriam-Webster Online Dictionary that states that one of the meanings of descriptive is "2 a: referring to, constituting, or grounded in matters of observation or experience ("the descriptive basis of science") b: factually grounded or informative rather than normative, prescriptive, or emotive ("descriptive cultural studies"). The same source gives for the word "normative" the following meaning: "prescribing norms" where a "norm" is either "an authoritative standard" or "a principle of right action binding upon the members of a group and serving to guide, control, or regulate proper and acceptable behaviour".

[27] The main difference between a complicate and a complex issue is in the number of involved dimensions. A complicate issue involves one dimension (time or space for instance) whereas a complex issue involves more that one dimension and all the interrelations between these dimensions. In the latter case we cannot apply an independence or an additivity principle so to use the various dimensions in isolation and mix together the results but we are forced to examine all the various dimensions at the same time.

seems obvious that the future is strictly determined. Unfortunately (or fortunately depending on one's point of view) this is not the case within the search for solutions of environmental problems since every abstraction process through which we define the boundary of our system, the exogenous variables and the endogenous variables with their mutual links defines something that has no normative power.
With this we mean (Rapoport (1989)) that models have no power either on systems or on reality since there is no link between a symbolic representation and its physical counterpart not even on the behavioural level.

7.2 *SD* as a descriptive tool

After having criticized and questioned the use of *SD* as a normative tool we examine it as a descriptive tool. From this point of view *SD* can be very valuable since:

1. it allows the experts to state their proposals both to deciders and stakeholders;

2. it allows deciders to explain their proposed policies to stakeholders and experts to verify if they are sound, convincing and acceptable[28];

3. it allows the stakeholders to oppose on a firmer ground to the proposed policies since their damages outweigh their benefits.

If a system that is thought to suffer some problem is described by a *SD* model it is possible (see section 3) to use a qualitative approach or a quantitative approach.
In the former case the model builders[29] may use *CLD*s so to establish qualitative feedback relations among meaningful quantities that describe the system under scrutiny.
In the latter case they (Forrester (1994), page 12) can start directly with *SFD*s that needs the adoption of a more quantitative approach rightly from the start. Though Forrester (1994) says that the latter approach is preferable other authors believe that it is possible to start from *CLD*s, since they are more easy to understand and master for non experts, and then translate them in *SFD*s without any loss of information (Burns (1979?) and Binder et al. (2001)).
Beyond the aforesaid potential advantages this approach may however suffer severe drawbacks in all cases where the degree of participation of stakeholders is

[28]From Merriam-Webster Online Dictionary we have that **convincing** means "having power to convince of the truth, rightness, or reality of something" whereas the same source states that **acceptable** means "capable or worthy of being accepted". As to the term **sound** from that source we take it as meaning both "free from error, fallacy, or misapprehension " and "agreeing with accepted views" since these are the meanings that more agree with our framework. It is obvious that these features are independent among themselves and can be present or absent in any combination.

[29]Depending on the adopted approach, van den Belt (2004), model builders may be either experts or deciders or stakeholders or any mix of these groups.

low (van den Belt (2004)) and their timing of participation is late since all that they can contribute is a feedback or a set of observations to experts' proposals that, usually, have to pass only stakeholders' acceptance but actors' filter.
We note indeed that in many even democratic decision processes actors are never put aside whereas this can happen with normal stakeholders. This can legitimately happen since the former bear political and administrative responsibilities whereas the latter can only use their vote power to punish the actors but have no veto power.
Notwithstanding these potential limits in this role *SD* may help in the search for solutions to environmental problems since it forces the experts to explain their ideas and show how they are supposed to act on the problem under scrutiny. On the other hand it may be a hindrance since any model is posed as an objective and unmodifiable reality that must be accepted because it has been elaborated by "real experts".

7.3 *SD* as a prescriptive tool

Once we accept *SD* as a descriptive tool it is easy to see how tempting can be to use it as prescriptive[30] tool or as a way through which the experts show how to act so that reality can be modified according to certain wishes so to solve the problem under scrutiny.
As a prescriptive tool *SD* can be used to show the utility of plants such as incinerators, dumping grounds, high capacity/high speed railway lines and so on. By properly building *SD* models of such plants experts can prove their positive effects on the environment by discarding undesirable effects or by not mentioning that the data on which the models are grounded are fuzzy predictions.
The main problems with this approach can be found at various levels.

1. At the level of the model itself. Once a model has been devised, validated and accepted by its users[31] it may be possible to show how acting on some parameters from a given set (the so called control variables) it is possible to modify in a favourable way its behaviour.
   In this way it is possible to "prove" how a bad situation favourably modifies and the original problem is solved. Unfortunately if this is true for the model it is usually far from being true for the system the model refers to. It is necessary indeed to gap the bridge between the model and the system and the context of the system itself or, in other words, to define and implement real policies and, at the same time, evaluate and monitor their effects. Evaluation and monitoring, in their turn, may involve either an adjustment of the policies or even the start of a model revision phase.

[30] Merriam-Webster Online Dictionary states that the word "prescriptive" means "serving to prescribe ("prescriptive rules of usage") where "prescribe" means "to lay down a rule".
[31] Model users are those who uses the model to derive decisions and policies. From this point of view they are the actors or deciders. A model can be also used by the stakeholders to oppose to such decisions and policies and even by some experts as a way to prove that some other experts are wrong and why.

2. At the level of stakeholders. Stakeholders can on one side be fascinated by the technicalities of the models but on the other hand may feel to have been excluded from any real decision process and to have only residual possibilities of intervention through marginal observations.
   From this perspective *SD* is seen as a tool to convince the stakeholders that the solution devised by the actors with the support of a group of experts is surely the best one given a objectively fixed set of economical, technical, political and even scientific constraints.

3. At the level of the experts. Experts usually do not form a compact and homogeneous group but are often divided in cliques that, though grounded on the same cultural background, may provide opposite recipes for the solution of the same problem. This may happen since each clique uses different data sets, interpret them according to different criteria, sees the same problems from completely different perspectives and may even denote with the same name objectively different problems. In this case it is possible to benefit of *SD* as a cognitive tool but if we pretend it to act as a prescriptive tool we are sure that problems will arise.

7.4 *SD* as a cognitive tool

SD is a way (Forrester (1994) and Sterman (2001)) to fruitfully use *System Thinking* since it allows us to think about systems, talk about systems and acknowledge that systems are important within a formally sound framework. In this way (Sterman (2001) page 9) we can understand which actions we can perform and which effects we can expect form those actions.
From this perspective *SD* is a "method to enhance learning in complex systems" (Sterman (2001) page 10). This is the first way in which *SD* can play the role of a cognitive tool.
Another way is when *SD* helps understanding "the sources of policy resistance and design more effective policies" (Sterman (2001) page 10).
Both these ways involve *SD* as a modelling tool. The way we are more interested in is where *SD* helps actors, experts and stakeholders to know each other better so to know and understand each other's beliefs, desires and intentions (see section 5). This way gains an even greater importance in the area of environmental problem solving.
The search for solutions to environmental problems, indeed, is an interplay among actors, experts and stakeholders[32] where each category has hidden assumptions, attitudes that hide the real motivations, biases but also values and interests to protect and goals to pursue.

[32]We note in passing how even both the environment and the "future generations" should be involved in the interplay, maybe with the use of middle men that could defend the interests of those categories during the decision process. Without this minimum guarantee it could be possible to decide the disposal of nuclear wastes in "secure" repositories or the CO2 underground or underwater capture even through perfectly correct and full consensual decision processes.

Within this framework SD can be used (van den Belt (2004)) so that actors, experts and stakeholders can gain a better reciprocal understanding of each other, of the problem under scrutiny and of the proposed solutions.
The availability of formal models, to be iteratively refined and modified, has also the following beneficial effects:

1. it forces all the parties involved at making explicit their hidden assumptions, giving up with attitudes and showing the real motivations;
2. it allows the discovery of any bias about a problem and its possible solutions;
3. it allows all the parties the expression of their goals;
4. it provides a common ground for the expression of policies and their evaluation.

For all this really to happen it is necessary that actors and stakeholders are involved very early in the process and are put in the position of building their own models with the guide of experts, evaluate and validate them so that any solution can be seen as a collective undertaking. In this way maybe the decision process may last longer but the implementation phase will almost surely run smoothly (Butler and Rothstein (2004), van den Belt (2004), Elliot et al. (2005) and Kluver et al. (2000) among the many).

7.5 SD as a meta tool

Both the solution discovering process and the planning process can be seen as systems (Saaty and Kearns (1985)) and so can be described through the use of models.
In this sense they can benefit from the use of SD that, in this case, acts as a meta tool since it allows the definition of a model of a model. We claim that this single step is enough, so there is no real danger of an infinite recursion, since the model of a model is a sort of fixed point in this process. We can see an example of this use in Haraldsson et al. (2006), page 4. In that paper they state that a CLD "reflects the understanding of a problem" so that "the problem definition and the question asked concerning the problem are reflected in the CLD". In this way if a model is being built by a group of people it may happen that the different participant have different mental models of the problem and related issues. They can therefore use the qualitative tools of SD such as CLDs to build a shared mental model for all the members of the group. That process is implemented with the so called "learning loop" (Haraldsson et al. (2006), page 4) and starts from a "Question" that is the hypothesis for the group and is either "verified or refuted through a series of iterations" (Haraldsson et al. (2006), page 4) in the learning loop[33]. If SD is used as a meta tool in either

[33] In Figure 3 we have defined a signed CLD with arcs denoting both direct proportionality (and marked with a $+$ sign) and indirect proportionality (and marked with a $-$ sign). We have also signed the feedback loops as positive or reinforcing ($+$) or negative or dampening ($-$).

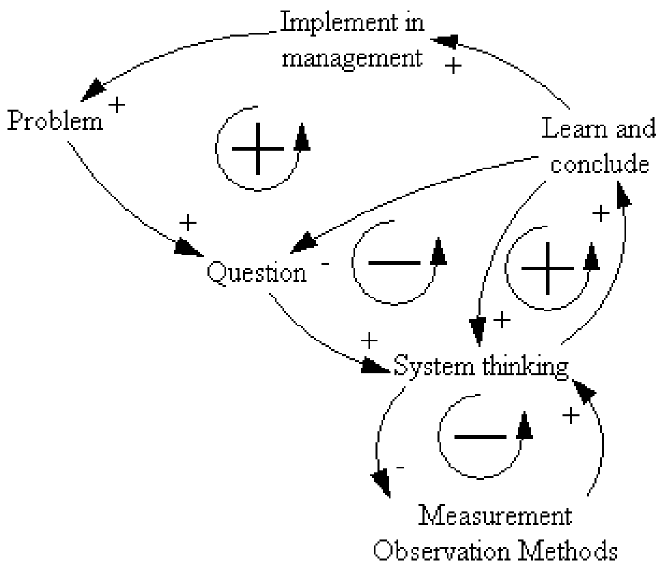

Figure 3: *The learning loop, from Haraldsson et al. (2006)*

a qualitative (through CLDs) or quantitative (through SFDs) way it may be possible a monitoring of the decision process to understand:

1. if it is effective i.e. it is going on towards the desired goal;
2. if the times and agendas are respected (since no process can last forever or turn in a pure waste of time owing to filibustering that, in practice, prevent the undertaking of any decision);
3. if all the parties are correctly involved and informed and none keeps hidden assets;
4. if all the parties participate in the process without exerting any kind of dictatorship and having the possibility to expose ideas, plans, values and goals in a respectful setting (Butler and Rothstein (2004)).

Similar considerations hold also for the design of monitoring and evaluation phases (that can turn in a redefinition of the problem itself and of the adopted solution, Collingridge (1983)) since such phases must be carefully designed and executed so that no false solution can be devised.

8 The various arenas

The process that may lead to the [partial] solution of environmental problems may last very long, from weeks or months up to years with the involve-

ment of permanent administrative structures such as an **environmental forum** (Pareglio et al. (1999) and Elliot et al. (2005)) as a structure that fosters the widest public participation to the various phases of a decision process for the solution of environmental problems.
During this hopefully creative period actors, stakeholders and experts meet many times in many places and at various levels. We can define these meetings as sessions or **arena**s since they are places where conflicts crop up and must be settled (Butler and Rothstein (2004)) so that the overall process can progress within a consensual framework.
In all these occasions SD can profitably play its roles of cognitive tool and meta tool but, within a consensual process (Butler and Rothstein (2004)), can be used also simply as a descriptive or prescriptive tool.
Within **technical arenas** experts can use SD as a descriptive tool to show how a problem may be faced from a particular perspective or expertise.
Within **political arenas** actors can use SD as a prescriptive tool so to explain the potential effects of a proposed policy and to get a feedback from stakeholders to such policy without disregarding the interactions among the various policies that are being planned to solve a given problem.
Within **critical arenas** stakeholders scrutinize the possibly proposed models, design their own models and evaluate the proposed policies and propose their own policies. In this case SD is used mainly as a cognitive tool.
Every category is in charge in any such types of arena but in any case the goal is the construction of a shared knowledge so that any solution can be reached at the end of a consensual process.
Last but not least, in **procedural arenas** SD can be used as a meta tool to evaluate the quality of the decision process and its effectiveness with respect to the goal and the various constraints posed by the problem under scrutiny.

9 Help or hinder, this is the question

At this point it should be clear how SD, in its various roles, does not represent a neutral tool but, rather, a way to look at problems and their potential solutions by wearing potentially distorting glasses.
SD can therefore represent both a powerful tool for reaching a consensus and shape a solution (a help) and a mind cage and a monkey trap[34] (a hindrance). In the former role SD is a valuable tool to help staying on tune with the problem and finding real and effective solutions. In this case experts (and SD experts

[34] A monkey trap is a mental situation that traps the decider so that he is able to imagine only one possible course of action that causes him a great loss that could be avoided (and substituted with a great benefit) through a small shift in perspective. It refers to the use of simple traps for catch of monkeys. Such traps are made by a cavity containing some appetizing food. A monkey can reach the food by entering in the cavity with an open and but cannot escape from it with his hand closed to hold the food. In this way the monkey is easily caught by the hunters and generally killed. To save his life he monkey should simply open his hand and leave the food in the cavity but this simple action is out of her imaginative capacity so that he loses his life.

too) work as a supporting team that tries to keep wishful thinking under control and maintain the decision process on route.
We strongly believe that all this can be accomplished in an indirect way by using SD as a descriptive and cognitive tool since in these roles SD can show its real expressive power in the attainment of a deeper and shared knowledge of the problem that actors must address and solve. We can state that the solutions are not in the model but models can help in finding them. This holds also when we use SD as a meta tool.
In the latter role SD can be used to produce premature solutions, though technically correct, but that reduce creativity and hide better solutions since an objective solution has already been found out without any possibility to discover it is, on the contrary, suboptimal.
All this can happen if experts (including SD experts) play a too strong and binding role and do not resist to the temptation of devising complex and detailed models already from the initial stages of the process. Even if such solutions may seem correct and be able to explain observed data they may prevent the definition of more creative and better solutions.
Unfortunately there is no general way to understand if SD is acting as a help or a hindrance: an evaluation is needed case by case and requires a careful examination of the under way process.
As a general rule we can state that:

1. actors tend to favour short processes and so "pre-cooked" models (and from this perspective they seem to favour SD as a hindrance) since they tend to enter a decision process with a small set of predefined and preferred solutions and wish such solutions be approved as soon as possible so to be quickly implemented;

2. experts have no objection to long professional assignments since these turn into high fees that can be easily justified by the complexity of the decision process;

3. stakeholders' attitude depends on the perceived urgency of a problem but they may be trained to participate in [long] consensual processes and, therefore, to favour SD as a help.

10 Some partial and tentative conclusions

In the present paper we tried to show how SD is not a neutral set of recipes that, given a problem, allow a group of actors to analyse it and find proper solutions that satisfy a certain number of acknowledged criteria.
From this perspective we presented and discussed the main characteristics of SD, the roles it can play, where it can play those roles and who are the categories of people (the actors, experts and stakeholders) who can benefit from all these features.
We therefore tried to present a framework where SD is only one of the meaningful elements that can be of great help in knowledge sharing and improvement

among the actors but can also be a hindrance since it may tend to freeze reality into the "objective" schemas of models. We note indeed that models can account for dynamics but cannot cope with non deterministic environments.
Within that framework we tried to foster what we think are the meaningful roles of *SD* and so those of a **meta tool**, of a **descriptive tool** and a **cognitive tool**.

11 Final remark and thanks

The topic of the roles that *SD* can play within decision processes, even if we restrict it to environmental problems, is too vast to be fully examined in a single paper and this paper is not an exception. What I have presented here is essentially a set of considerations that will be part of the my PhD Thesis "Methods and Models for Environmental Conflicts Analysis and Resolution", considerations to be probed and enriched with real world cases.
I wish therefore to thank my tutor, Professor Giorgio Gallo from "Dipartimento di Informatica" of "Università degli Studi di Pisa", who accepted to run the risk of taking on the task of super visioning my Thesis, for his countless suggestions and corrections.

12 System Dynamics and System Thinking

In this section we rely on Richmond (2001) and Forrester (1968) for some general comments on System Dynamics and System Thinking.
The starting point is the concept of **system** (Forrester (1968)) as a set of parts working together for a common purpose. When the number of such parts is high as well as their interconnections we speak of **complex systems** whose behaviour may be:

1. counter intuitive and
2. highly non linear

so that a sound understanding of their behaviour under different circumstances can be hardly predicted with accuracy.
This usually occurs since when we build **mental models** of [complex] systems we tend to make the following general assumptions or (according to Richmond (2001)) "meta assumptions" when describing the relations of a certain number of causes or factors on a given effect or outcome (see Figure 4):

(1) causes act independently one from the others,

(2) there is no influence from the outcome on any of the causes (no feedback),

(3) there is no delay so that causes act instantly and all together,

(4) causes exert a linear influence on the effect.

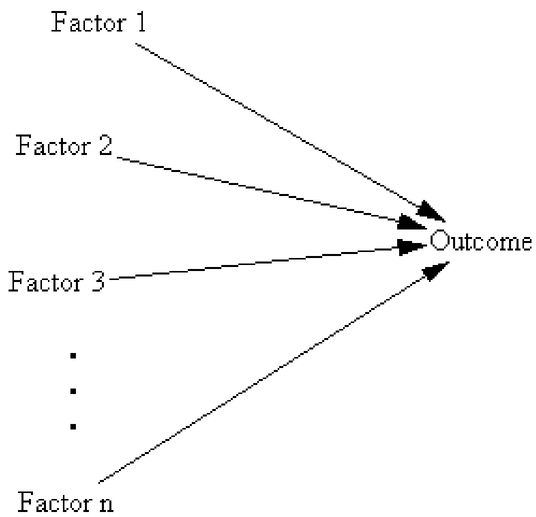

Figure 4: *Open loop thinking, from Richmond (2001), page 9*

We note that "meta assumption" (1) can be paraphrased as follows: we vary the cause **Factor i** all other causes being at a constant value or "all else being equal". This hides the assumption that **Factor i** does not influence any other cause so that a variation of **Factor i** can only influence directly the outcome and not indirectly it through some direct influence on any other cause such as **Factor j**.
"Meta assumption" (2) means that there is no influence from the outcome on the decision process so that there is no possibility of a monitoring or of a control of the effects of any action on the actions themselves since there is no return of information from the effect to one of the actions that caused it.

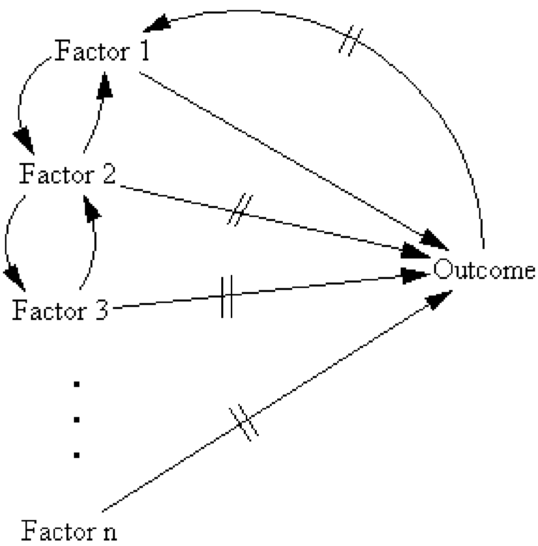

Figure 5: *Closed loop thinking*

"Meta assumption" (3) means that any action exerts immediately its influence on the outcome so that material flows can instantly cover any distance and any variable can adapt its behaviour to any needed change.
Last but not least, "meta assumption" (4) means that if we double the strength of a factor we double the size of the corresponding outcome. This relation can be translated as[35]:

$$y(t) = kx(t) \tag{1}$$

where $x(t)$ is a representation of the cause with time, k is a constant of proportionality and $y(t)$ is the representation of the corresponding effect. In case of

[35]We note that $y(t) = kx(t) + m$ does not represent a linear system (if $m \neq 0$) since (1) we could have an output even without any input and (2) the principle of superimposition of effects is violated. Actually $y(t) = kx(t) + m$ is an affine transformation.

more than one cause we could write something like this:

$$y(t) = \sum_{i=1}^{n} k_i x_i(t) \tag{2}$$

so that we can isolate a cause from all the others by posing $k_j = 0$ but for the $i-$th cause we want to analyse.
We note that "meta assumptions" (1) and (4) are at the basis of linear system theory with its principle of superimposition of effects.
A more complete picture of a real situation is depicted in Figure 5. In that figure we represent a more realistic set of "meta assumptions" (Richmond (2001)):

(1a) causes act interdependently one with the others,

(2a) there is an influence from the outcome on some of the causes (feedback),

(3a) there may be some delay[36] from some of the causes to the outcomes and from the outcome on some of the causes,

(4a) causes exert a non linear influence on the effect.

The new set of "meta assumptions" prevents us from reasoning according to the basic principles of linear systems (see "meta assumptions" (1), (2), (3) and (4)) and in many cases force us to step to quantified models (or models where we have mathematical relations among causes and effects) on which to execute simulations with ad hoc software packages.

12.1 Something about systems

Systems (Forrester (1968)) are described according to a system philosophy by identifying into reality quantities that we want to describe to address a problematic situation.
According to this approach systems can be seen as set of variables that describe those quantities and all the relations among those quantities/variables. Whenever we speak of a system we therefore refer to a portion of reality that we want to describe essentially to improve its performance according to some measurement criteria.
We note that systems may be of many types so we have:

1. natural systems,
2. environmental systems,
3. social systems,
4. physical systems.

[36] Delays are represented with a || on the arrowed causal links. Delays can be of many kinds and involve both conservative and non conservative flows, further details on Richmond (2001) and Forrester (1968).

Social systems are the most difficult to describe since in many cases the observations we need to execute in order to get some measurements and data about them run the risk of affecting their behaviour. It is a sort of indetermination principle that prevents, essentially, to consider social reality as externally and objectively given.
As to natural systems we note (Ford (1999)) how their description in terms of variables and relations is by no means easier since they are there and we only need to look at them carefully to get an accurate description. Also in this case it is possible to be biased by pre-conceived mental models that steer us in describing reality from a subjective and non neutral point of view. It is important to note, indeed, how descriptions, in many cases, constraint the range of possible solutions of problems we claim to have described through a given model of a problematic system. We note how an environmental system can be seen as the product of the interaction of a natural system and a social system so that when we speak of an environmental system we assume the interaction of a society of some sort with a natural system.
In all these cases (and very often also in the case of physical systems) it may happen that we see what we want to see, what our mental models allow us to see so that our cultural and social backgrounds behave like filtering spectacles that pre-interpret and filter reality.
In any case, with all these caveats, we usually search for ordered structures so to see the effect of relations and devise theories that allow us to explore the behaviour of systems.
The structure we search for accounts for both coordination, organization and relations among the various elements. We can use, for this purpose the following approaches (see section 7):

1. **descriptive** or how things really are,
2. **normative** or how things should be according to the rules we have designed,
3. **prescriptive** or how we can change things from how they are to how we want them to be.

12.2 Systems and feedbacks

The concept of **feedback** is a legacy of Control Theory and Cybernetics where we deal with man made physical systems where control mechanisms and retroaction mechanisms are introduced in the design of a system so to control it and steer its behaviour in the desired direction.
In Forrester (1968) such mechanisms are introduced in all systems to explain how an effect can be a cause of itself through a chain of links that propagate information back and forth. To understand what we mean by this we give an example and them comment on it. In Figure 6 we show a simple Flow Diagram (FD) where we have a conservative flow (involving an input flow f_in and an output flow f_out and a level L) and a certain number of informative (and

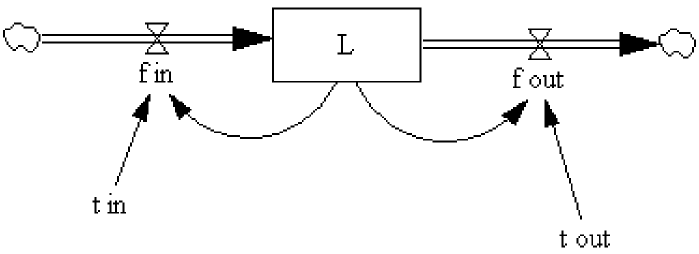

Figure 6: *Flow diagram with feedbacks*

so non conservative) information flows that reflect the influence of the current value of the level on the behaviour of the two flows. In this way we link the evolution of the level L to the current values of the incoming and outgoing flows that, in their turn, depend on that value.
From this point of view (see also Figure 7) we see how a material flow generates information that can be used at a decision level to regulate the flow itself. We note how *t_in* and *t_out* represent the influence of the world outside the model and so the boundary of our model as well as the two clouds (the source and the sink of the material flow). In Figure 7 the feedback loops can be more easily

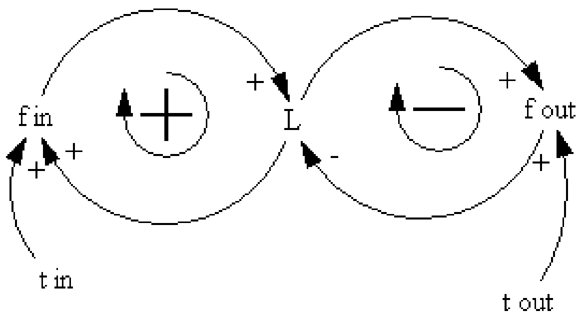

Figure 7: *Causal loop diagrams of Figure 6*

seen. In this figure we represent the so called Causal Loop diagram (CLD) corresponding to the FD of Figure 6. We note that we can translate easily a FD in the corresponding CLD whereas the opposite translation requires that we in some way fix the types of the variables we used in the latter diagram so, in some case, there is no unique translation form a CLD to a FD.
What we want to stress with this simple example is that:

1. flows of materials can be more or less easily identified in the system we want to model,

2. flows of information are associated to what we want to describe and for what purposes,
3. this arbitrariness can be found also in the definition of the boundary of a model.

We recall how the boundary is represented by a set of variables that model the influence of the outer world on our system and that we can, in many cases, proceed to a closure of a model if we can link those variables to the behaviour of inner variables of the model.
We can see an example of this process of closure in Figure 8 where we have drawn (possibly unrealistic) dependencies among the external variables we saw in Figure 6 so to make them internal and minimize the boundary of the system reducing it to the source and the sink only.

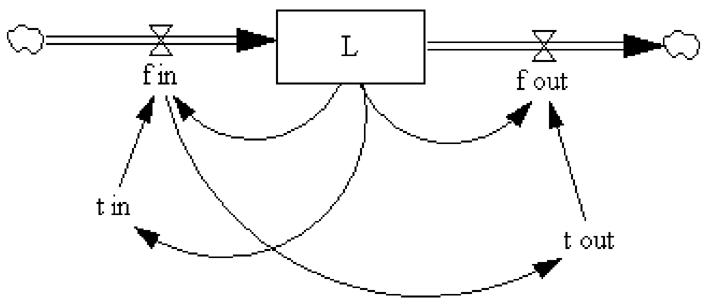

Figure 8: *Closure of the FD of Figure 6*

In this way we obtained the model of a some what isolated model where the source and sink of the material flow are the only unspecified links between the system and its outer world.
In Forrester (1968) systems are classified as:

1. either open,
2. or closed (with feedbacks).

Open systems are typically functional systems where we have:

$$output = f(input) \tag{3}$$

In this case there is no effect from past actions on future actions in the sense that an open system does not consider its own behaviour and does not react to it. Examples of open systems that we find in Forrester (1968) are a car or a watch.
Closed systems are influenced by their past behaviour in the sense that past outcomes drive future actions. If we consider (Forrester (1968)) the set made of a car and its driver that can steer it we obtain a closed system. The same holds

for the set made by a watch and its owner that can regulate it.
Obviously closed systems are more interesting and will be examined more thoroughly in what follows.
As we have seen we have two types of feedback:

1. **negative feedback**,
2. **positive feedback**.

Negative feedbacks are **goal seeking** since they are essentially driven by the discrepancy between the current state and a goal state. On the other hand positive feedbacks are characterized by a self sustained growth.
In any case the classification depends on the point of view from which an observer defines the goal of a system.
Feedback structures may have also a **hierarchical** organization since in some cases we can have (Forrester (1968)) a feedback system with many composing elements where every element may be a feedback system with respect to a subgoal.
We note how given a system structure we can detect any possible feedback loop so that if it is positive it can be associated to a growth or development whereas if it is negative it can be the cause of fluctuations and instability owing, also, to the presence of delays along the chain of feedback links.

12.3 Something more on feedback loops

A **feedback loop** or **feedback circuit** is (Forrester (1968)) a closed circuit that connects in a sequence:

1. a decision,
2. an action,
3. a level that accounts for the effect of the action,
4. information about the current value of the level,
5. influence from that information on the decision.

Information is a continuous flow and represent the basis for the decision that, in its turn, drives the flow of actions.
We note how this description fits perfectly well within the framework depicted by (Forrester (1968)): financial systems or social systems but my require some adjustment in case of natural or environmental systems.
Actions modify the level and this produces a perception of the value of the level and such perception may differ from the real value of the level so that the information that derive from it may be:

1. out of date,
2. wrong.

From this we can easily see how any decision process is really based on perceived values of levels according to the scheme we show in Figure 9 so that the decision we take is based on the *perceived_level* and it cannot be but in this way since the *real_level* is hidden by noise or an inevitable delay.

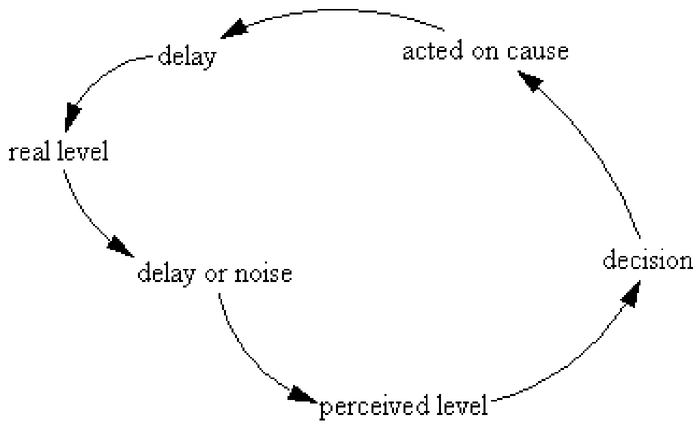

Figure 9: *Noisy or delayed decision process*

From that scheme se see how this occurs also the other way round since our *decision* acts on one of the causes (the *acted_on_cause*) that, again with an inevitable (and in many cases unforeseeable) delay modifies the value of the *real_level* and so on.
The presence of delays and noise influences the circulation of information that depend not from a real situation (whatever this may mean), that cannot be known neither at each instant nor exactly (Forrester (1968)), but from past from past observed conditions that have been analysed and understood (Forrester (1968)).

12.4 Types of dynamic behaviour

As we have seen we can have the following types of dynamic structures:

1. **negative feedback loop**s that show a goal seeking behaviour with or without fluctuations around a constant value that are caused by the presence of delays,

2. **positive feedback loop**s that show either an increasing or a decreasing behaviour.

In all cases where more two feedback loops are present, one positive and the other negative, the presence of non linearities may cause a shift of dominance from one type to another. In this case initially we can have a dominance of the positive loop so that we have one or more variables that show a rapid growth but after some time we have a shift in dominance so that the negative loop becomes the dominating one and those variables show a goal seeking behaviour. According to (Forrester (1968)) we can define the following elementary structures[37].

(1) First order negative feedback loops. In this case along the loop we have an algebraic inversion of sign. The necessary elements are:

   (1a) a level L,
   (1b) a rate R,
   (1c) a desired level DL,
   (1d) an adjustment time AT,

   so that the rate R is determined solving the following equation:

$$R = \frac{DL - L}{AT} \tag{4}$$

   From equation (4) we can both understand the meaning of "algebraic inversion of sign" and see that if L grows from a value $L_0 < DL$ when we have $L = DL$ we have $R = 0$ so that the growth of L stops.
   In this case the variable DL is an exogenous reference value.

(2) Second order negative feedback loops. In this case two levels are involved with a retroaction chain that is guided by a difference. If delays are present we can have oscillations. We give an example of such a structure in Figure 9 where we have:

   (2a) $RR = \frac{GO}{DD}$,
   (2b) $DR = \frac{Delta}{AT} = \frac{DL-L}{AT}$,
   (2c) $GO = \int DR - RR\, dt$,
   (2d) $L = \int RR\, dt$.

(3) Positive feedback loops. Also in this case we need a level L, a rate R and a time constant SDT so that the dynamics can be represented by the following equations:

   (3a) $R = \frac{L}{SDT}$,
   (3b) $L = \int R\, dt$ or $\frac{dL}{dt} = R = \frac{L}{SDT}$,

   so that it is easy to evaluate a solution in closed form of the behaviour of L with time under the form:

$$L(t) = L_0 e^{\frac{t}{SDT}} \tag{5}$$

   with L_0 initial value of level L.

[37]We refer to Richmond (2001) for another classification with the corresponding set of paradigmatic elements.

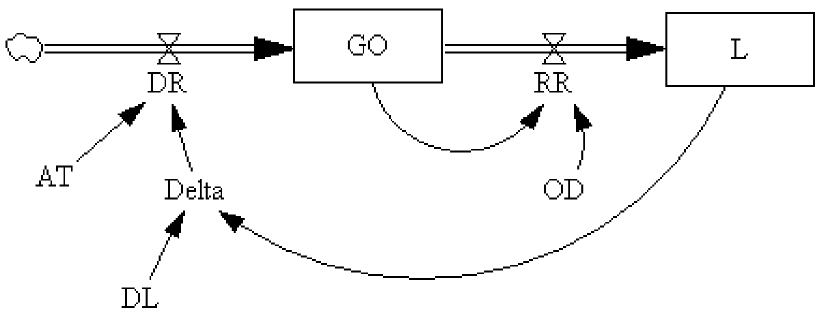

Figure 10: *Second order negative feedback loops*

12.5 Models and simulations

Models (Forrester (1968)) are substitutes of systems and can take many forms and have many aims. Within our framework we are mainly interested in **abstract models** as set of rules and relations that drive any reasoning. In our decision processes we use concepts that may have no strict correspondence with any real system a model represents but (Forrester (1968)) are abstraction based on our experience filtered and modified in order to give rise to mental models that try to represent reality (see section 12.6).
Every model, be it mental or descriptive or mathematical, may represent a portion of reality (or a system) with a higher or lower degree of accuracy . We can state a relation of inverse proportionality between the accuracy of a model and its complexity since simpler models tend to be less complex and if we want more accurate results (as to the simulation of the desired phenomena) we must must devise more complex models.
This is particularly true for **dynamic models** that describe how [complex] systems behave over time and that usually require a translation form mental or descriptive models (typically CLDs) in FD models with the proper equations describing the relations among all the variables we have introduced (for descriptive purposes) in the model.
We need therefore a **quantification step** where we assign an equation to all the endogenous variables and:

1. initial values to levels,
2. constant values or functional expressions to auxiliary converter variables.

In addition to this we have to fix:

1. the time horizon of a simulation,
2. the value of the time step $\Delta\, t$.

Once the quantification (static part) is over we can start with a simulation of the model through the use of simulation modalities that allow the change of the values of exogenous variables, essentially those who describe the intended policies, so to see which effects we attain on the model (and hopefully on the associated system) from applying a given policy. For further details on environmental systems we refer to Ford (1999).

12.6 Mental models

According to this line of thought our starting point is, in general, a **mental model**.
Mental models (Forrester (1968)) generally suffer the following drawbacks that forces us to formalize such models in order to reduce their impact:

1. are defined in an insufficient way,
2. their underlying hypotheses are not clearly stated,
3. can be hardly communicated to others since are usually expressed by using ambiguous verbal formulations,
4. cannot be effectively used since if we adopt solutions with analogy with past experiences we may attain wrong conclusions and wrong results.

From all this we can see the necessity to shift to dynamic models whose validity and utility depend on how clear the structure is, how well the hypotheses are expressed, on the correctness of the structure of the equations and on the easiness of model communication.
Once a model has been formalized we need to understand and evaluate:

1. its exactness as the ability to describe faithfully the phenomena we are interested in,
2. its utility in aiding the design the right policies to address the problematic situation we tried to represent with the model,
3. its clearness as a tool for the fostering of a common and shared knowledge about that problem,
4. its possibility to incrementally improve the knowledge and understanding of a system.

We therefore judge a model (Forrester (1968)) as it clarifies a reasoning and allows us to observe the consequences of our hypotheses. The focal issues are therefore:

1. better understanding,
2. ease of communication,
3. better ownership.

For further details about each of them we refer to (Forrester (1968)).

12.7 System Thinking and mental models

The starting point (Richmond (2001)) of any decision process aiming at fixing any perceived problematic situation is to build a **mental model** that is to say a selective abstraction of a reality based on a certain number of assumptions about such reality.
We have already seen how such assumptions form the so called "meta assumptions" (see section 12) and drive both the construction of our mental models and what we expect from the simulation of our mental models. If such "meta assumptions" are wrong also the deductions we make from the model will be wrong.
The main problems with mental models are that we generally lack the needed computational capabilities to construct and simulate them and whenever we construct them our models are lacking as to content and structure.
The **content** (Richmond (2001)) relates with what we decide to include in a model or exclude from it. The main problem with the content is that, in many cases, we insert in a model too many details so to obtain a detailed narrow view but losing the general view of the problem. In order to obtain good mental models the first step is to improve the quality of their content by inserting only all the necessary elements and discarding useless details (that may provide a richer picture but that add nothing to a problem oriented description of the system).
Once the right details have been chosen (and form the content of our model) we have to choose how to represent them. The representation benefits from System Thinking and the methods of SD that provide the right "meta assumptions" (see section 12).
From this perspective SD provides a **shareable language** (Richmond (2001)) for the representation of the content and for the proper communication of such content. Such a language allows us to simulate our models (at this point more correctly termed formal models) and to get a coherent picture of a system.
In order to improve the quality of our mental models (the first stage of our formalization process) and of our simulations we must adopt the correct framework and, therefore, (see section 12) the right perspective.
This means that we must change perspective from a deep and narrow to a broad and shallow: the former perspective is that of an expert which knows a lot of a narrow field whereas the latter can be attained by a group of stakeholders that cooperatively, possibly under the guidance of some SD experts, engages in a model building effort. What is really important is discovering the whole pattern without getting lost in useless details.
The other key point (Richmond (2001)) is thinking in terms of causes and effects interlinked in causal loops where every effect can become a cause of itself through more or less complex causal chains. At the same time it is important to understand how the behaviour of a model depends from its internal structures so that it is possible to isolate the so called **paradigmatic substructures** that are able to reproduce the typical patterns of behaviour (see section 12.4).
One way to improve the quality of the content of our model is to resort to

the right "meta assumptions" (see section 12). On of the "meta assumptions" (Richmond (2001)) is that of the interdependence of the causes within causal feedback loops so to frame the content in a dynamic perspective. Another "meta assumption" involves the presence of delays that prevent a cause to act instantly and an effect to be revealed immediately, in zero time.
As a side effects of all this we have that we look for causal relations where a quantity is (in complex conjunction with others) a cause of another and not simply correlated with another. We need strong links so to be able to state that if a quantity varies in a certain direction (increase or decrease) a causally linked quantity varies in the same or in the opposite direction.
Another "meta assumption" is that of non linearity so that whenever we have complex interactions of non linear functions it may be very hard to foresee the behaviour of a model but through simulations.

12.8 The role of time

In this closing section we want to address very briefly the role of time is the construction and use of models and in the logic of actions execution.
From what we have seen up to this point we can state that deciders act on the basis of perceptions of a reality and making previsions about its desired evolution. **Previsions** drive deciders'**decisions** that, in their turn, determine deciders'**actions** to which there correspond some **effects**.

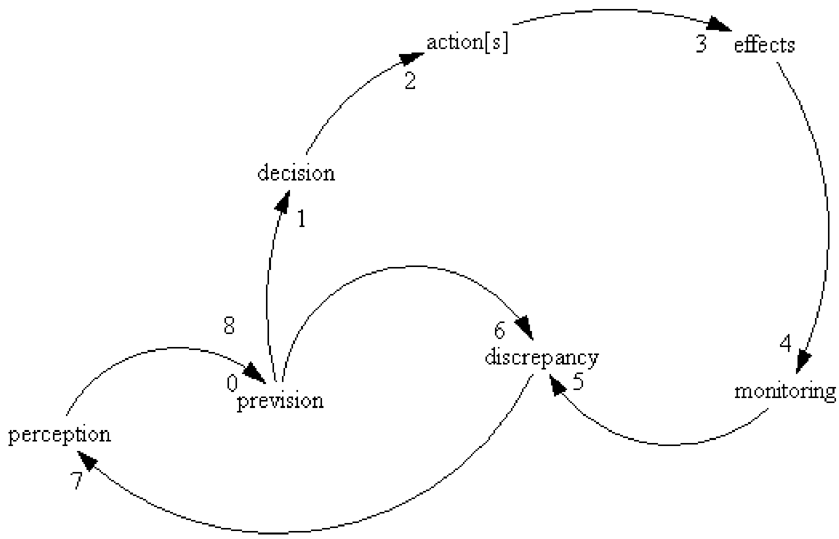

Figure 11: *The time loop*

Unfortunately all this requires time since:

1. perception requires time,

2. decision requires time,
3. performing actions requires time,
4. effects revealing and detection require time,
5. discrepancy evaluation requires time,
6. discrepancy perception requires time,
7. making new previsions requires time,

and so on.
We have depicted all this process in Figure 11 where we have a clock that starts at 0 with a perception. At each tick of this clock we have a label of something that occurs at that tick. It is easy to see how the whole cycle requires 8 ticks of time and also that this cycling can potentially last forever. Since each tick has an arbitrary and (in many cases) a-priori unknown duration it is easy to understand that many kind of problem can arise from this time loop.
Such problems may arise from:

1. the structure of the loop,
2. the various delays,
3. the fact that some of its elements may be wrong or imprecise.

The last point may involve, essentially, monitoring, perception and prevision.
Monitoring means measuring the effects of the actions and, in many cases, is a difficult task since, in many cases, actions have undesired but also unexpected and unknown effects whose measurement is far from being obvious.
Perception in many cases may be focused on what we expect to occur so it may be a self revealing prophecy missing to perceive the real consequences of deciders' decisions.
Making previsions is generally very difficult and error prone so decisions based only on previsions should be handled with care and backed up with a strong and deep analysis of the current conditions so to discard extreme (too pessimistic or too optimistic) previsions.

A System Dynamics within consensus based decision making processes

The present section contains some notes about the use of System Dynamics (SD) as a multi role tool within processes of consensus based decision making (Butler and Rothstein (2004) and Elliot et al. (2005)) applied to environmental problems and strategies.
Decision making processes are time consuming processes involving actors as decision makers, stakeholders and experts in a succession of phases (Pareglio et al. (1999)) that involve also feedback loops and whose aim is either the solution of environmental problems or the planning (and management) of environmental strategies.
Decision makers are those that have the responsibility of undertaking, implementing and managing the proposed solutions whereas **experts** provide for technical consultancy and expertise as a support for the definition of a problem and the design of potential solutions and **stakeholders**, since they bear the consequences of a problem and both the benefits and the consequences (as side effects) of the proposed solutions, can act as both opponents and supporters of these solutions.
From this perspective, the section examines the use of SD (van den Belt (2004)) as a tool for the building and fostering of environmental consensus so that the chosen solution or strategy is perceived as the best from all involved parties. In this way its implementation can occur more easily, without or with less obstructionisms and within the foreseen time bounds.
Within this framework, SD can therefore play the role of **analysis and clarification tool**, of a **knowledge sharing tool** and of a **scenarios planning and testing tool**. In all these roles SD is a formalizing model that allows the definition of qualitative and quantitative relations for the description of models that represent, at variable levels of abstraction, the portion of reality under scrutiny.
In the first role SD can be used by actors so to deepen the knowledge of the problem and clarify and make explicit the hidden assumptions of the single actors.
In the second role SD allows the definition of a shared knowledge of a problem so that it is possible to attain a solution that is the best for all the actors. This allows the framing of a solution in a win-win context.
In the last role SD allows the evaluation of every tentative solution through the definition of possible scenarios (i. e. possible evolutions of a model depending on the proposed actions) so that actors can rate the possible consequences and benefits and accept a solution if it satisfy their expectations.

A.1 Scoping of SD

SD can intervene at different stages of the decision process and at different levels of involvement and understanding (Wolstenholme (1990), Ford (1999) and

van den Belt (2004)).
A decision process is characterized (van den Belt (2004)) by a timing dimension and by a degree of participation dimension. The **timing dimension** ranges from **early** to **late** so that the use of SD ranges from a framing tool to a decision communication tool: at the former extreme SD can fully play the aforesaid roles so to be used (van den Belt (2004)) to scope the question and to build capacity and integration among the actors. At the latter extreme SD sees the aforesaid roles emptied of real significance so that SD is turned in a formal tool for the description of decisions taken elsewhere that can be only refined in small details.
Similar considerations hold also for the **degree of participation dimension** that (van den Belt (2004)) ranges from **low** to **high** or from a low involvement in the building up of models (that is [almost] fully left in the hands of the experts) to a high involvement in such building up so that models can be seen as a joint effort of all the actors' activity.
This aspect is strongly interlinked with the issue of SD understanding since a common knowledge of SD tools is necessary to let decision makers and stakeholders profitably contribute with the experts to the modelling activity. This aspect is also a point of conflict between experts and mainly stakeholders that are usually judged not well trained for the use of formal methods such as those of SD. A possible solution (Kluver et al. (2000) and Elliot et al. (2005)) may reside in an early involvement of stakeholders combined with a high degree of participation.

A.2 SD and consensus

Consensus characterizes processes through which conflicting interests and perspectives find an equilibrium point where all the actors see their expectations satisfied at the best.
The search of a consensus among the actors must be seen as the search not of a solution that satisfies a minimal set of requirements but a constructive process of composition of opposing requirements so that actors can be satisfied (or at least declare that can live with) the devised solution. The attainment of the widest possible consensus among the actors is a time consuming activity that is usually in conflict with more or less tight time constraints. Within this framework SD can prove a valuable tool since it allows the keeping of the design process on a concrete and formalized ground. In this way time wasting and self-serving objections can be rejected more easily so to keep the actors decision process on the track and within the usually exogenously fixed time constraints.

A.3 Applications

After having covered the theoretical aspects of these issues the section faces their practical aspects. To examine such practical aspects of the proposed method in the concluding sections of the section some applications to the decision processes for the localization of environmentally "controversial" plants (such as incinerators, electric power plants, solid waste disposal plants as well as big infrastructures such as highways, railway lines, airports and the like) are briefly presented and discussed in some detail.

B How System Dynamics can be a help or a hindrance

The present section aims at examining some of the various meanings and scopes of System Dynamics (SD) within the entangled arena of human affairs where interests groups make use of formal models to dress their opinions, interests and taking stands with the chrism of objectivity. In this framework SD can either be a help to unmask such tricks and to reveal the true positions at stake but can also be a hindrance since its "objectivity" can present a partial solution as a definite and immutable one.
The section has a sequential structure that forces us to present the topics in a given order though they should be examined in parallel. This is true for what concerns actor, experts and stakeholders, on one hand, and problems and solutions on the other hand but is true also for the various role of SD since it is very hard and rare to find in practice pure roles but they are mixed with all the other ingredients in an often confusing patchwork.
One of the aims of this section is indeed that of presenting SD as a meta tool to disentangle such a skein and clarify from time to time who is using SD and far what purpose.
The section, therefore, presents the main features of SD, who can use it and why. A section on the various roles of SD follows. Then we present the various arenas where SD is played and a discussion of the hamlet's dilemma of the title to close, traditionally, with a section devoted to partial and tentative conclusions.

B.1 SD by the way

SD looks at reality from an holistic point of view so that reality is seen as a complex web of interrelated components that influence each other and also themselves through causal closed chains or loops. From this perspective, SD aims at defining **models** of **systems** as abstract representations of portions of reality[38].
A given portion of reality reveals itself through phenomena that can be described and that can represent problems that must be solved in someway.
Within this framework, SD tries to identify some entities that can be used to describe the phenomena of interest and their interactions through causal chains. The real explanatory power of SD resides in its passing from linear causal chains to closed chains of both positive and negative feedback loops.
In this way SD defines the so called **causal loop diagrams** (CLDs) as models of systems that are portions of reality, with all cautions of the case.

[38]The problem of defining what is meant with reality, if a reality exists or we have a plurality of realities and how can such realities be known and communicated is far beyond the scope of this section and the possibilities of its author. For our purposes with reality we mean a subjective shared knowledge whose construction is one of the objectives of a process that uses SD as one of its tools. One of the aims of this section is the explanation of what this, more or less exactly, means.

The next step involves the definition of the relations between our portion of reality, that we are trying to describe as a system with a model, and its external world and a characterization of the various entities we want to use to describe the model.
For this purpose we define types for the needed variables in order to characterize conservative material flows and non conservative information flows in graphical models that mimic differential equations by using level variables as well as flow, auxiliary and constant types variables.
In this way we can define **stock-flow diagrams** (FDs) representing systems where external world exerts its influence on the model through either exogenous (i. e. constant) variables or levels' initial values as opposed to endogenous variables that form the heart of the model.
FDs can be used to model differential equations of any order that are simulated continuous time with difference equations by fixing an initial/final time and a time step.
In this way we can obtain the characteristic time trajectories of all endogenous variables, trajectories that can be compared with available data, measured on the portion of reality we are trying to model and that represent our reference patterns: if our variables succeed in reproducing such patterns within a small error we can validate the model otherwise a more or less deep revision process of the model is required up to a full redesign of the model itself and of its interactions with its outer world.

B.2 Actors, experts and stakeholders

Environmental problems (see next section) involve people at various decision levels and timings (van den Belt (2004)) both as individual and as groups. At each of these levels people involved can belong to one or more of the following (non disjoint) sets:

1. actors A,
2. experts E,
3. stakeholders S.

Actors represent people that has the political and/or economical responsibility of taking decisions in all the phases, from the design to the implementation to, maybe, monitoring and evaluation. Such decisions tend to influence the lives and interests of **stakeholders**, since they cause a change in the status quo, and are taken with support of **experts** from various fields. Among the actors there may be some of them that benefit from the "privilege" of having the real power over the decisions to be undertaken, we call them **real actors**.
Actors are usually part of hierarchical structures so that they have natural timings and levels of involvement in a decision process. Stakeholders involvement, on the other hand, can occur at various levels and timings of a decision process (van den Belt (2004)).

Actors and stakeholders tend to form coalitions of proponents and opponents in a decision process and such coalitions involve experts as party opinionists that, in this role, may be more a hindrance than a help since they may act as unquestionable authorities that hinder the creative search of solutions from both actors and stakeholders. Experts, see Gordon (1994) Dalkey (1969) and Kluver et al. (2000) among the many, indeed should be involved in a neutral and possibly anonymous way so to provide the technical ground on which the search for solutions should move (see next section).

B.3 Problems and solutions

A problem is, roughly speaking, a perceived bad situation. In this sense it is either a failure of the status quo or an evolution of the status quo in a direction that is perceived as negative with respect to a desirable outcome. In both cases an alignment process is needed with more or less urgency. The [not only] key point is perception. Perception can be from either a subset of actors or a subset of stakeholders or even from a set of experts. Problems are, indeed, characterized by:

1. their level of perception,
2. their level of urgency,
3. their scope both in time and space.

Once perceived, problems must be defined more or less formally. At this point, problems claim for solutions. **Solutions** are represented by policies that guide the evolution of a system toward a desired goal. This guidance can be either top-down or bottom-up directed (Elliot et al. (2005), van den Belt (2004), Pareglio et al. (1999)). Here we have one of the many trade-off of any decision process: quicker decision processes usually turn into longer implementation phases owing to resistances posed from stakeholders that feel to have been unduly excluded from the process whereas longer decision processes may be followed by quicker implementation phases because all stakeholders agree on the undertaken decisions and perceive them as fair and envy-free (Brams and Taylor (1996)).
As **level of perception** we denote the perception from either [some of] the actors or from [some of] the stakeholders or from both. Such types of perception do not weight the same and are guided by distinct goals and time-scales. Anyway for a problem to be perceived as such a "pain threshold" must be exceeded where such a threshold is usually problem-dependent and can be manipulated at various levels.
The **level of urgency** defines the possibility of real planning. If this level is high no participative and consensual planned solution (Butler and Rothstein (2004)) is usually possible but authoritative and top-down solutions are imposed by the **real actors**. The main issue is that, in many cases, mainly when the perception level of a problem is low, the situation is let free to evolve

uncontrolled until the crisis is so near that the urgency level is raised, the perception is favoured and a last minute emergency solution is imposed.
Last but not least the **temporal or spacial scopes** contribute to the definition of the proper actors and stakeholders. It is obvious that, with respect to a problem and its potential solutions, not all stakeholders have the same benefits and suffer the same costs and, in a similar way, not all the actors can exert the same decisional power and influence.
Discarding emergency driven solutions, given a perceived problem where a planning process may be carried out usually a more or less wide succession of sets of solutions can be devised[39]. At this point all these solutions must be ranked according to the many different criteria that have been proposed till one is chosen to be implemented. This is the true hard part since both tangible and intangible goods enter into play and multiple criteria may be advocated (Vincke (1989)).
At his level the question of the feasibility of each solution is posed as well as the comparison between bad and good solutions (with respect to what? or to whom?) and between rigid and flexible solutions (Collingridge (1979), Collingridge (1983)). Both flexibility and rigidity must be seen in the costs due to an abandoning or a radical change of a solution that proves highly negative in front of commonly recognized criteria.

B.4 The various roles of SD

SD can play various and different roles in the interactions among actors, experts and stakeholders for both the definition of the problems and the search for solutions. The usual role is that of a faithful and neutral representation of reality in the hands of the experts that pretend, in this way, to have the only real knowledge of a problem and the only right solution so that all the others involved subjects can only approve without any dissent. Fortunately this is very seldom the case and there is a wide area of manoeuvres for the design and implementation of consensually defined solutions (Elliot et al. (2005), Butler and Rothstein (2004)). As a basic form of knowledge, in the following subsections we are going to examine such roles so to start a discussion on each of them.

B.4.1 SD as a normative tool

The distinction between **normative** and **descriptive** decision theory has been posed in Rapoport (1989) as a distinction between "what ought to be" in a normed world and "what it is" in the real world. We use such a distinction here between SD as a normative tool and SD from other perspectives among which we pose a descriptive role.

[39] The whole process, if we include also the monitoring and evaluation phases, spans generally over more or less long period of times ranging from some weeks to months and even years. During these periods many solutions may rise and fall many times, others may evolve and be modified and so on. We therefore speak of a succession of sets of solutions.

Sometimes SD is indeed used as a normative way to approach reality. As it is shown in books such as Roberts et al. (1983), Kirkwood (1998) and others in this stream of thinking, it is tempting to say that reality behaves as it is imposed by a model so that, obviously, if we modify some parameters of a model a necessary set of consequences will occur and reality will submissively bend. This attitude derives from hard sciences such as physics, mathematics and engineering, very apt at working with complicatedness more than with complexity, but it is out of place with regard to environmental problems that require a multidimensional and multidisciplinary approach.
This point of view may be legitimated both from the use of hydraulic metaphors of levels and flows within our models and by the fact that our models mimic differential equations.
Given that the outer world is correctly represented by a set of manageable variables whose influence can make the system behave in some predictable ways and given that these ways are governed by well posed differential equations it seems obvious that the future is strictly determined. Unfortunately (or fortunately depending on one's point of view) this is not the case within the search for solutions of environmental problems since every abstraction process through which we define the boundary of our system, the exogenous variables and the endogenous variables with their mutual ties defines something that has no normative power.

B.4.2 SD as a descriptive tool

After discarding the use of SD as a normative tool we are left with it as a descriptive tool. From this point of view SD can be very valuable since it allows the experts to state their proposals both to actors and stakeholders.
This approach may suffer severe drawbacks since the degree of participation of stakeholders is usually low (van den Belt (2004)) and their timing of participation is late since all that can contribute is a feedback or a set of observations to experts' proposals that, usually, have to pass only actors' acceptance.
With all its limits in this role SD may help in the search for solutions to environmental problems since it forces the experts to explain their ideas and show how they are supposed to act on the problem under scrutiny. On the other hand it may be a hindrance since any model is posed as an objective and unmodifiable reality that must be accepted because it has been elaborated by "real experts".

B.4.3 SD as a prescriptive tool

Once we accept SD as a descriptive tool it is easy to see how tempting can be to use it as prescriptive tool or as a way through which the experts show how to act so that reality can be modified according to the wishes so to solve the problem under scrutiny.
The main problems with this approach can be found at various levels.

1. At the level of the model itself since acting on an SD model through a set of predefined exogenous variables so to show how a bad situation favourably

modifies has nothing to do with the definition and implementation or real policies, the evaluation and monitoring of their effects and, maybe, their adjustment.

2. At the level of stakeholders that can be captured by the technicalities of the models but with a strong feeling to have been excluded from any real decision process with only a residual possibility of intervention through marginal observations.
   From this perspective SD is seen as a tool to convince the stakeholders that the solution devised by the actors with the support of a group of experts is surely the best one given a objectively fixed set of economical, technical, political and even scientific constraints.

3. At the level of the experts that usually are not a compact and homogeneous group but are often divided in cliques that, in many cases, are hard to understand if one consider that each clique founds upon objective data and theories to prescribe policies that are told destined to success.

B.4.4 SD as a cognitive tool

The search for solutions to environmental problems is an interplay among actors, experts and stakeholders where each category has hidden assumptions, attitudes that hide the real motivations, biases but also values and interests to protect and goals to pursue.
Within this framework SD can be used (van den Belt (2004)) so that actors, experts and stakeholders can gain a better reciprocal understanding of each other, of the problem under scrutiny and of the proposed solutions.
The availability of formal models, to be iteratively refined and modified, has also the following "beneficial" effects:

1. it forces all the parties involved at expliciting their hidden assumptions, giving up with attitudes and showing the real motivations;

2. it allows the discovery of any bias about a problem and its possible solutions;

3. it allows all the parties the expression of their goals;

4. it provides a common ground for the expression of policies and their evaluation.

For all this really happen it is necessary that actors and stakeholders are involved very early in the process and are put in the position of building their own models with the guide of experts, evaluate and validate them so that any solution can be seen as a collective undertaking. In this way maybe the decision process may last longer but the implementation phase will almost surely run smoothly (Butler and Rothstein (2004), van den Belt (2004), Elliot et al. (2005) and Kluver et al. (2000) among the many).

B.4.5 SD as a meta tool

Both the solution discovering process and the planning process are systems (Saaty and Kearns (1985)) and so can benefit from the use of SD that, in this case, acts as a meta tool.
In this way it may be possible a monitoring of the decision process to understand:

1. if it is effective i.e. it is getting on toward a goal;
2. if the times and agendas are respected since no process can last forever or turn in a pure waste of time owing to filibustering that, in practice, prevent the undertaking of any decision;
3. if all the parties are correctly involved and informed and none keeps hidden assets, if all participate in the process without exerting any kind of dictatorship and having the possibility to expose ideas, plans, values and goals in a respectful setting.

Similar considerations hold also for the design of monitoring and evaluation phases (that can turn in a redefinition of the problem itself and of the adopted solution, Collingridge (1983)) since such phases must be carefully designed and executed so that no false solution can be devised.

B.5 The various arenas

The process that may lead to the [partial] solution of environmental problems may last very long, from weeks or months up to years with the involvement of permanent administrative structures such as an **environmental forum** (Pareglio et al. (1999) and Elliot et al. (2005)).
During this hopefully creative period actors, stakeholders and experts meet many times in many places and at various levels. We can define these meetings as sessions or **arena**s since they are places where conflicts crop up and must be settled (Butler and Rothstein (2004)) so that the process can progress within a consensual framework.
In all these occasions SD can profitably play its roles of cognitive tool and meta tool but, within a consensual process (Butler and Rothstein (2004)), can be used also simply as a descriptive or prescriptive tool.
Within **technical arenas** experts can use SD as a descriptive tool to show how a problem may be faced from a particular perspective or expertise.
Within **political arenas** actors can use SD as a prescriptive tool so to explain the potential effects of a proposed policy and to get a feedback from stakeholders to such policy without disregarding the interactions among the various policies that are being planned to solve a given problem.
Within **critical arenas** stakeholders scrutinize the eventually proposed models, design their own models and evaluate the proposed policies and propose their own policies. In this case SD is used mainly as a cognitive tool.
Every category is in charge in any such types of arena but in any case the goal is the construction of a shared knowledge so that any solution can be reached

at the end of a consensual process.
Last but not least, in **procedural arenas** SD can be used as a meta tool to evaluate the quality of the decision process and its effectiveness with respect to the goal and the various constraints posed by the problem under scrutiny.

B.6 Help or hinder, this is the question

At this point it should be clear how SD, in its various roles, does not represent a neutral tool but, rather, a way to look at problems and their potential solutions by wearing potentially distorting glasses.
SD can therefore represent both a powerful tool for reaching a consensus and shape a solution (a help) and a mind cage and a monkey trap (a hindrance).
In the former role SD is a valuable tool to help staying on tune with the problem and finding real and effective solutions. In this case experts (and SD experts too) work as a supporting team that tries to keep wishful thinking under control and maintain the decision process on route.
In the latter role it can be used to produce premature solutions, though technically correct, but that reduce creativity and hide better solutions since an objective solution has already been found out without any possibility to discover it is, on the contrary, suboptimal.
All this can happen if experts (including SD experts) play a too strong and binding role and do not resist to the temptation of devising complex and detailed models already from the first stages of the process. Even if such solutions may seem correct and be able to explain observed data they may prevent the definition of more creative and better solutions.
Unfortunately there is no general way to understand if SD is acting as a help or a hindrance and an evaluation is needed case by case and requires a careful examination of the outstanding process.
As a general rule we can say that actors tend to favour short processes and so "pre-cooked" models (and from this perspective they seem to favour SD as a hindrance) whereas experts have no objection to long professional charges and stakeholders' attitude depends on the perceived urgency of a problem but they may be trained to participate in [long] consensual processes and, therefore, to favour SD as a help.

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