Introduction to system thinking and causal loop diagrams

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System Thinking is a common concept for understanding how causal relationships and feedbacks work in an everyday problem. Understanding a cause and an effect enables us to analyse, sort out and explain how changes come about both temporarily and spatially in common problems. This is referred to as mental modelling, i.e. to explicitly map the understanding of the problem and making it transparent and visible for others through Causal Loop Diagrams (CLD). This report will discuss how to use system thinking and Causal Loop Diagrams as an effective tool in your study and research.

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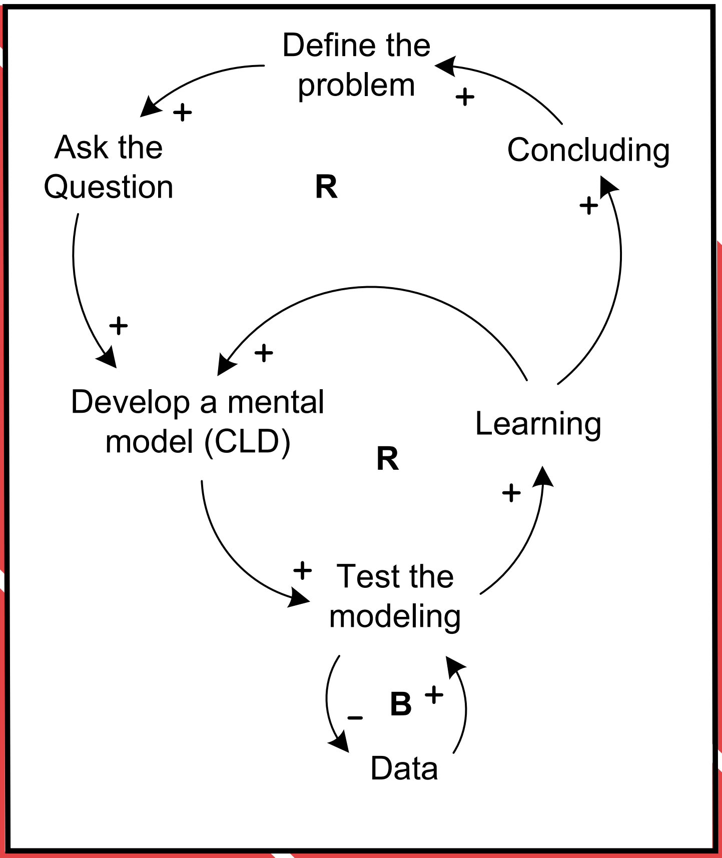

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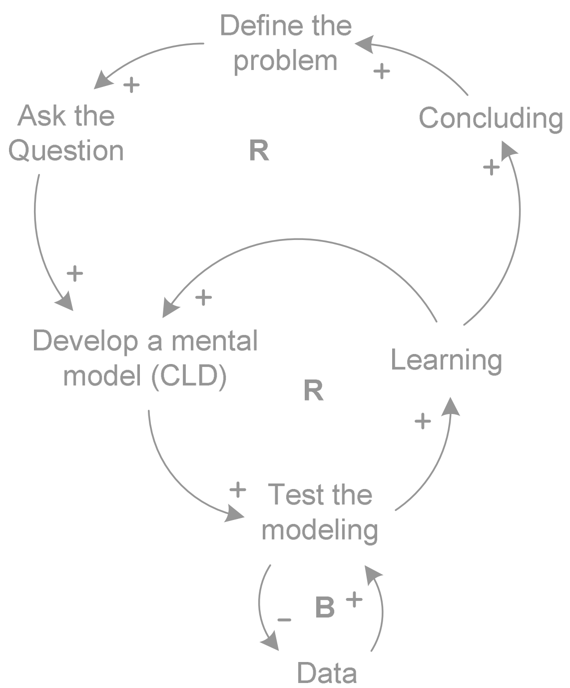

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2004

1.0 Introduction

This is an introduction to System Thinking and modelling. System Thinking is a common concept for understanding how causal relationships and feedbacks work in an everyday problem. Understanding a cause and an effect enables us to analyse, sort out and explain how changes come about both temporarily and spatially in common problems. This is referred to as mental modelling, i.e. to explicitly map the understanding of the problem and making it transparent and visible for others through Causal Loop Diagrams (CLD). Here we will discuss how to use system thinking and Causal Loop Diagrams to understand and analyse complex problems.

2.0 System Thinking

System thinking has been evolving and developing over the last 60 years and is increasingly having more influence on science. In brief terms, system thinking is a science that deals with the organisation of logic and integration of disciplines for understanding patterns and relations of complex problems. System thinking is also known as principles of organization or theory of self-organization and the way of using it involves "systemic" or "holistic thinking". It is a science based on understanding connections and relations between seemingly isolated things. System Thinking embeds two other concepts, System Analysis (SA) and System Dynamics (SD). In general terms system thinking is the mental modelling and science of structuring the logic and asking the relevant questions, but it also has practical applications through System Analysis and System Dynamics (figure 1).

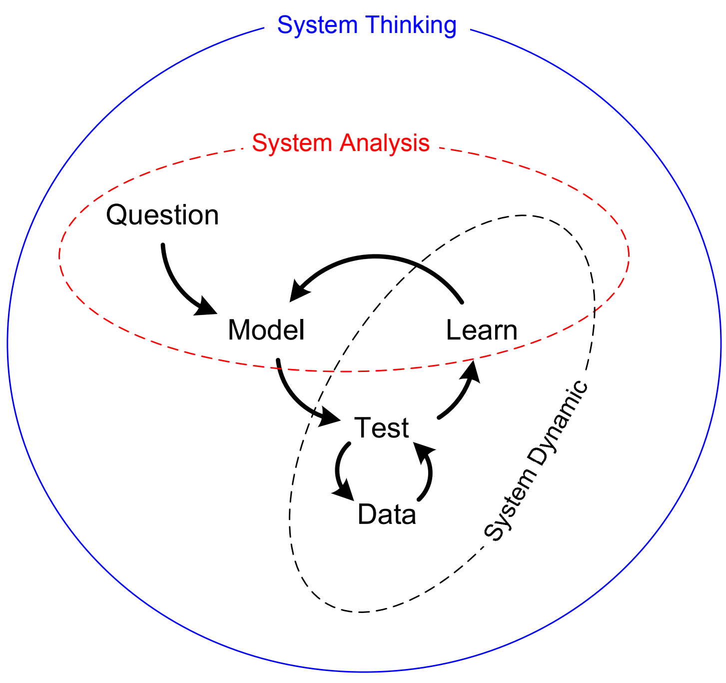


Figure 1: All investigations into properties and function of a system can be described through System Thinking, which involves a mental model representation (System

Analysis) of the problem. System Dynamic is a mathematical recreation of the problem in order to explain the past and understand the future.

System Analysis is about discovering organisational structures in systems and creating insights into the organisation of causalities. It is about taking a problem apart and reassembling it in order to understand its components and feedback relationships. System Analysis involves group modelling, where we ask the initial question of the problem and create a mental model structure, using Causal Loop Diagrams, to reflect that problem.

The term "System Dynamics" was coined in the sixties by Jay Forester at MIT (Forester, 1961). System Dynamics refers to the re-creation of the understanding of a system and its feedbacks. It aims at exploring dynamic responses to changes within or from outside the system. Here we create designs to explain the past and predict the future. Furthermore, System Dynamics deals with mathematical representation of our mental models and is a secondary step after we have developed our mental model. System Dynamics also deals with and numerical analysis and understanding uncertainty of the practical representation in the developed mathematical model.

All models, in the form of written text, conceptual or mathematical, have an inherent "system thinking" structure built in them, since they are built according to certain thinking and logic. A model is successful when the thinking behind it is successfully transferred from the model builder to the observer (Haraldsson and Sverdrup, 2003). A model that lacks explanation of its principles is essentially useless. The use of a common language to transfer this understanding is thus critical so that this communication is effective between user and builder. This is the reason for the development of the Causal Loop Diagram concept (described in chapter 5).

2.1 The system theories evolution- a brief history

In the 1920s, the Russian multi-discipline researcher Alexander Bogdanov formed the first comprehensive theoretical framework, describing organisation of living and non-living systems. Bogdanov clarified principles of organisation in his theory of Tektology by defining them as the totality of connections among system elements. He identifies three elements that characterise complex systems (Capra, 1997):

- Organised complexities, where the whole is greater than the sum of its parts;
- Disorganised complexities, where the whole is less than the sum of its parts;
- Neutral complexities, where the organising and disorganising activities cancel each other.

Ludvick von Bertalanaffy independently followed up the work of Bogdanov and initiated the general system theories in the 1940s from which the modern cybernetic movement emerged. Bertalanaffy made it clear that system theory was a science of wholeness, which could guard against superficial analogies in science. In fact, Bertalanaffy elaborated that duplicating the same knowledge between isolated disciplines was unnecessary since system thinking transferred the principles among fields (Lagerroth, 1994).

The cybernetic movement, formed after World War II was a group of mathematicians, neuroscientists, social scientists and engineers, led by Norbert Wiener and John von Neumann. They developed important concepts of feedback and self-regulation within engineering and expanded the concept of studying patterns, which eventually led to theories of self-organisation (Lagerroth, 1994; Capra, 1997). The Neumann group discovered an important feature with system thinking; the ability to shift the attention back and forth between details and wholeness through different levels (system levels) and observe how different kinds of laws act within each system level. It enabled a contextual analysis of seeing different system levels interacting in a larger whole, e.g. the interaction of species in an ecosystem or the urban society and people.

Another significant discovery by system thinkers is the implication that all sciences are in principal non-linear. This was clearly expressed by the Nobel Laureate Ilya Prigonine where, in his research on complex systems, he concluded that only non-linear equations are capable of describing systems far from equilibrium. Prigonine's studies led him to the development of new thermodynamic principles that could describe the phenomena of self-organisation, which he called *dissipative structures*. Apart from conventional thermodynamics, which describes the world as a place with ever decreasing energy and progression towards equilibrium, dissipative structures maintain their energy flow far from equilibrium and can evolve towards increased complexity (Capra, 1997). This was further elaborated by Maturana and Varela in their theory of *autopoiesis* (self-making), that described self-organisation of living systems (Lagerroth, 1994).

The sixties and seventies saw some interesting developments where people started to work on a trans-disciplinary level. The environmental movement identified many complex problems that integrated the economy and resource management, and saw the need to address them as a whole. The concept "sustainable development" is perhaps the most recognised term to address the need of interdisciplinary approach. In recent years, scientists are realising the importance of creating an educational basis that incorporates a system approach, and for the last decade or so System Thinking has been finding its way into universities and corporations.

3.0 Seeing structure and logic in problems

To some, many of the environmental problems are a recent phenomenon that has developed during the last 30-40 years. Increasing concerns about them has motivated us to ask ourselves many different questions on how and why they exist to begin with. Our immediate response, understandably, would be to resolve the most visible symptoms to the problems by applying some sort of quick fix method that gives swift results and restores the issue to its apparent original condition. Problems often appear to be solved since we have "fixed" their symptoms but they may unexpectedly resurface in another form.

What is characteristic for solving problems are the so-called “end of pipe” solutions. It is a tactic based on “curing” the symptoms rather than pin the source of a problem. This is not intentionally done by policymakers but rather stems from lack of understanding of how the symptoms manifest. The first approach to increased air pollution was to filter the smoke stack since this was the most obvious “source” of the problem. Similarly, constructing longer sewage pipes to dilute the sewage waste was considered a solution to coastal management. In the seventies, it was considered economically viable for the state and corporations to apply the “end of pipe” approach instead of upgrading the machinery or changing production methods. This “short term” approach was the general view to environmental problems since they were not fully understood and not perceived as a direct threat to the society. The climatic debate is perhaps the best example of the failure of this approach. For instance the carbon dioxide debate has made many of the “smoke stack” solutions obsolete. Coal fired power plants are now considered a large source of carbon dioxide and filtering its smoke stacks is a secondary problem and does not solve the problem of carbon dioxide increase in the atmosphere.

End of pipe solutions are not unique for the power industry; they can also be related to our socio-economic and ecological strategies. Northern Europe for example has experienced for several decades high sulphur deposition as a result of industrial production. This problem is often referred to as the problem of “acid rain”. It is a typical problem that is transboundary which has its source in one geographical region but is transferred with winds to another region and deposited. In the eighties lake ecosystems in Scandinavia started to “die off” due to increased lake acidity. The immediate response to this problem was to “fix” the symptoms (of decreased lake acidity) and initiate lake liming programs, which involved basically a pouring of calcium carbonate into lakes in order to reduce the acidity effects. The purpose of lake liming was to restore the original pH level in the lake to recover the initial ecosystem.

After several years of research (and lake liming) it was discovered that runoff from land was primarily responsible for acidity in lakes. Sulphur deposition on soil affected groundwater and runoff water, which then affected acidity in lakes. As a result decision makers initiated “soil liming” programs as a means to deal with (“fix”) the worst affected areas. Some people started to ask if it would not be more reasonable to address the problem of its source, i.e. to deal with the industry that is primarily responsible for the sulphur emissions. That approach was much more complex and involved much broader definition of the problem, i.e. involved the participation of the emission countries. It was (and in some form still is) reasoned that, as long as the externalities of environmental degradation were not included in the economic activities, it was reasoned that environmental degradation of this kind was economically acceptable. Liming soils was a much larger task and more costly than liming lakes. This was no longer a problem that focused only on soils or lakes but a problem that also had impact on agricultural productivity, forest productivity and socio-economic output of these systems. For decision makers this was suddenly an immense problem that needed new focus involving all actors.

The acid rain story is just one of many similar ones where politicians find themselves dealing with problems that are complex and involve uncertainty. "Acceptable risk" is one way to deal with uncertainty, since it involves "let's wait and see" or "no-decision" strategy for assessing damage. The problem of using "no-decision" strategy is that it involves "a decision" to allow current scenario to continue and only address it when it becomes visible. Since symptoms are manifestation of an underlying problem it is difficult to assess how "large" the problem is without addressing the uncertain part. If we can map out the underlying problem we can make visible the uncertain parts and assess them.

Transboundary pollution is a Regional problem that is impossible to deal with on a country level. It would seem reasonable for the emission country to bear part of the costs for ecological degradation. This sort of problem is impossible to deal with in the absence of all of the alternative stakeholders and without increasing the so-called "system boundaries" of the problem. When we view the problem on a local level we only see the symptoms and often dismiss the feedback to the "doer" (figure 2). This is not intentionally done but rather stems from our problem solving strategy. Our problem solving strategy is often based on linear thinking, which neglects the feedback and the behaviour in our problem. We again, become focused on treating the symptoms rather than dealing with the underlying cause.

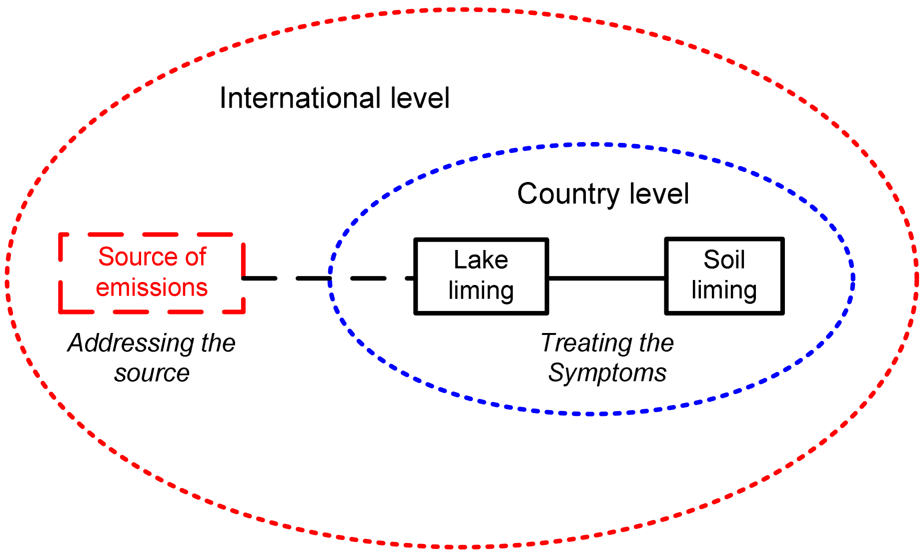


Figure 2: In order to deal effectively with the dilemma of acid rain all the actors need to be included.

3.1 Mental models and feedbacks

Many failed policies stem from misunderstanding of problems and can be explained by the structure of logic we use. We all have and use mental models in our daily work to simplify how the world works around us (Dörner, 1996). This mental model of reality we use continuously to learn and analyse situations and making decisions. Normally we don't have problems with our mental "reasoning" because it appears to work in most cases, e.g. balancing the check book at the end of the month. Similarly, the use of smoke stack filters on emissions works as long as we ignore the long-term consequences of CO_2 production and climate change. As a consequence we tend to develop routines and skills that are based on our mental models e.g. driving early to work to avoid traffic or putting on a jacket before going outside, etc. These routines seem very simple and obvious and not necessarily connected to mental modelling, but we have grown unconscious of our routines since the models we have developed about them are working just fine and they involve instant reaction, i.e. the action involves instant changes (feedback) that I can observe in time and space. We base all our decisions on our mental models and since we often become so dependent on our routines and skills we have difficulties to detour from them in order to take in new understanding (see figure 3).

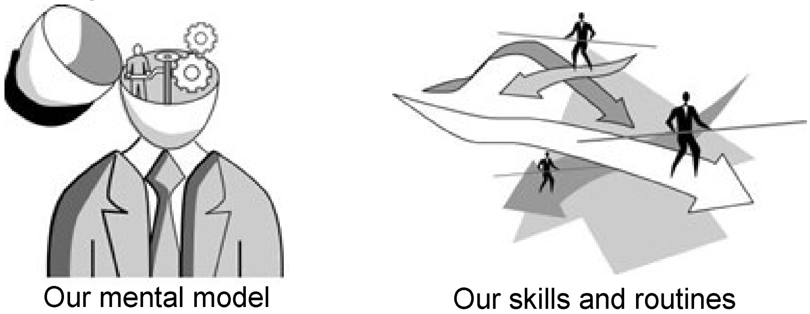


Figure 3: From our mental model we develop our skills and routines.

The human mind best understands models that are linear and static, which describe a set of linear relationships that *do not change* over time. If for instance we are situated downtown during rush hours we observe that almost everything is moving, but when we take a picture of the situation, we "freeze" the moment (Grant, 1997). That is, everything is fixed according to the particular moment of time when we took our picture. Static models are "frozen" models or so-called linear models where time is not an independent variable. All "movement" in static models is extracted like in correlated examples, e.g. correlation between number of cars and number of bus passengers or of lake water quality and reproduction of fish. We know that when it is cold outside we need to put an extra sweater on (see illustration below). Here time is not relevant to us since we use the temperature to determine the amount of clothes needed to maintain a comfortable temperature. This is how our mind works in most cases, our simplification works well in most situations. We only encounter problems when our static representation of reality (routines and skills) is inefficient to simplify the complexity of the real world (figure 4).

Figure 4: Our linear thinking works in most parts.

Most problems are dynamic, and that means that variables and relations vary with time. The most essential factors concerning dynamic behaviour are the feedbacks. In a dynamic behaviour the feedback is determined by time or the so-called time lag. We can estimate the amount of clothes needed for certain temperature, but our initial assumption does not take into account fluctuation in temperature during the day because it is not linked with time e.g. the instant feedback of realising that its way too cold when you step out of the door. If we know that it will start to rain later in the day (assuming weather forecast) we start to link time to our mental model and just to be on the safe side we take a rain jacket with us. Just in this simple example we have created mental model with a feedback (see figure 5). Another example of feedback could be a model that describes a fluctuation in household water consumption or urban traffic during the day.

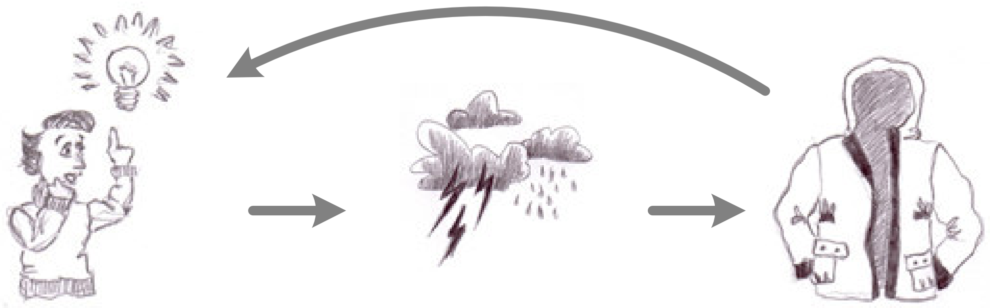


Figure 5: We tend to think in feedback terms without realising it.

Although the human mind can understand behaviour through time it performs poorly when confronted with complex dynamic behaviour that incorporate many variables and time lag. Usually we have no problem to grasp behaviour of two to three dynamic variables. But problems start to arise when variables exceed three or four components that move dynamically. The mathematics are just too complex for us to understand, especially the longer the time aspect is (similar to the dynamics of the economy or interaction in an ecosystem). At this stage it is very important to structure our logic such that we can identify what, how and when to act in complex situations (Dörner, 1997). This is how and why system thinking was developed in the first place.

Traditional education has taught us that reality is made of linear relationships, but in reality, it is made out of circular arranged events. We tend to see everything in straight lines. According to Senge (1990) *A linear view always suggests a simple locus of responsibility. When things go wrong, this is seen as blame- "he, she, it did it" –or guilt- "I did it." At a deeper level, there is no difference between blame or guilt, for both spring from linear perceptions. From linear view, we are always looking for something that must be responsible (p78).* A linear view also tends to put the individual into the centre of attention rather than taking the neutral approach. In mastering system thinking, we give up the assumption that there must be an individual or an individual agent, responsible for the problem encountered in a system.

When we work with system thinking we work with the concept of "feedback". Feedback is responsible for changes within systems, i.e. action causing reaction. Feedback does not mean opinion or encouraging remarks. Feedback means response to an action or inverse flow of influence in regard to an action. It is any action that causes an effect back to the starting point of the action. Feedback is thus both the cause and the effect. The most important issue about the feedback perspective in system thinking is the suggestion that *everyone shares responsibility for problems generated by a system.* Thus no "one" factor is solely responsible for changes in a system (Senge, 1990, 1994). With CLDs we have the possibility to conceptualise and construct our circular connections and the feedbacks in our problem. By drawing our mental model in such a way we can predict the behaviour of our problem.

4.0 What is a System and what is behaviour?

In nature and in the human environment everything is connected to everything else in a complex web of interactions. For us to grasp only fraction of these connections we need to isolate the issues we want to observe and confine them into a systems. What is a system? A system is a network of multiple variables that are connected to each other through causal relationship and expresses some sort of behaviour, which can only be characterized through observation as a whole (Rosnay, 1979; Dörner, 1996; Sterman, 2000). The principal attribute of a system is that we can only understand its dynamic behaviour and interaction by viewing it as a whole.

What kind of system are there? Basically everything can be categorised and defined as a system. One way to describe a system is to review a technical one which we can easily sort out, e.g. a bicycle. A bicycle can be considered as a *system* or a whole where its functions are dependent on interactions of its parts, the frame, chain, wheel, breaks etc (see figure 6). In isolation, the parts can never be identified as a *bicycle* because the function of the bicycle is not embedded into individual parts but into the interaction between all of its parts. A person that has never seen a bicycle and sees one lying on the ground will never consider it other than a pile of metal welded together. Only if one sees someone riding a bicycle he/she will gain understanding of the functionality of the "pile of metal welded together" and connect its use in a broader term to transport or leisure etc. As a result we can only understand the behaviour of the bicycle if we see someone ride it (see figure 6).

Figure 6: A bicycle is a system, which is characterized by its behaviour, the interaction with the cyclists.

What is essential in this aspect is the bicycle rider. Without the rider the behaviour of the "bicycle system" does not exist. We have now made distinction between the *parts* and the *whole*. The *parts*, which we analyse in a system, are the physical bicycle components by themselves and the whole is the interaction of the parts and the behaviour of the bicycle as a functional unit.

Let us now look at a natural system. Properties of a forest cannot be analysed just by looking at one tree. Factors such as the climate, grazing animals, soil and topography, are components, which characterise a forest and can thus not be excluded if we want to understand a forest as a whole (figure 7).

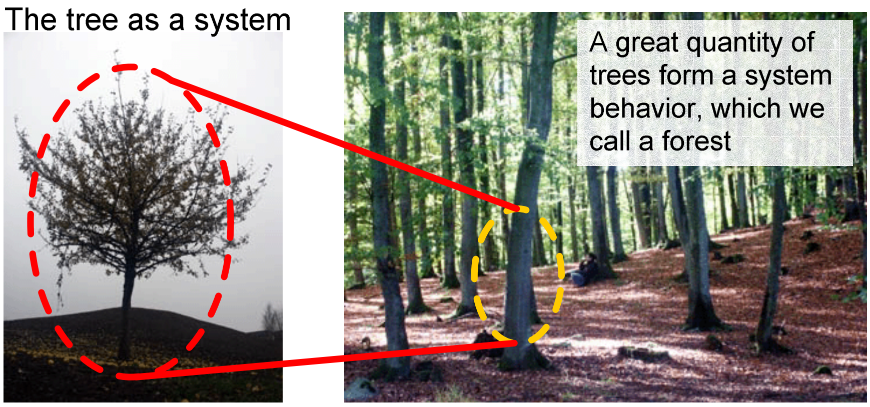


Figure 7: The forest is much more than can be observed in individual trees.

The tree by itself is a system that takes in nutrients and water and exchanges gases. Alone the tree stands fragile against winds and rains but collectively in a forest the trees change the evolution of the topography, the soil and the microclimate. This is the behaviour of the forest system. A forest itself also hosts many specialised species that thrive on the conditions created by the forest and these conditions are mutually the *whole* created by the parts (the trees).

People and society are also a system. Similar to the forest the individual person collectively creates the society and all the specialisation. We as individuals stand fragile alone, because our capacity for survival is limited. In a group we can specialise and have certain functions, which collectively benefit the group as a whole, and for the individual. A team of sailors are an example of individuals that have specialised functions on board a boat. Together they accomplish more than if all of them were merely individualists and uncoordinated. They work together toward a benefit that is accomplished by their cooperation.

Another example of a large system is a city, which can be viewed as a system whose purpose is to provide employment, housing and other social benefits for its inhabitants. People have specialised jobs and functions in the society but collectively we all increase the quality of life of all the individuals (see figure 8).

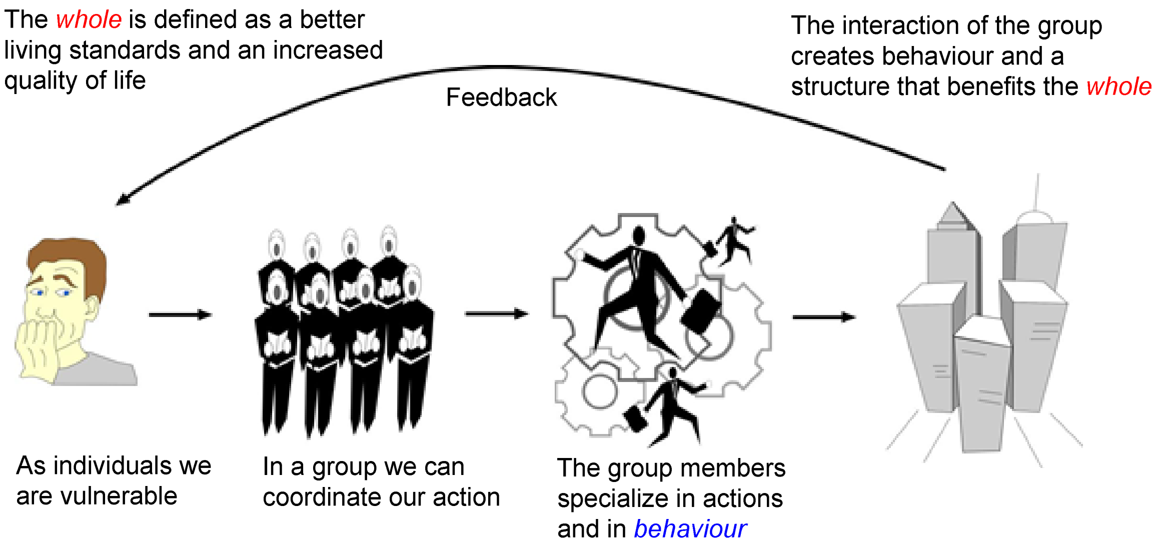


Figure 8: By participating in a large dynamic group, the individual acquires certain benefits that are only generated by the *whole*.

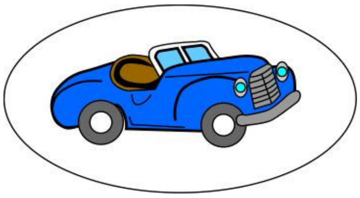
We can state that when we use system thinking we are observing the *dynamic relationship* between all the parts within a system. The system is steered by its feedback and in order to understand the behaviour of the system we need to understand the feedback and its system boundaries.

4.1 System boundaries

All systems are defined by its boundaries. In order for us to understand a system properly we need to understand how systems behave and what their properties are. Systems are usually confined by certain inflow and outflow of energy. What makes it difficult sometimes is to see the pattern that confines the system, e.g. determining where boundaries between forest and prairie.

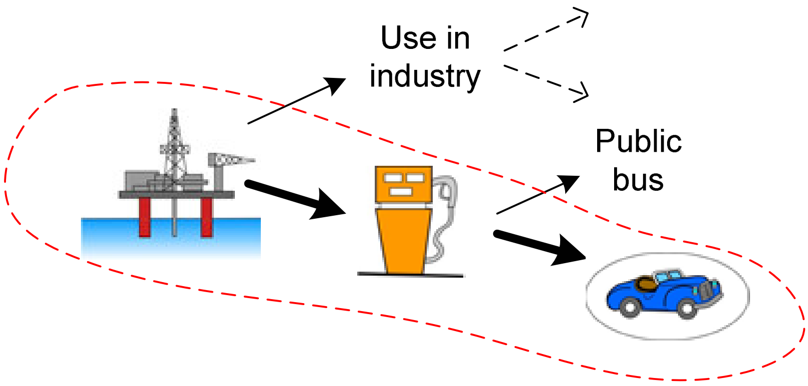
The principle of system thinking is that all behaviour in a system is a consequence of its structure. The structure of a system determines its development, success and failure. The solution to solving a problem within a system is right there and going outside it to look for a cause of the problem is either erroneous or indicates that we need to expand our system boundaries. Of course we cannot solve all problems within our defined boundaries. This is because a system contains sub-systems and is always embedded within a larger system and. For example a corporation may be experiencing difficulties that originate not internally from its own policies but from governmental regulations or the macro economy (Cover, 1996).

A car for example can be considered a system that has special functions. The variables (components) in the "car system" are the engine, gearbox, steering system, tires, electronics and etc. What we consider a "car" is the sum of *functions and interactions* between all of these components in the car. The car maintains its functions through *feedback processes* of all its properly placed components. We know for example that the tires must be placed under the car not on top of it, and they need to be circular not square for them to operate with satisfaction. We also know that the car will not operate properly if we take away some of the components such as the headlights, windows, etc. This we know because we have a fairly good understanding of how the car behaves as a system when we drive. Not because we understand all the details how the car is built, but how *its system behaviour* is, e.g. the driving itself, re-fuelling, small maintenances, etc. The system boundaries for the "system" car would be the physical structure itself incorporating all its components (engine, fuel lodge, battery, etc) or simply "the car".



How can we be sure that this would be our definition of the system "car"? One way to look at it is to observe what goes in and out of the system. For the car example we know that the car is in simple terms dependent on fuel, oil and air. It transforms these materials through its system to exhausts fumes and kinetic energy. What is important to notice here is that the "car system" is not dependent on fuel or oil from explicitly one geographic region, or is restricted to exhausts its fumes at a certain time or location. These aspects are not important, the car runs excellently as long as its criteria for functionality (the feedback processes), fuel, air and oil are met. The system is considered to be in balance.

We could *extend* our system boundaries to incorporate the fuel and air pollution but then we would be increasing our system level observation and the "car system" would become one variable (sub-system) of many in a larger system. Such a system (if considered) could be called "fossil fuel system" or "air pollution system", but these are all definitions we set for ourselves when observing certain aspects of reality.



Similarly we could downsize our system boundaries and decide to analyse e.g. the battery in the car. The battery is a sub-system in the "car system" and can also be defined and confined by boundaries. The variables would be water, acid, lead, copper, structural organization of the container etc. The "battery system" is characterised by its production of electricity and like the car it functions perfectly if certain basic criteria are met e.g. adding occasionally water etc (figure 9).

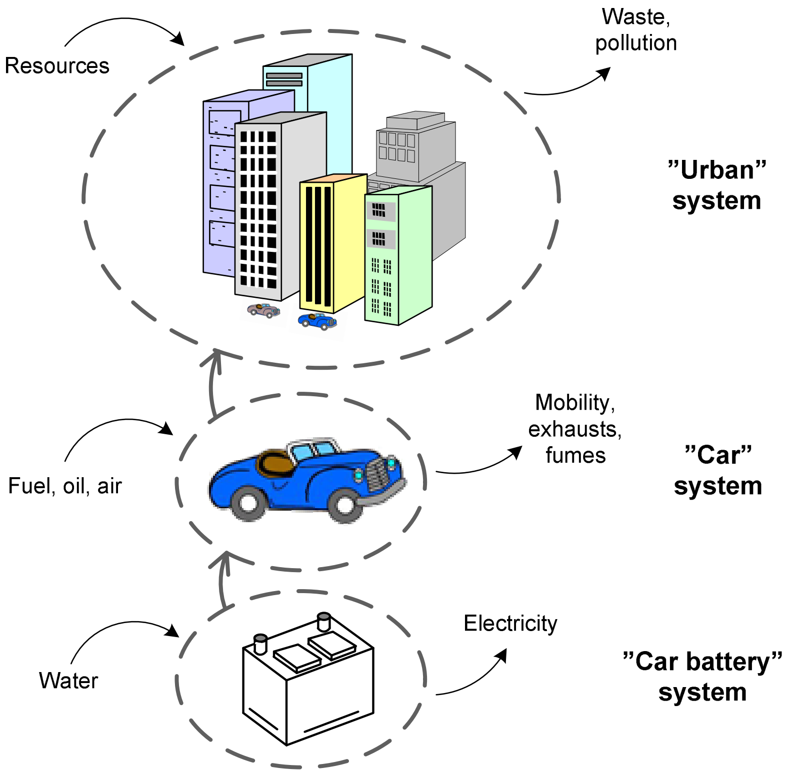


Figure 9: system, system levels and system boundaries.

In figure 9 a city is a large-scale system, which converts resources and energy into waste and products through complex interaction of the variables in the city. The economy, social organization, infrastructure, cars and people are all examples of components which interact within the urban system. The system boundaries are less clear for the urban system than for the car battery or the car since the city contains many sub-systems that are based on sub-systems and so on. More generalization is needed in larger systems such as for a city. Rudimentary, from a perspective of a geographer the urban system can be confined and defined as a geographical point where resources are converted to energy and waste. An automobile is a system made up by components such as engine, gearbox, car battery, tires etc. The automobile system boundary is defined by its physical size and the interaction of its components. The production of kinetic energy is the automobile's system behaviour and it is in balance if necessary materials maintain it (in this case fuel, air, oil etc.) The car battery is a system confined by its casing and the components water, lead, copper, acid, iron etc. which create electricity through interaction. The delivery of electricity is the system behaviour of the battery. The system is in balance if necessary materials and service maintain it (in this case water and recharge of electricity from a generator).

When we define and confine a system we need to understand its basic behaviour, understand what is flowing in and out of the system, physical units or simply information. Then we need to define the system level we are observing, is it on a molecular scale or a global scale? "Does the system which I observe move between different system levels?" E.g. dealing with local climate change in global perspective.

4.2 Identifying complexity

It is important to understand *dynamic complexity* and not *detailed complexity*. When we construct our mental model and define our system we need to be aware of the level of details. Generalisation is often the key to understanding complex systems. The following figure 10 illustrates how our understanding of the system increases to certain extent until we have added so many components in our mental model that our performance and understanding decreases due to its complexity (Haraldsson and Sverdrup, 2003). This happens because our ability to grasp the total dynamic of the problem becomes weaker and weaker the more variables we add (figure 10).

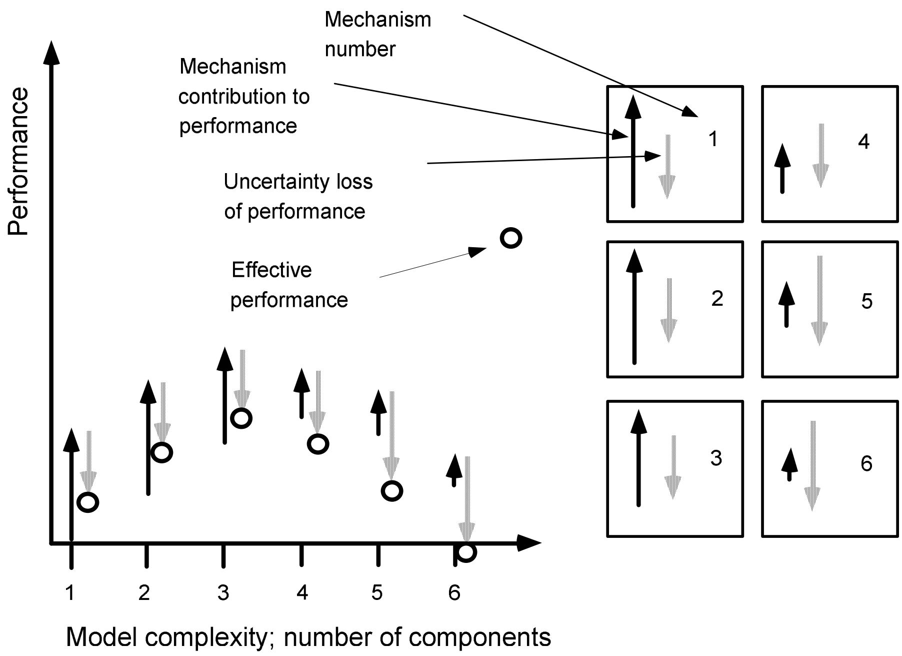


Figure 10: There exists an optimum understanding/performance in relation to model complexity.

When we create mental models we do not intend to capture the whole reality in one model. Such models are as complex as reality itself. What we want to do is to map part of the reality in such a way that it gives us a basic understanding of the complex problem. In figure 10 we can see that at one point we have generated the highest understanding from the system in proportion to its complexity. That's where our level of details in our model should not be more. For example if we are trying to understand car pollution in a city system, going into engine details would only add unnecessary details and complexity and weaken our understanding of the system's behaviour on an aggregated level.

The example in figure 9 shows different systems and system levels. Every system incorporates some sub-systems like the above example. The car battery is theoretically a sub-system on a very detailed level within the urban system and similar can be said about the automobile. But what can be seen here is hierarchal tracing of the urban system. The automobile is defined as an interacting component within the urban system, influencing its development. The car battery, is defined as an interacting component within the automobile system.

We can now observe how systems are integrated into other systems. Variables that we choose are in fact sub-systems themselves and their components also sub-systems and etc. It is important when defining and confining a system (and its boundaries) to identify the system level that we are operating on (figure 11). Do we have variables that are working on several different system levels simultaneously? As seen in figure 10, we can conclude that the larger number of variables we are considering the greater the complexity and our uncertainty around these variables. When we are observing a large-scale system that contains endless number of variables and integrates through multi system levels (such as the global climate), there is a need for simplifications. We need to generalise and ask the appropriate question that confines our system boundaries within determined spatial and time scale (figure 11).

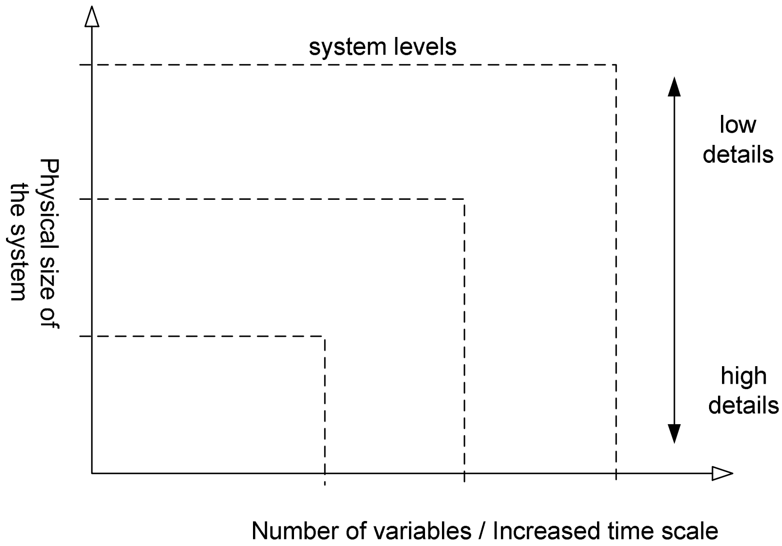


Figure 11: Large systems incorporate many variables which requires more generalisation and accurately refining of the question we want to answer. Notice that with increased physical scale of the system the time dimension changes and our generalisation for the variables in our study (Haraldsson and Sverdrup, 2003).

When we are defining our system boundaries in time and space we need to observe so-called supersignals (Dörner, 1996). Supersignals (or key components) are the variables that create the patterns or the feedbacks we observe from the interaction of the variables within the system. For example when we learn to drive a car or to ride a bicycle, we learn, by detecting the feedbacks we get from steering in different directions, accelerating or braking. Supersignals gives us the key variables that we use to move between system levels in time and space. They are our key to understanding the system behaviour and the classification of the system. An example of this is the car which has a lifetime of 10-15 years. All its components, e.g. the battery have a lifetime that runs within that period. If we were to aggregate our observation to an urban system level, then only the "car" (not its components) would be considered as a key variable (or supersignal) among other variables within the system, such as road etc.

This is because the urban system has a longer lifetime (over 100 years) than the car. Therefore the behaviour of the car within the urban system can be simplified. When we are defining the level of detailness in our system we should select the level needed to understand the interrelationship among our "goal" variables, the one we want to influence to answer the question we pose for the system. When we have defined that level, then detailed knowledge of the underlying components is not needed (similarly with the car and urban system). In the case of the driving, detailed knowledge is not needed on the construction of the engine; we can operate the vehicle without such knowledge. Our supersignal in the driving process comes from the overall behaviour of the underlying variables in the vehicle which can be defined as a behaviour variable. Identifying the system level can by done by determining what features can be collapsed into a single supersignal (figure 12).

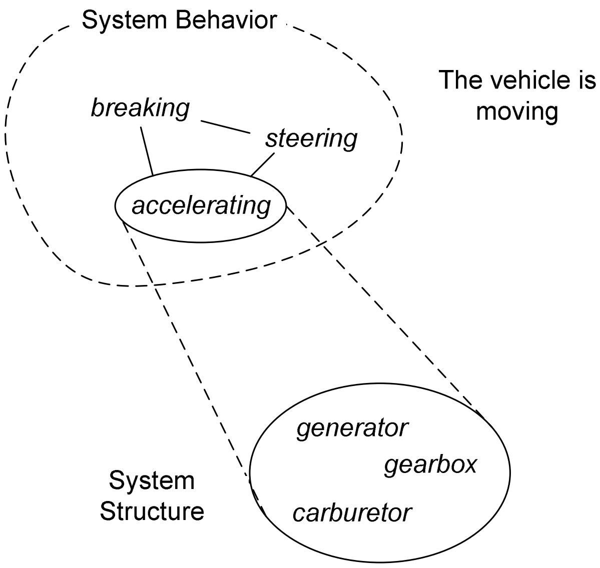


Figure 12: Supersignals create the system behaviour through the structure of the variables on the lower details.

Identifying the system level and its boundaries requires great consideration on defining the problem and asking the basic questions we want answers to (Haraldsson and Sverdrup, 2003). It requires a group effort from individuals that are stakeholders in the problem or have invested interest. The key is to share and communicate the information on the problem. Dörner (1996), stresses the need to identify the goal variables and their dependencies in order to understand the causal relationship. Similarly, it is important to identify the hierarchal structure of the variables and how they are embedded spatially and temporarily in order for us to make an accurate hypothesis on the problem.

4.3 Sorting the problem

System Thinking starts by defining a problem. Defining a problem often requires a group work with relevant stakeholders and problem owners. After specifying the system boundaries of the problem and focusing the question, all the key variables relevant to the question are listed. Ideally, the variables relevant to both the question and the answer to the problem should be discovered during the process. As discussed in figure 11, the variables should be sorted according to spatial and temporal influence e.g. where in the hierarchal system levels are they placed. Sterman (2000), points out that it is important to distinguish between what components are interactive within the system (internally) and thus enclosed by the system boundaries, and the components that are outside the boundaries but influence on the system (externally). For instance, if we are investigating grass growth in relation to herbivores, climate would be considered as an external influencing factor on the system but herbivores an internal factor within the system.

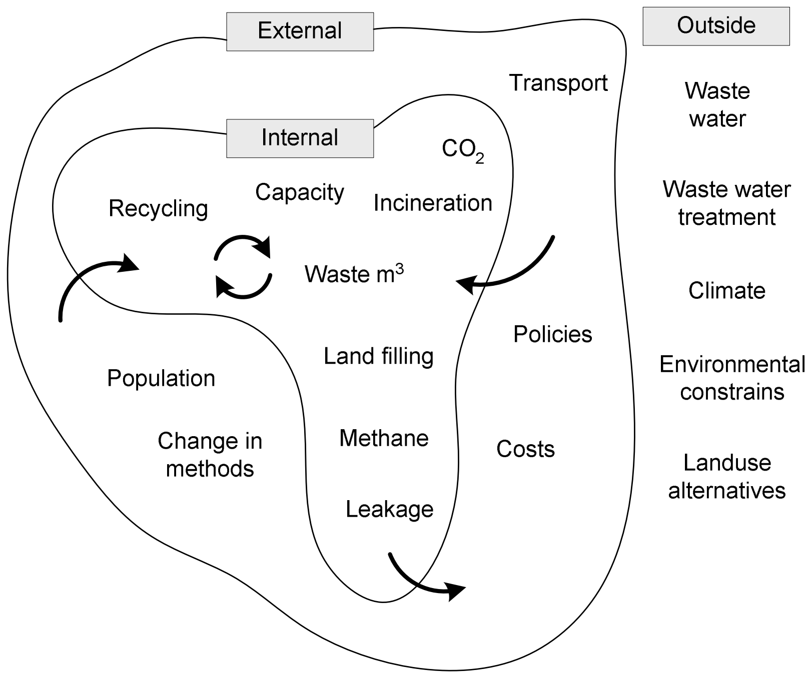


Figure 13: An example of internal and external factors in a system describing solid waste treatment.

What is interesting from figure 13 is that variables describe different action and events. If the question was; how do different alternative waste management reduce the solid waste production, then we can see that the internal variables are moving in a short timescale (daily) as external variables are moving on a yearly basis, e.g. population growth. Using this information we can do the system level approach (as done in figure 11), we place the different variables according to their influence in time and space and our focus on details within the system (figure 14).

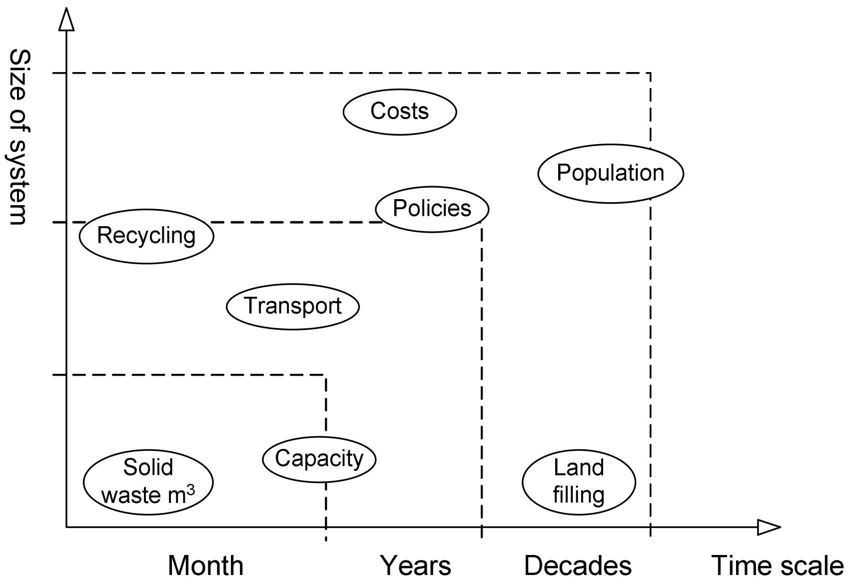


Figure 14: A system can be sorted in time and space in order to help us to focus on were in the problem our effort should be put.

In this example the driving force is the solid waste generation that runs on a monthly basis but is influenced by capacity of the land fill and the population size that is generating the waste. This enables us to estimate what the observation time scale should be for our long-term planning and how to work with our scenario analysis.

We should also sort out in our problem what are "soft" variables within the system. Normally we use words to describe our variables that are linked with quantity, e.g. solid waste, capacity. It is also possible to use variables that are information such as "policy" or "mental capacity". Since we are dealing with structures and feedbacks in our problems, using soft variables becomes as important as using quantifiable ones. Very often soft variables are the only thing that can be considered in a problem in order to understand its behaviour, e.g. social issues.

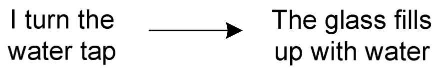
5.0 Understanding Causal Loop Diagrams

As you probably have noticed there has been quite a lot mentioned about feedback in the examples above. In this chapter we will look closer at how exactly feedback is formed in a system and linked in causal loop diagrams (CLD). The Causal Loop Diagrams concept was first discussed in the sixties by Jay Forester (1961) and further elaborated by researchers such as Rosnay (1979), Richardson and Puch (1981), Senge (1990) and Sterman (2000). The function of CLD's is to map out the structure and the feedbacks of a system in order to understand its feedback mechanisms. The CLD's are used to understand how a behaviour has been manifesting itself in a system so we can develop strategies to work with, or counteract the behaviour. We also want to know to what extent and how the problem is connected with other "systems".

Every time we are observing an issue or problem, we ask questions. Every time we want to understand a process, we ask questions. We form questions as; why this or that is happening in the problem and how can it be solved or understood?. The CLD's *always reflect our questions. Therefore we can confine the system to the question asked, thus the question becomes the system boundary around the problem.*

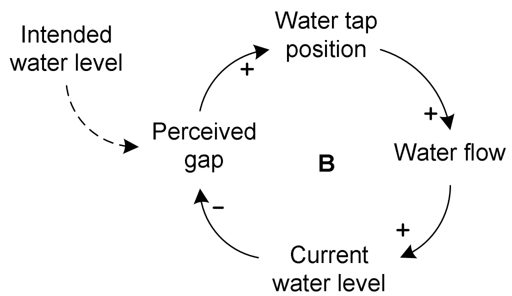
5.1 Drawing Causal loop diagrams

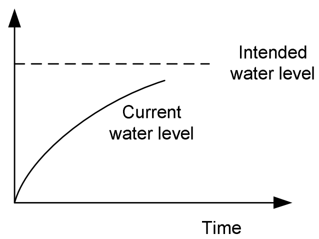
CLDs describe the reality through causalities between variables and how they form a dynamic circular influence. We want to observe the world through feedbacks rather than linearly. We want to observe repeated patterns that may be used to predict the behaviour in the problem. It's about understanding cause and effect. Let's look at one example that is very familiar to all of us- filling a glass of water. If we would state it from a linear point of view we could say, *"I want to fill a glass with water,"* which of course sounds very logical but tells us only half the story. We may control the rate of water flowing into the glass (as the statement implies) but the level of water in the glass also signals us when to close the faucet. The traditional logic would be something like the following:



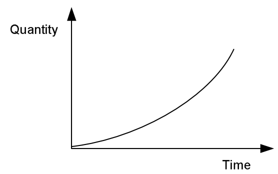
If we use the CLD language, we use feedbacks to explain the process. We start by asking the initial question: "I want to understand how water flows into the glass and what I do to fill it up." Instead of looking at the action from an individual point of view, where the "I am" is the doer and at the centre of focus, we shift our perception to the structure of the action. The "I am" simply becomes a part of the feedback process, not standing apart from it. Suddenly we have shifted our attention to the structure of the behaviour and we can observe that the structure is causing the behaviour. The CLD allows us to follow the action in details and we can read the "feedback" in the CLD like a story. Since we desire a certain water level in the glass, let's start by turning the water tap (modified from Senge, 1990);

> *I want the water level in the glass to be high and that will be my intended water level. I turn on the water tap so the water starts to flow. It increases the water level in the glass. With higher water level the perceived gap from the current water level and the intended water level changes. As a result to changed "gap" (which reduces the difference), I change the water tap position and etc.*

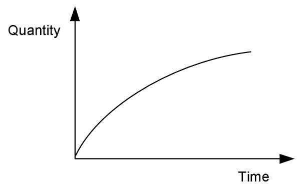




We have now transformed the traditional linear thinking into a circular argument. Lets at last observe the difference in the perception between the original statement: *"I want to fill a glass with water"* and the new one we have just formed with the CLD; *"The action to fill the glass of water created a system that caused the water to flow in at low water level and to stop the flow when the water level reached my intended water* *level"*. Both the statements express the same intention but describe the process in a different way. As observed, *the effects of the last variable influence the input of the first variable (the one we started with)*, which results in a self-regulation of the system, indicated with a "B" for balancing, in the middle of the loop. Systems always behave in a circular organization forming feedback loops. Regulation of a system can either result in a *self-reinforcing* system or a *self-balancing* system. A reinforcing system (or amplifying) is a system in growth; such as a bank account, economic growth or bacterial growth. Note that the intended water level and the current water level have been plotted on a time axis. The CLD's are always drawn on a temporal scale. This is expressed graphically as Reference Behaviour Patterns (RBP). A reinforcing system is an escalating effect due to equivalent influences between the components, which can be either a downward spiral or an upward. (see below):



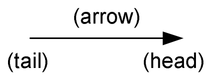
CLD can also display systems that are seeking a specific goal, such as the water in the glass example. In a *balancing* system there is a variable which hampers the exponential growth or is a limiting factor to the growth of the loop. Filling the glass of water is an illustration of a system seeking a specific goal balancing system since the glass can only hold a certain amount of water. This is a system that moves towards stabilisation or a balanced state (see below).



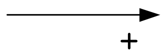
To put system thinking in practise, several rules have to be followed so that "cause" and "effect" can be illustrated in a right way (see following table).

The Causal Loop concept explained (adopted from Roberts *et al.* 1983, p56)

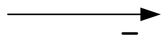
The arrow shows a causality. A variable at the tail causes a change to the variable at the head of the arrow.

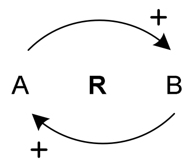


A plus sign near the arrowhead indicates that the variable at the tail of the arrow and the variable at the head of the arrow change in the *same* direction. If the tail *increases*, the head *increases*; if the tail *decreases*, the head *decreases*.

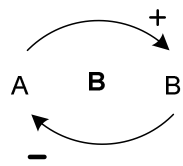


A minus sign near the arrowhead indicates that the variable at the tail of the arrow and the variable at the head of the arrow change in the *opposite* direction. If the tail *increases*, the head *decreases*; if the tail *decreases*, the head *increases*.



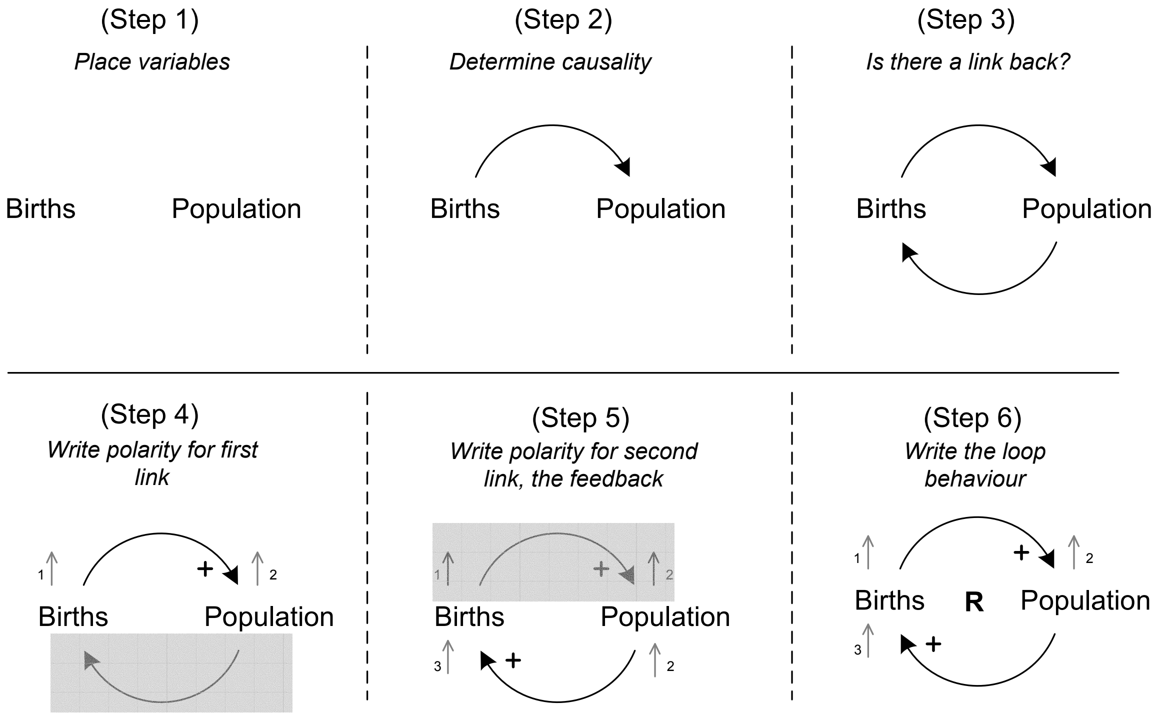


The letter **R** in the middle of a loop indicates that the loop is *reinforcing* a behavior in the same direction, causing either a systematic growth or decline. It is a behavior that is moving *away* from equilibrium point.



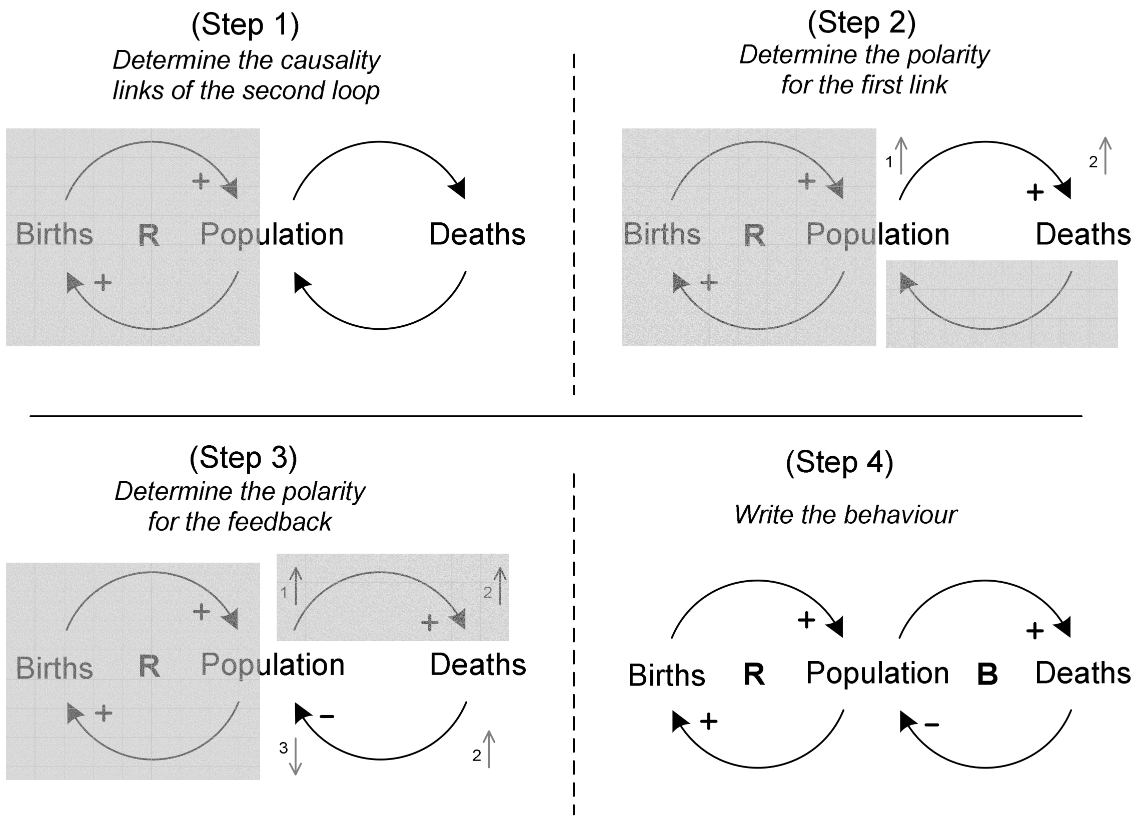
The letter **B** in the middle of a loop indicates that the loop is *balancing* and moves the system in the direction *towards* equilibrium or a fluctuation around equilibrium point.

To further illustrate Roberts explanation of the causal loop concept lets look more closely at the variables at work in the loops. Lets consider a reinforcing system of population that has high birth rate and thus a net increase in population. We can use six steps to work out our CLD (see explanation 1);



Explanation 1: connecting the links.

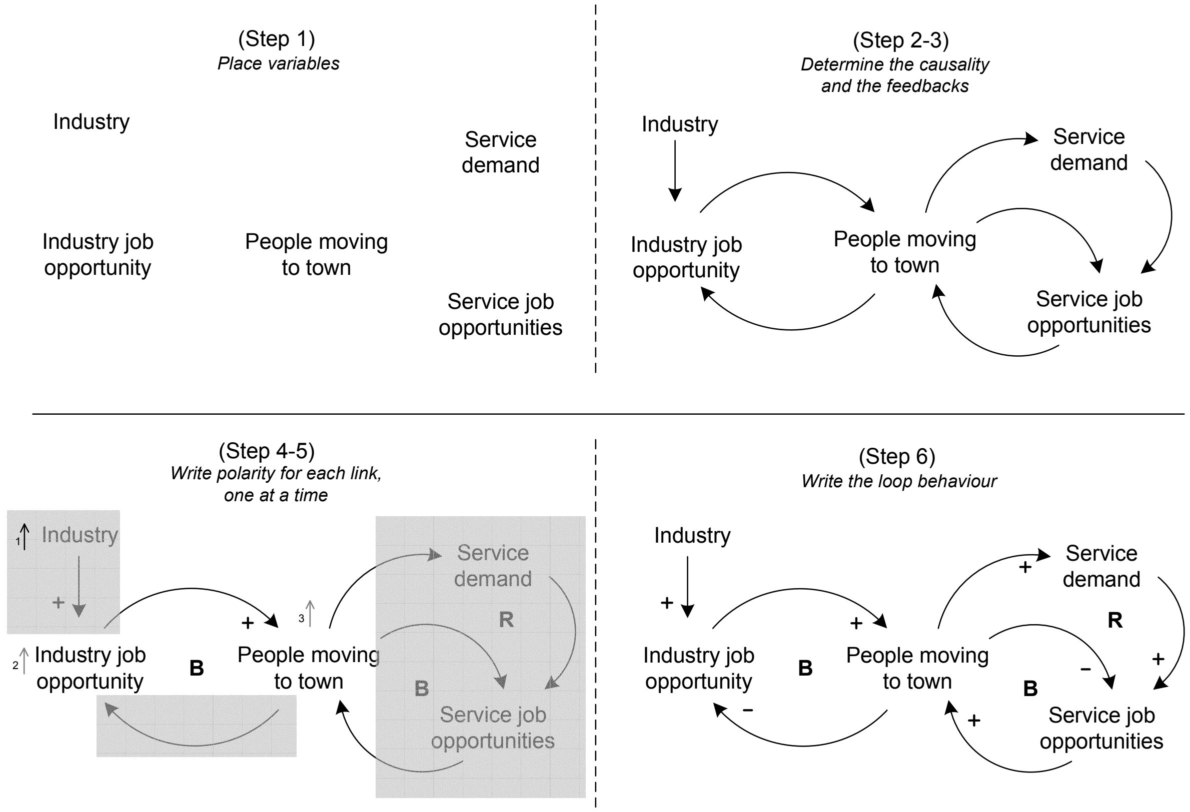
When determining causalities between variables, we always look at the links separately. Remember when you are done putting the polarity (signs "plus or minus") on the loop you can erase the small assisting arrows. They are only there to help us determine the loop behaviour. The shadowed feature (see explanation 1) placed over links indicates that we are only considering one link at the time. The feedback from the last variable to the first one (where we started) determines the behaviour of the loop. Increased birth came back to birth as an increase (from population). If the variable death is added to the graph we would work with the loop as in explanation 1 but add the "death" part afterwards (explanation 2).



Explanation 2: Adding a second loop.

In the actual situation the death rate would balance the increase in population up to the point where number of births equal number of deaths. The first phase would be reinforcing and the second phase would restrict the population size. Despite the complexity of systems, it can be stated that reinforcing loops are always temporary states in systems; they will be balanced out by a one factor or another. The important factor is to identify how long the reinforcing situation will endure, it can last from minutes to millions of years depending on what we are observing.

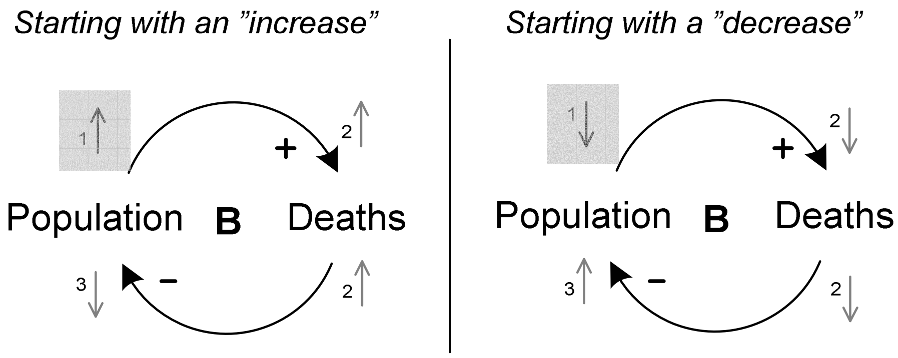
Lets look at a slightly more complicated CLD on urbanisation and job opportunities. In a city there are people moving to town since an industry has established there. Lets assume that we have decided on the question; "what happens to job opportunities when people move to town?" We have sorted out the variables that are part of the system and we start to construct the diagram (explanation 3).



Explanation 3: Job opportunities and people moving to town.

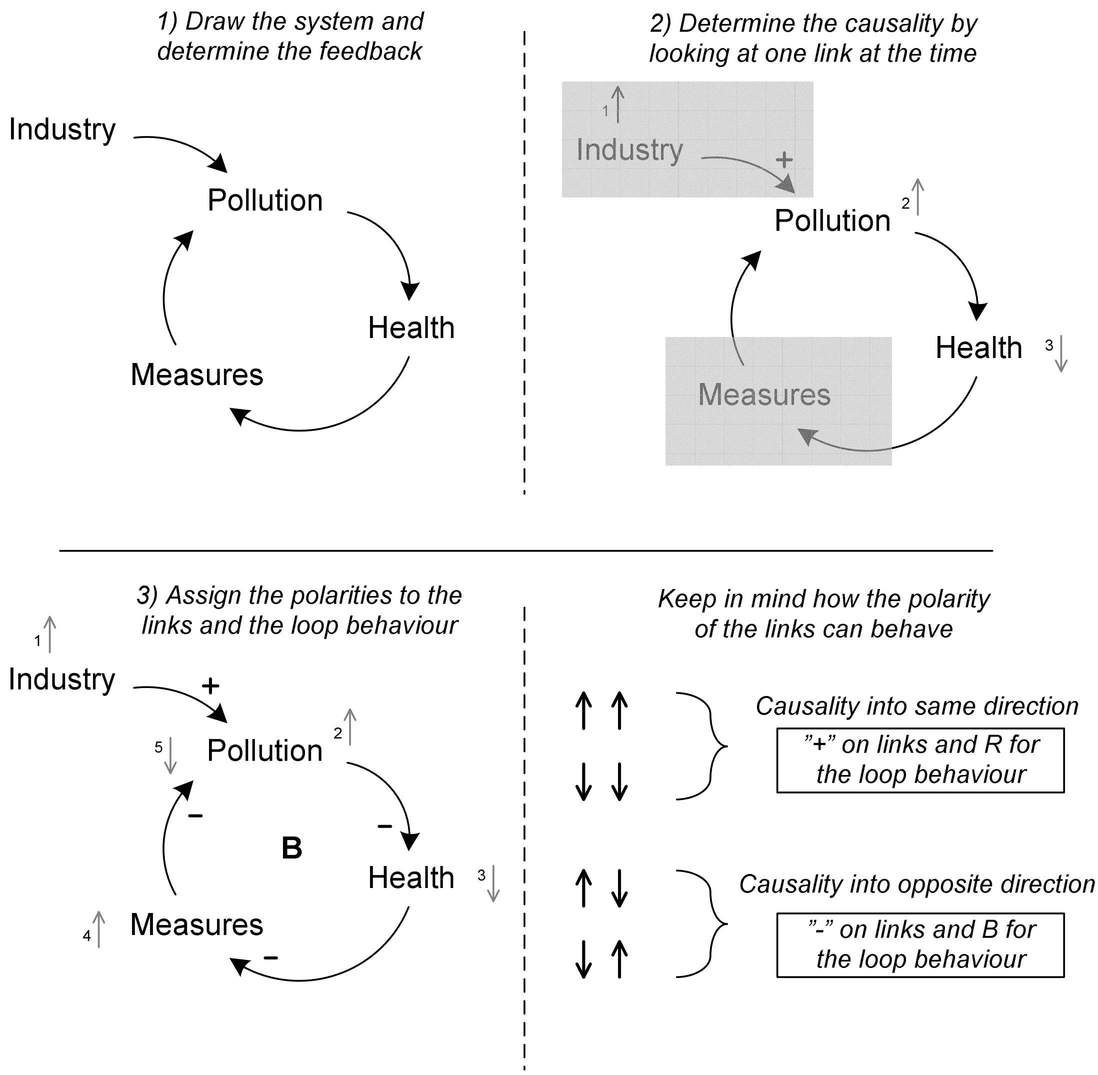
Now we should read the story out of the loop (in explanation 3). As the industry is placed in town there are industrial job opportunity created (more industry, more job opportunities). It drives people to move to town, and when people move to town, they take the industry job opportunities (more people, less job opportunities). This is our first loop. The second loop stems from a secondary effect of people moving to town. It creates demand for service, which in turn creates an opportunity for jobs in services (to service the industry workers), again "more demand" causes "more opportunities". Now, when the service job opportunities increases it feedbacks back to "people moving to town" and causing more people to come. People moving to town also take jobs in the service sector, thus reducing the number of service job opportunities. We have thus three loops here that affect people moving to town. The variable industry is not affected by any other variable in the loop and is thus an external factor in the system behaviour. It is an external factor due simply to the fact that it was not part of the question "what happens to job opportunities when people move to town?"

It is very important to understand that once we have put polarities on the causality links, they always stay the same. You can start with "reduced" births, which will reduce population etc. The polarity stays the same. Sometimes when reversing a causal loop, e.g. starting with a decrease, we are faced with a situation when interpreting a minus or a plus sign can lead to some confusion. Lets look at the following example of population dynamics (see explanation 4).



Explanation 4: how to read, starting with a decrease.

This causal loop suggests that the *more* people there are, the *more* deaths there will be. The connection to total population is that the *more* deaths there are the *fewer* people there will be. This sounds very reasonable but we can also look at this in reversed way, when there is a *decrease* in the total population. This is what the CLD states; *the fewer people there are, the fewer deaths there will be… the fewer deaths there are… the more people there will be.* But is that necessary true? If death goes down, does population actually rise? No it doesn't unless the population is connected with a birth loop. What this loop states is that when *the fewer deaths there are…the more people are* ***left remaining*** *in the total population.* Alternatively if number of deaths decreases, the population still decreases but at a slower rate than before. It is important to use the right wording when explaining the CLD's and remember that we don't change the polarity ones it is set. It should read correctly in either direction. We can look at another example with industry and pollution. There is an industry that is causing pollution and affecting the health of the population. We want to analyse this problem in an historical perspective and look at what was done to solve it. Our question will be; what triggered the response to industrial pollution? After defining the variables we draw the system and assign the polarities according to example 5.

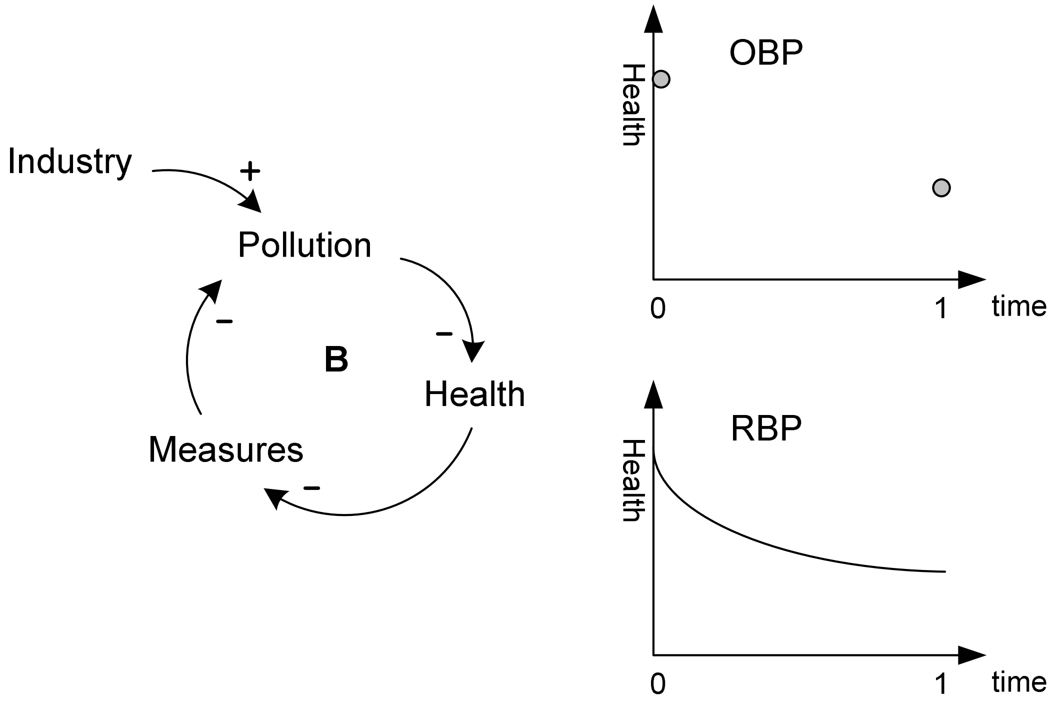


Explanation 5: Assigning polarities and behaviour to a loop.

After we have assigned the pluses and minuses we go through the whole loop and compare the starting and the ending arrows for the initial variable in the loop, “Pollution”. The loop is a balancing system, indicated with B, since the last variable, “Measures” is influencing Pollution *(↑↓)* in the opposite direction. (If we would have a system that had starting and ending arrows in the same directions *(↑↑)* we would have a reinforcing system, indicated with R). From this simple example we explained how the solution” only focused on the pollution itself but not the industry. Industry is only a “one way” influence into the loop, because we haven’t defined anything that affects the industry. Of course we could have a link between “measures” and “industry” but that would be another question and added later.

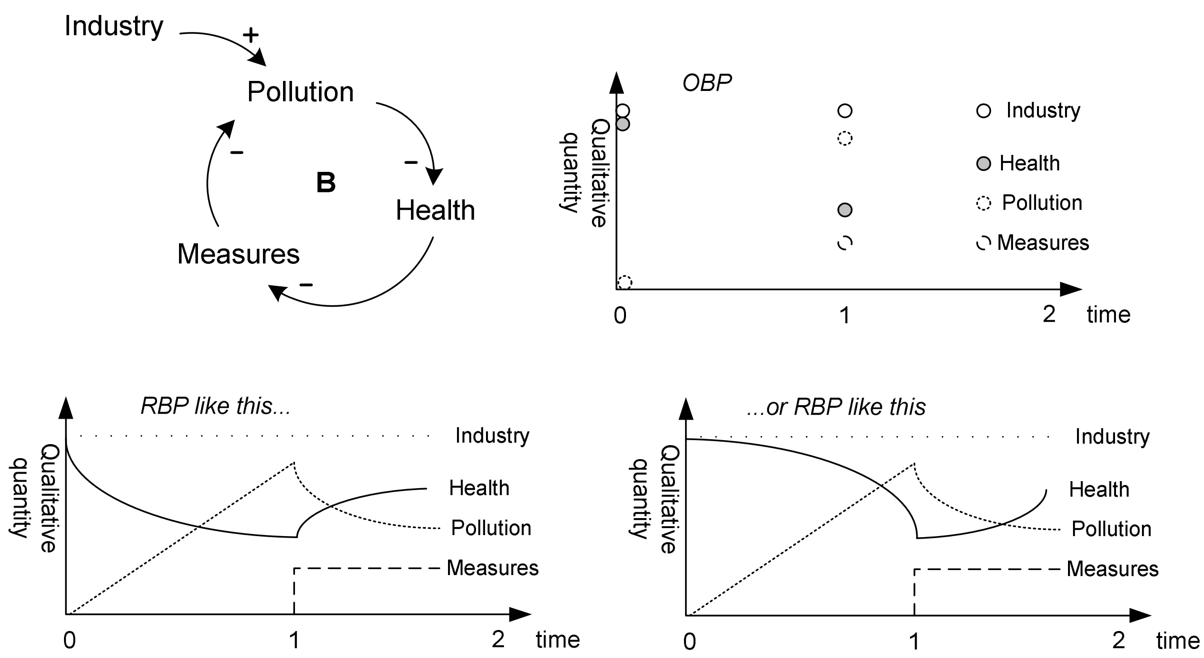
5.2 Reference Behaviour Pattern and Observed Behaviour Pattern

As discussed earlier the Reference Behaviour Pattern (RBP) is a graphical representation of the behaviour over time of one or more variables in the loops we are analysing. We use RBP to chart our understanding of the system. When we are drawing causal loop diagrams we should sketch a diagram from each loop to graphically visualise the behaviour of the variable we want to observe in the loop (look at example filling a glass with water). Observed Behaviour Pattern (OBP) is used to show historical states of the variables at a given period. For example if we look at the Pollution CLD we just drew before and look how health develops through time, we can express it in OBP and RBP (see explanation 6). We know historically that Health was better before the pollution increased so we can assign it as so in the graph.



Explanation 6: OBP and RBP are a useful way to understand how a system behaves.

Here of course we assume the industry is maintaining its pollutant output so we plot the health decreasing toward some conceptual level. Historically the health got worse so we can plot the OBP and draw the RBP into those points. We plot the loop as non-linear since the loop is showing a balancing state. The slope of the loop is less important, it might also be just a linear decrease, but then we are going more into numerical aspect. We could also look at any other variable or put them all together into an OBP and RBP in order to get a better understanding what is actually happening in the CLD (see explanation 7).



Explanation 7: Different alternatives of RBP graph behaviour.

The RBP is purely conceptual but can give an indication on how the behaviour of the variables could develop if we would change something in the loop. We have the information that historically the variables had the qualitative quantity as explained in the OBP so we can then draw the behaviour between the dots. In the diagram we only increased the time axis to see what effects of immediate measures did to the behaviour. Take note that measures is here applied as a sudden action, it can also be a gradual action but it would then change somewhat the behaviour of the variables but not their direction (towards balancing state). In the RBP (explanation 7) there are two alternatives to show how health behaves, one is not more right than the other, unless more information is provided about how health deteriorated and recovered.

When we are analysing loops in our CLD we can generate a RBP fundamentally according to the behaviour of the basic six graphical structures. All systems fall within the structure of linear or non-linear relations (figure 15) or by combination of two or more diagrams.

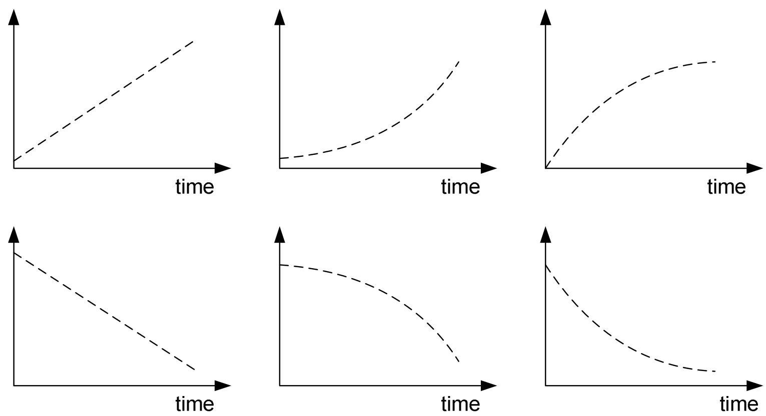
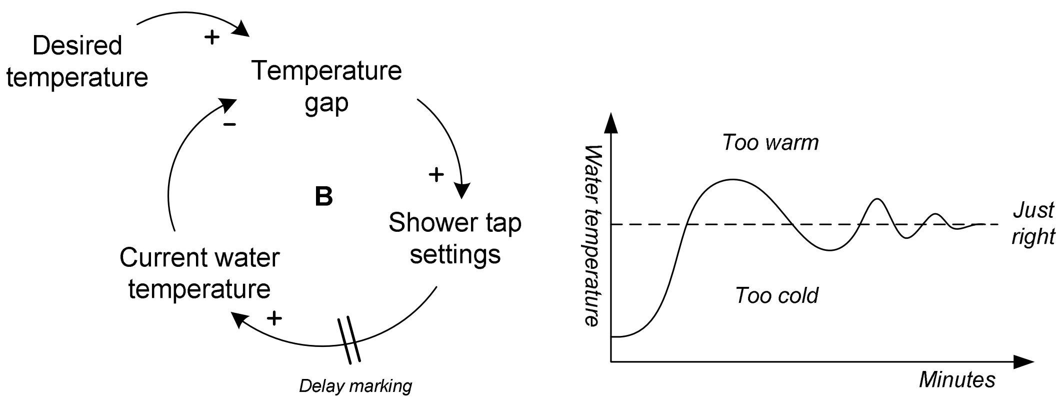


Figure 15: All loops and systems can in basic terms be categorized according to the above principles or combination of them.

The behaviour form in figure 15 is also expected when considering the overall behaviour of a system that contains a large structured CLD. The RBP is more often a combination of loop behaviours as will be illustrated in the following examples.

5.3 Delays

Everybody is familiar with waiting time, standing in the line at the bank, keeping patience while the car is getting warm in the winter time, etc. All systems have some kind of *delay*, which can range from seconds to days, centuries or millions of years. Delays are what cause systems to fluctuate. A delay is when an action between two components in a system is much slower than the rest of the system. A good example is when we take a shower. Everybody knows that it takes some seconds for the hot water to become warm. Since it is cold in the room we want the water to become warm as quickly as possible so we turn the shower tap wide open. But it takes some time for the water to become warm since the pipes in the house are long and the water has to travel some distance before reaching the shower head. When the actual hot water arrives it is so hot that we are forced to turn it down and increase the cold water tap which results in a too cold water. We continue until the water is just right for showering. If we construct a CLD of the water temperature and the RBP it could look something like this (explanation 8):

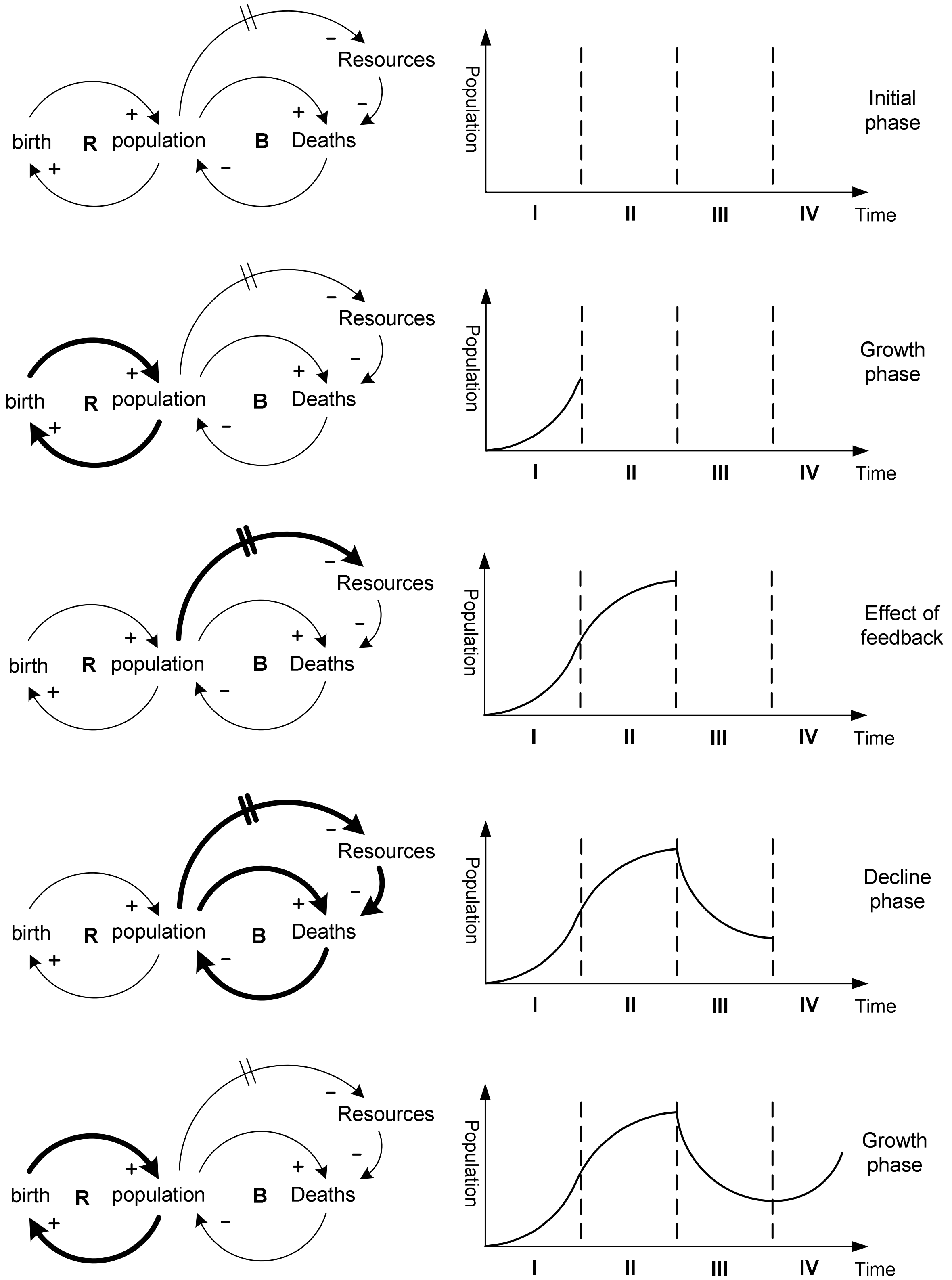


Explanation 8: Showering and delays.

Like before, drawing a delay is a conceptual exercise for us to understand how the delay is affecting the system. In the shower case the delay is only in minute's term and we draw it between the shower tap settings and the water temperature since it is in that link that the water make the journey until reaching the shower tap. Delays are hard to predict within a system. Most of the time we do not know how long the delay period is so we tend to use trial and error approach to assess the delay time (similarly when we take a shower). Usually one rule of thumb can be applied; the longer the time delay, the larger the oscillation and its effect on the system. This poses difficulties when we are analysing a problem, we may not discover the feedbacks that have long delays. Our task here is then to work in some way like a detective, finding out what variables might involve long delayed feedbacks. Decision can often create instability and oscillations in the system that are not necessarily felt instantly. Thus we might push some variable very hard without getting any instant results. But the harder we push the system the harder the system pushes back. This is important to realise when we are considering long-term conditions.

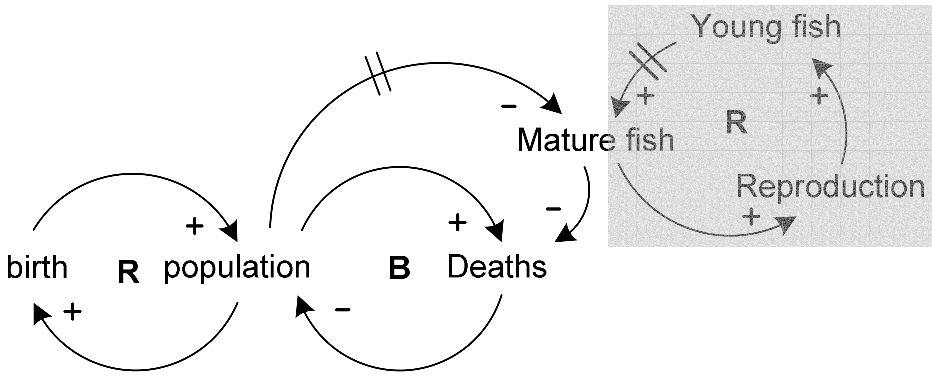
6.0 Loop Analysis

One powerful aspect of using CLDs is the possibility to analyse loop dominance in a system. Loop dominance describes which part of the feedback in our CLD is strongest or most active at a given time in our system. Since our CLD is a description of something happening over time, feedbacks can be dormant and only become active when some of the variables are "turned on". Even if we have drawn our CLD on paper, we have to "tell the story" with the CLD, i.e. from the starting point in our CLD describe what happens when the variables are being influenced in their causalities. Here is where the RBP become a handy tool for us. In the following examples we will go through a simple CLD of a fictional nomadic human population on an island that lives of its resources. As with any population, we can assume that the population is increasing and has a natural lifespan, so the observation span is at least one generation. Limited resources are introduced which will affect the livelihood of the population by increasing the number of deaths. In the following explanation the population CLD will be illustrated in five steps. The first steps show the initial phase (idle stage) and the in the following four steps the thick arrows show what loop is experiencing loop dominance behaviour (see explanation 9):



Explanation 9: Loop dominance.

What we see here in explanation 9 is that loop dominance is shifted according to the structure. The first loop dominance is the population growth phase. The population is allowed to grow since the resources are abundant and the effect of reducing them is not showing for a long while. When the feedback "kicks in", the loop dominance becomes the decline of population by high number of mortality. It is important that in this example the resources, which could be fish, also is a population that needs to recover (see explanation 9). This is why the number of deaths continues for some time until number of fish can sustain the human population. In the RBP, we can qualitatively express the levels when the population stabilises and when it does the growth phase of the population starts again.



Explanation 10: The fish population is hidden from the human population.

In explanation 10 the fish population is hidden from the human population so in this case they cannot perceive how they will behave. Furthermore the human population will make their catches only from the mature fish stock. Due to the delay from the young fish becoming mature and thus reproductive, the behaviour is not perceived by the human population.

6.1 Analysing the loop behaviour of conflict using RBP

Observing a RBP can also be done by looking at each loop in the CLD as isolated and drawing the behaviour for each one of them. The sum of the results from each of the loops is then used to predict the RBP from the whole CLD. Lets look at a short story that describe a diplomatic skirmishes between two communities. The following is observed:

> *"Coruscant and Tatooine are planets which are respectively and frequently engaged in skirmishes, over intergalactic trade routes The UN-Galaxy council tries to terminate the skirmishes as quickly as it can. A common pattern in their confrontation is that Coruscant feels threatened by Tatooine trade's expansions and starts to behave aggressively towards Tatooine in order to block and terminate their potential contracts. Tatooine usually retaliates aggressively towards Coruscant but ends up being penalized for what was originally Coruscant´s acts of aggression." The question: What is the effect of the UN-Galaxy council actions on aggression?*

It can be helpful to create a string of events of the problem so we can create a starting point in our CLD. Strings of events is basically a sequence of how one event results in another event in the problem. Often we draw the string of event as how the behaviour of the problem was documented (figure 17).

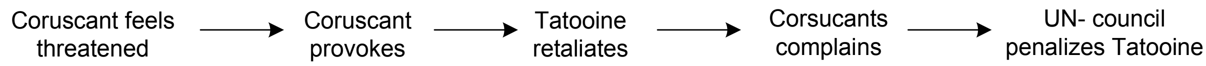


Figure 17: string of events of community conflict.

We can use this documentation of events to help us construct the CLD, and there after we identify how many feedbacks are working in the problem. There is one reinforcing loop (R1) and two balancing loops (B1 and B2) that feedback back to R1 (figure 18). When we read through the diagram we start with the variable *Coruscant feeling of threat* which is the variable that fuels the conflict. It causes Coruscant to act aggressively towards Tatooine, therefore increasing Tatooine's aggression as a result. When Tatooine becomes aggressive, Coruscant uses the situation to file complaints towards the UN-council regarding Tatooine aggression (more aggressive more complaints). Due to increased complaints from Coruscant, the UN-council intervenes and forces Tatooine to stop all aggressive actions. As the more the UN-council intervenes the lower the threat situation seems for Coruscant, which reduces their aggressive tactics.

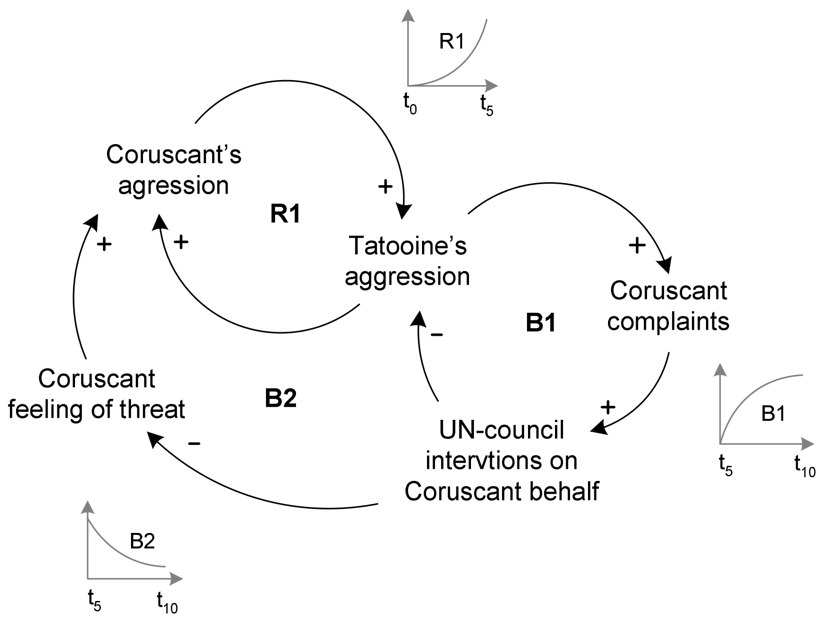


Figure 18: A small RBP behaviour is extracted from each loop and time sequenced.

In the story, it is Coruscant that starts the conflict therefore we can use Coruscant aggression as an observation variable in the RBP (figure 19). In the RBP, the behaviour of each loop can be used to estimate how aggression will develop through the entire loop. When the CLD is read, we read "through" three loops (R1, B1 and B2) that have their special behaviour in the CLD. We can use that information to map the causal links on to the RBP diagram. Since time is not important, it is possible to use causal links to represent each time step (figure 19).

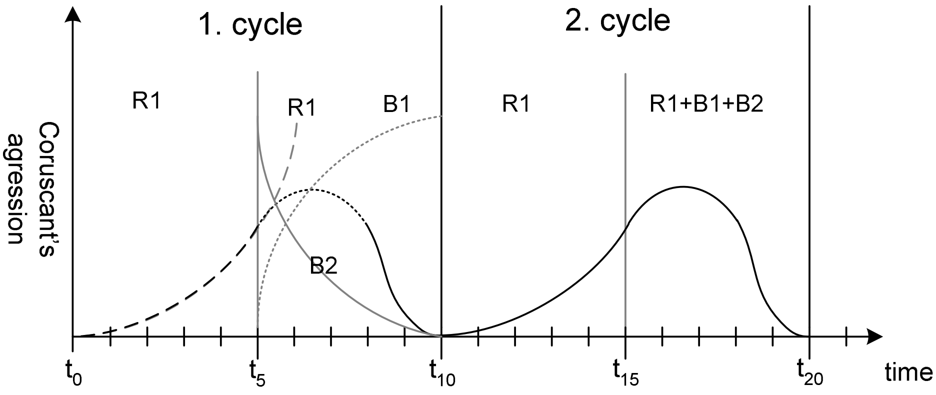


Figure 19: By superimposing the "small" RBP's into the graph, it is possible to get a conceptual behavioural cycle out of the causal links.

One CLD cycle is thus the number of causal links from the starting variable until it feedbacks. In figure 19 we count the number of links to be 10, i.e. five links to reinforce the aggression (the whole loop around) and 5 links to let the feedback reduce the aggression again. The pattern repeats it self in the second cycle. Observe that the "small" RBP's are superimposed into the graph (in the first cycle) in order to help us to know where they "kick in" in the RBP. The reinforcing loop is active for the first five steps until the balancing parts sets in. In order to read out the behavioural cycle, it is necessary to read twice through the loop. It can be expected that all the variables in the CLD will have the same behaviour as the observed variable, either in phase with it or out of phase.

6.2 Analysing the loop behaviour of bicycle riding

Lets look at another example of loop behaviour. This example involves a young boy riding a bicycle.

> *John is riding his mountain bike in the country site one beautiful morning. After several stunt tricks and jumping he discovers that he has damaged the rear tire of his bike. He can hear a hissing sound of air passing through the tire and he recognises that soon the tire will be completely deflated. In order for him to be able to bicycle home he realizes that he needs to pump air into the tire several times on the way. But this action will also damage the tire further by increasing the size of the hole and therefore deflate the tire more quickly each time its inflated. Question: What is the effect of inflating air into the tire on the air in the tire?*

We do the analysis of the actions here by constructing the strings of events and use it to help us constructing the CLD. The purpose of it is to understand the documented sequence in the story how the bicycle riding caused the damage and deflation to the tire (figure 20).

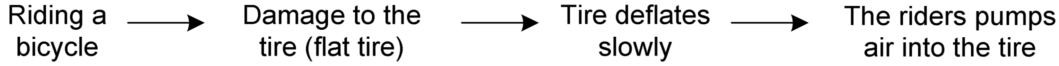


Figure 20: Strings of events of riding a bicycle.

Here the CLD needs to address the air in the tire and what variables are affecting it, thus amount of air supply, bicycle ride and damage to tire. When we read through figure 21, it is the amount of air that is interesting, therefore our RBP should focus on reading through the diagram starting from "air stock".

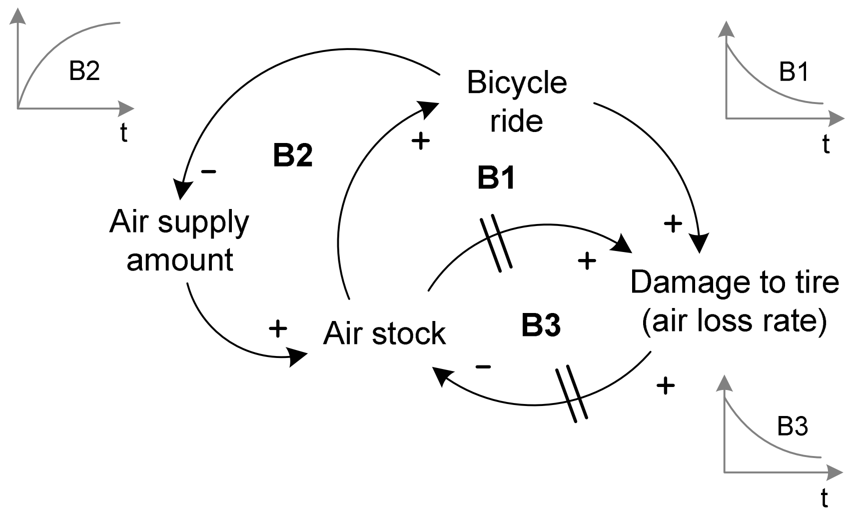


Figure 21: The bicycle ride and the attempt to keep the tire inflated. A small RBP behaviour is extracted from each loop and time sequence.

The bicycle CLD reads as follow: Bicycle ride causes increased damage to the tire, which is interpreted here as larger hole in the damaged tire and higher air loss rate. This causes air stock the tire to decrease but only after certain delay because the hole is small. The reduced air stock causes the rider to stop his pedalling. He increases the air supply (through pumping) in the air stock. That allows the rider to continue the bicycle ride. But increased air stock increases the size of the hole in the tire by allowing higher air loss rate. We have concluded one cycle in the CLD. Once again, we can use the number of causal links to construct the RBP (figure 22).

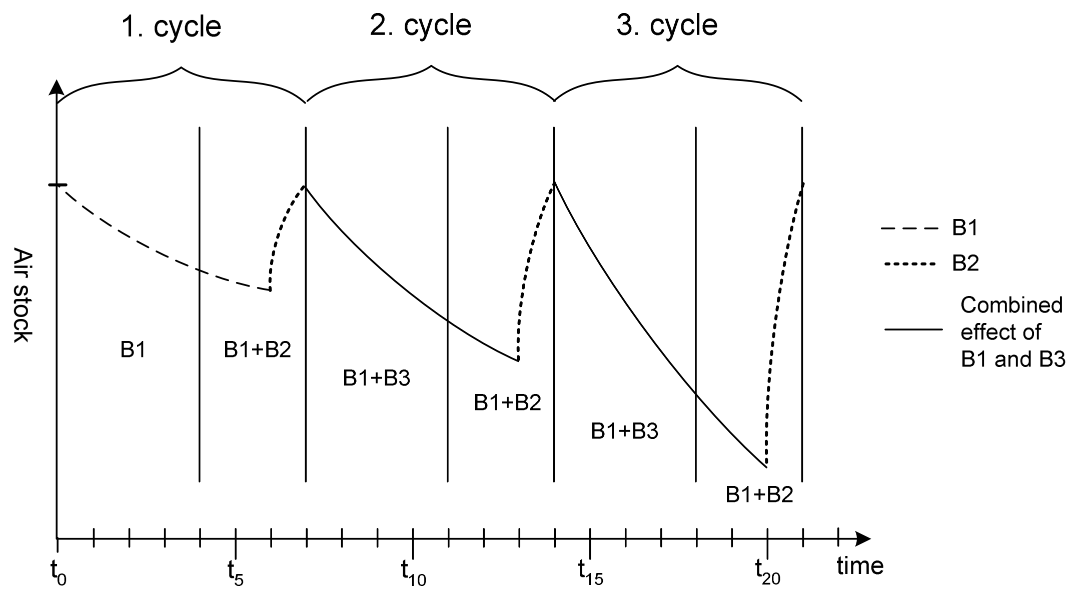


Figure 22: When the small RBP's and the time sequence has been determined we create an overall behaviour of the CLD by putting together the time sequences and the graphs.

We read the delays as at least 2 causal links duration, therefore the loop B1 reads 4 links and the loop B3 four links. Air stock is shown decreasing over time as the result from bicycling and pumping air into the tire. In the first cycle (figure 22), the loop B1 is only one active since we start by reading through the CLD from that variable. Then B1 and B2 are active simultaneously since the inflation is delayed before the air stock is full again. In the second cycle the deflation is faster since loop B1 and B2 are acting combined. The RBP assumes that larger effort is put into inflating the tire in order to keep the tire fully inflated, which is illustrated with the steeper and longer curve as more cycles are iterated.

6.3 Analysing the loop behaviour of Mouse Empire

Let us now look at a system that has a dependency on another system. Suppose there is a mouse population confined within a small space (in a room). The population is solely depended on one food source for its survival within its area and the food is only available during a limited period of time. We can imagine that the food source is a large loaf of bread that is sitting in a net woven bread basket, hanging from the ceiling but out of reach for the mice. This is a special type of bread that brakes apart with old age and as the aging process begins, pieces start to fall onto the floor. The pieces are large enough for the first couple of mice to live of it for a while and populate to a "Mouse Empire". Our question for this problem could be; how long can the population sustain itself and what would the population graph look like through time? We need to identify two systems, the first one is the mouse population and the second one is the food supply. What is stated in the description is that the bread is not affected by the mice, only the aging process. Therefore there is only one directional influence from the food supply to the mice population (figure 23).

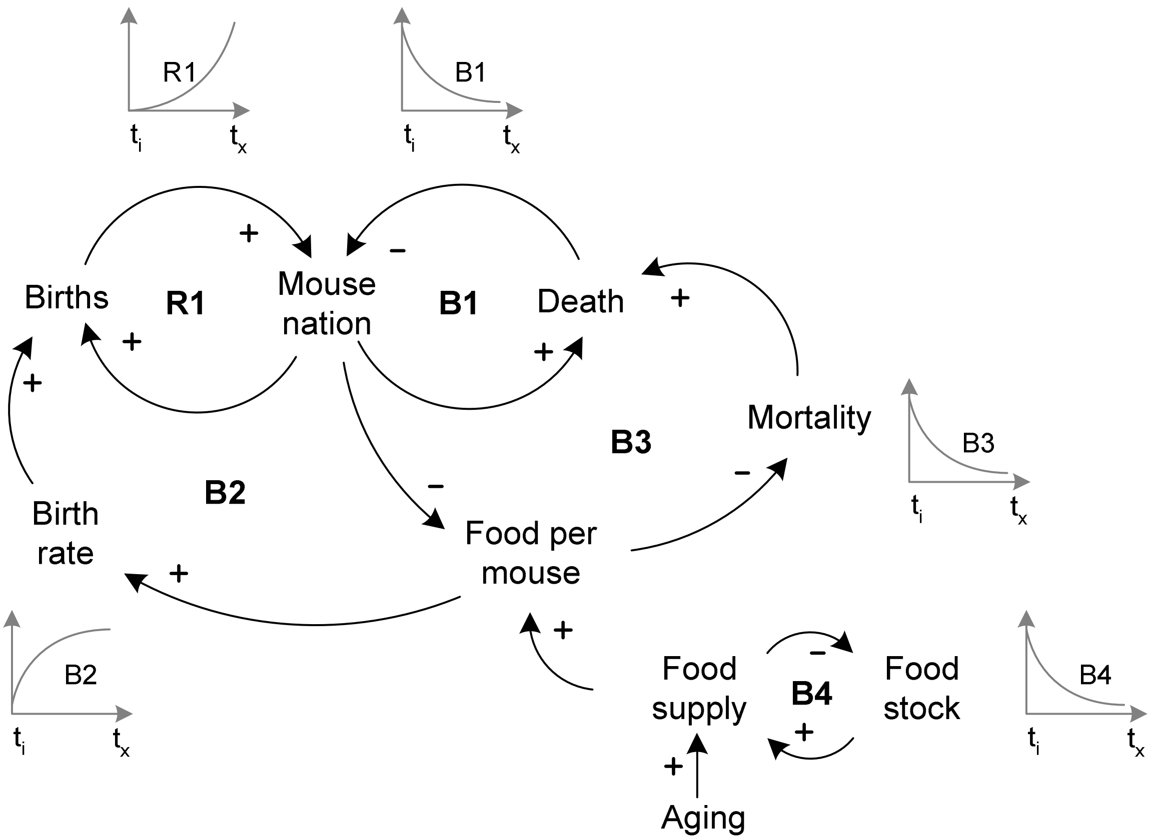


Figure 23: The CLD Mouse Empire is constructed of two loops (population and Food stock) that are only connected through one directional link. The mouse population is receiving influence by the amount of food available, but not affecting it back, e.g. directly eating from the food stock.

The loop in figure 23 tells the following story; when the bread in the basket starts to age, pieces of the bread escape the "net woven" basket and land on the floor. This is good news for the mice that got trapped in the room when the house owners went on a long vacation. The mice are able to live of these pieces. Since the mice are there to stay they populate due to the available bread that falls on the floor. Unfortunately there comes a time when all the bread has fallen to the floor. The mice have not food and start to die off, one by one. Drawing a RBP of the story could look something like in figure 24. There is a population increase phase as long as the bread falls on the floor. When the food stock is exhausted (the loaf of bread), the last pieces of the bread are eaten from the floor; the population is not increasing any more. The latter phase of the diagram shows the decline in the population, the mice start to die-off. What is interesting about this diagram (compared to the previous examples) is the fact that the cycle is non-repeatable. This is due to the fact that all the events are unique, e.g. the bread is out, and the population is dead. The cycle cannot be repeated unless a new pair of mice is introduced and a new loaf of bread placed in the basket.

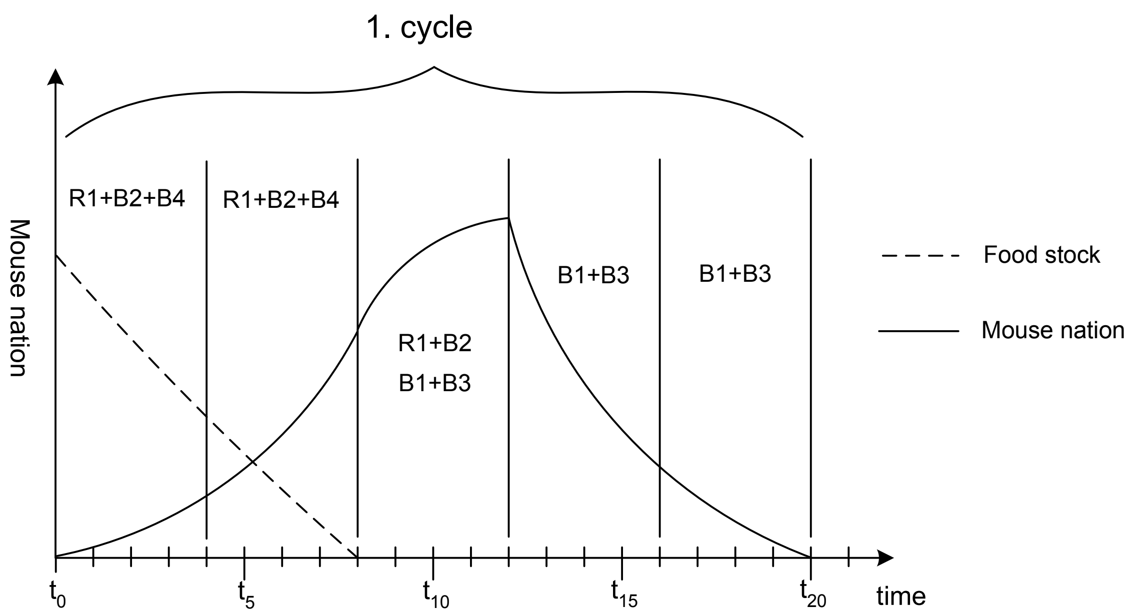


Figure 24: A RBP of the mouse empire. The diagram does not show repeated behaviour but events that are conditioned, e.g. food source being exhausted.

It is not important to know exactly what the actual length of the time steps are or how steep the decline of the population should be, such knowledge is only approximate. The important factor here is to learn the behaviour of the system. If numbers are important, it is possible to carry the CLD structure into mathematical modelling. Then the actual slopes of the curves could be learned. When we create causal loop diagrams and the reference behaviour patterns, we can predict the overall behaviour of the system and in what sequence different causal links will behave. The only thing we cannot determine is the time delay itself, if it is 1 hour, 1 day or year. In order to determine the time delay we need to perform computer simulations.

There are exercises in the chapter 9. Start with the smaller examples and work your way into the large ones. Use the above examples as a guide to solve the exercises.

7.0 Working with the CLD- the Learning Loop

A Causal Loop Diagram is only interesting if it answers the right questions posed from a problem. How we understand a problem is how we ask the questions. When we start working with a problem or an issue there are several steps needed to follow in order to effectively analyse it with the CLD. First of all, there needs to be a problem definition, i.e. it has to be real enough so you can create boundaries around the problem and put it into context with its surroundings. Most of the time, the problem is not visible, but only its symptoms are. So when a person is describing a problem, it may be the behavioural symptom emerging from the underlying problem that is being described. Our task always starts by defining the problem and what symptoms are emerging from it. Here, the use of group work is invaluable since it brings together different personal viewpoints on the same problem and helps identify the hidden links that may only be discovered from the group discussions. When analysing and defining a very complex problem, it helps to have people from different disciplines in the group discussions. The group work should never be downplayed as unnecessary since it always creates a better insight to the problem than an individual could do alone. We have to remember that the insight created into the problem is only as good as the groups or the individuals understanding the issue is. For example, a group of mathematicians, astrophysicists and engineers can do their best in understanding medical illness on a cellular level, but they will never be able to create the necessary insight to the problem as medical doctors in the field could do. Their understanding would be a superficial understanding of the problem and therefore for the group to succeed they would have to be well informed on the background knowledge in the medical field. Including a medical doctor to the group would greatly advance their understanding of the problem and the possibilities to ask the right questions.

The ability to ask the right questions depends on the ability to put together a group of people with sufficient background knowledge in order to get as correct definitions to the problem as possible. We have to remember that the CLD reflects our understanding of the problem, therefore the problem definition and the question asked for the problem is reflected in the CLD. The old saying, “All models are wrong but some are useful”, refers to our ability to avoid the superficial interpretation of the problem as much as possible. Most of the time, reading extensively about an issue can be sufficient to get some insight to a problem, since we can recognise certain behavioural feedbacks from other similar problems and apply our experience on how the problem will behave. It is important to take notice that formulating a question for a problem is the same thing as formulating a hypothesis.

The first steps towards creating a CLD should be as follow:

1. **Define the problem:** “What is the problem?” How does it manifest itself and what is it doing. What are the system boundaries?
2. **Ask the question:** Define specifically what you want to answer in the problem, e.g. “What is the role of temperature in agricultural management?”, “How does water influence plant growth?”, or “How does waste incineration increase revenues and pollute the environment?” Remember that it’s possible to have many questions to one problem but the rule is; one question, one CLD. Multiple questions, multiple CLD’s.
3. **Sort the main actors:** Create a list of relevant variables that are related to the question and sort them in a hierarchical order according to importance, the most important variables for the question are listed first and etc. It is better to create a long list of variables that you think are important for the question and then take away unnecessary ones. A good rule of thumb is to have no more than 8-10 variables at start. It is pedagogically better with fewer variables and it gives us something to start with.
4. **Start a simple CLD:** Draw the links between the variables you selected. Make one loop at a time and check if it is reasonable. Always check when you make a link if there is a link back (feedback). Continue with the rest of the variables. We often discover while drawing that we missed something, but that is normal. Continue until you have a first version of the CLD.

5. **Create a RBP:** Use the RBP to explain the behaviour in the model. It is not important to draw all the variables, but the ones that explain the feedback behaviour. Compare the RBP with an observed reference pattern (OBP). Is there a difference?
6. **Test the CLD model:** When you have finished the first version of the CLD check if it is reasonable; do the "Norwegian" laughing test. If you find your self laughing at the result then clearly something is wrong with your assumptions. Ask others to give feedback on your CLD; test your understanding on them or use the literature. Use the RBP to explain to them how the variables are behaving in the model.
7. **Learn and revise:** The CLD is never right the first time, it is an iterative process. The discussions around it creates a new insight and new questions. More often we go back to revise the CLD and adjust it to the new understanding we gained.
8. **Conclude:** It can take many iterations to be content with the final version of the CLD. When we make conclusions, we are answering our initial question. We should check if our conclusions actually change the initial question. It often does. The initial question is changed because the iteration process with the CLD actually changed the definition of the problem and thus shifted the focus of the question.

If you are alone working on a problem, always explain the CLD to someone who has not been involved in the process. Explain the problem, how you defined it and what question you wanted an answer to. The person is likely to ask simple questions on how or why you put this link there, or why you put it there in the first place. Look at it as an opportunity to get feedback on your thinking, how you structured the CLD in a cause and effect. Explain the CLD as "My" understanding of the problem and ask for assistance to check if "My understanding is difference from yours". We often expect others to think the same. Asking for feedback is reassurance for you to check if the thinking is logical.

The CLD building process can be described as a learning loop. The learning loop is our roadmap to the problem to see where in the process of learning we are about the problem. Developing a mental model involves the whole process of identifying, sorting and drawing the variables into a CLD. The model behaviour is then tested on actual historical data. When we make conclusions, it is a result of the knowledge and understanding that is available at the time being. When a new insight has developed, it calls for redefinition of the problem and the questions and thus the process continues further (figure 24).

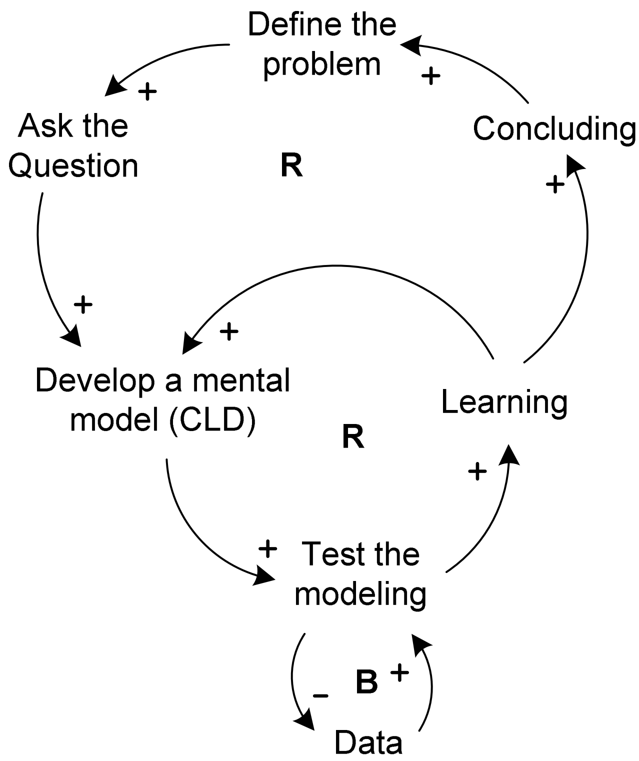


Figure 24: We use the learning loop as a roadmap to design the CLD and aid us in the process (adapted from Haraldsson & Sverdrup, 2003).

7.1 Advice on how to phrase the CLD and avoid pitfalls

Drawing CLDs takes, like everything else, practice to acquire skills on how to gain insight and understanding into the problem one is analysing. A CLD can only be useful if it is interpreted correctly. We have to remember that it is our reality we are reflecting, not the reality "of the CLD". There are some pitfalls we can avoid when drawing CLD's (modified from Richardson and Puch, 1981).

1. **Variables should be self explanatory.** The variables in the CLD should be nouns or noun phrases, not verbs. Let the variables reflect measurable quantities that can go up or down, rise or fall, grow (e.g. litres of water, population, money etc). Units helps us keeping a focus on what story the diagram is telling.
2. **Remember, the action is in the arrows.** Use variable names that are neutral. When you are using the words "increase of" something (e.g. increase of money) you are doing the job for the arrows (let the arrows do it's job). For instance, increase of spending leads to decrease of increase of money, just state *"Money"*.
3. **Clarify the actions.** Make it clear what the variable does when you send an action through it with the arrow. For example, *"tolerance for crime"* not *"attitude toward crime"*. Do not use causal-links to mean *"and then…"*, just simple interpret it as an increase or a decrease.
4. **Always use units.** If you cannot state any units for the variables, just invent some. Psychological variables are difficult to quantify but you can use e.g. scaling from 0-10, and call it stress, happiness or angrer "units".

5. **Use positive wording.** Give variables a positive meaning rather than a negative one. When reading polarities in a loop, it is hard to read a "decrease" in a variable called *"depression"*. It would be easier to phrase it *"happiness"*. But sometimes it is unavoidable to use negative meanings.
6. **Avoid double explanations of variables.** If there is more than one event in a variable when an action runs through it, separate those events into new variables, explaining what they are doing.
7. **A loop has to have a feedback.** Remember that you can only classify a feedback loop as reinforcing or balancing if it is circular. The figure 25 is a pseudo loop, it does not contain any feedback.

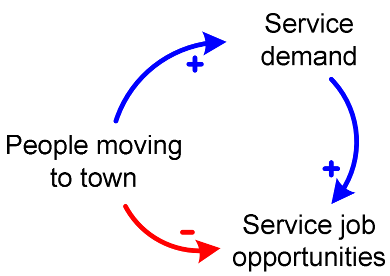


Figure 25: Links relating to job opportunities; this is *a pseudo-loop.*

7.2 Formulating goals and objectives

Every task has to have clear goals and specific objectives. Without concrete goals, there are no criteria that can be used to judge whether progress is in fact being made (Dörner, 1996). Once faced with a problem the first task should be to state the purpose and how we are going to achieve the objectives. Defining the goals and the objectives is equal to formulating the hypothesis. It should be one of the first steps taken in the problem analysis because it is not directly obvious in every situation what it is really we want to do. It minimises the time unwisely spent when we gather information for our analysis.

You should treat goals and objectives equally as the questions asked for a problem. As discussed earlier, there should be one CLD for each question. When making the first analysis of a problem, e.g. deciding how the system boundaries should be stated, you should consider the goals. According to Dörner (1996), it is better to state a specific goal, rather than as a general one. Specific goals will enable us to arrange the information by sorting out what is important and unimportant for the CLD. It also gives us an idea about what elements in the system are directly linked and which ones are not and how we should use our information.

According to Dörner (1996), there are two types of goals, a positive goal and a negative goal. A positive goal is working toward a desirable condition. "We want fish harvesting to reach 1143 tons this year", is a definitive and a positive goal. A negative goal is desiring certain condition not to exist or intentions to avoid something. Using the logic "not" is difficult to grasp when formulating goals. We do not talk of "noncar" or "nonhouse" since these terms are much more difficult to define than just a "car" or a "house". "Things have to change", "the present situation is intolerable" are examples that imply unspecific or vague goals.

When deciding the complexity level of the CLD model you need clear goals. Clear goals will give you clear objectives to answer in the CLD. The first step is to specify one main goal we want to accomplish by the study and then define several strategies or partial goals for the CLD. It is also possible to define several goals at the same time, which is often the case for complex systems. But one principle should be considered, contradictory goals are the rule, not exception. For example, trying to lower unemployment and at the same time reduce inflation is often thought of as a contradictory goal. Or when businesses want to minimise investment costs and at the same time increase profits is also a contradictory goal. As long as we are aware of contradictory goals it is fine, but in situations where we are not aware of it (which is in most cases), we will have difficulties in reaching the original goal. Prepare for contradictory goals and how you treat them in your analysis. When you are revising your CLD, always go back to your original goal with the study and how it affects the specific objectives. Make the goals concrete. Use the following steps for goals (Dörner, 1996):

- State specific main goal for the study and develop a hypothesis
- Formulate partial goals and objectives to reach the main goal
- Use goals that have a positive approach to the problem
- Document your statements and verify them with your CLD

In all modelling work there is a need to predict and assess the possible effects the model is supposed to project. This approach can also be applied to the CLD modelling. Two approaches exist, the so-called *"forecasting"* and *"backcasting"*. Forecasting is used to describe or estimate possible future conditions and trends. Forecasting is useful to help us identify possible resource shortage or how to design policies. Forecasting focuses on three questions; what can happen?, what ought to happen? and what is likely to happen? Backcasting focuses on defining a desirable future that is attainable. Backcasting differs form forecasting in such a way that it focuses on identifying desirable and attainable futures not probable futures. With the backcasting method it is possible to determine what actions are required to achieve our desired future. When conducting a backcasting one works backwards from a desired future point and checks the feasibility of achieving that point (Mitchell, 1997). By conducting backcasting we are identifying the consequences of different choices.

8.0 Summarization on mental modelling

When constructing a model the following guidelines should be followed. The first step is the development of the mental model. The second step is the dynamic simulation of the mental model using computer programs such as Stella, Powersim or Vensim.

Developing a mental model (CLD).

1. Define the problem. Create the system boundaries.
2. Ask the question, state explicitly the purpose and goals
3. Sort main actors in the problem and list them according to hierarchal order.
4. Draw the Causal Loop Diagram (CLD) and test it.
5. Draw Reference Behaviour (RBP) and Observed Behaviour Pattern (OBP)
6. Learn and revise
7. Conclude

Transferring the CLD into a computer model involves the following steps:

1. Identify what will be stocks and flows in your model- draw the outline of the model and possible sub-models on paper.
2. Identify actors, conditions and drivers variables
3. Start very simple using the core variables in your system. Be sure you understand what you are doing.
4. Keep track of the units in the model do not mix different parameters.
5. Test your model with conceptual figures against extremes in the model. Do the "Norwegian laughing test"; does the model reflect the CLD?
6. Design and test different policies, or "what if" method.

Although system thinking looks promising in theory, it is easy to misinterpret the concept if the methodology is incorrectly used. Several researchers (Roberts, *et al.*, 1983; Sterman, 2000) have expressed the importance for people that develop logic to identify the possible failure in reasoning when constructing scientific arguments. There are three main indicators that describes how the scientific methodology of system analysis can be successful. First, complex problems require deep knowledge of the underlying causes and cannot therefore be solved solely by analytical techniques. Secondly, the researcher needs to be skilled in organising and structuring, thus being able to determine how to draw system boundaries. Third, the researcher has to be able to follow important causal behaviours and recognise them further on in the analysis. The success of using the System methodology comes with the ability to work trans-disciplinary. The best results are obtained by the use of group work in the initial phases of the problem formulation and the structuring. Then the thinking and the logic behind the model is really put to the test.

It is important to understand that the System Thinking is a communication tool that bridges the disciplines. It is a tool for creating a shared insight and asking questions that may lie outside one's expertise. Unfortunately, the conventional educational system is quite rigid in its form of separating disciplines. By using System Thinking, we acknowledge that science is an approximate science, since causal behaviour can never be 100% determined, only approximated. This insight gives us the possibilities to make generalisations in research that can be critically evaluated and moved across disciplines, which is so much needed for tackling the problems of the modern society.

9.0 Excercises- practising CLD's and RBP's

Before you continue you should work out these simple examples. Read the tasks and create simple CLDs and RBP diagrams. Before drawing a RBP use OBP to place different events on the graphs, what you "think" will happen at certain time period. Also plot RBP of different actors on a single diagram to observe the dynamics. In each problem you should start by asking the question "what is the problem". Use the guide on how to state goals and create questions for the problem. Allocate at least 30 min for each task.

1. The urbanisation of south Fantasia

Fantasia is an island in the South Atlantic Ocean. The islanders have been experiencing high economic growth in recent years. Urban development has especially increased in south Fantasia where harbour conditions are excellent. The only drawback with this location is the limited land space available for development for industry and housing which could increase prises and make the area economic unattractive. Create a Causal loop diagram and reference behaviour pattern describing the interaction between economic development, urbanisation and land availability. Draw RBP of urbanisation.

2. The hydro dam in Mos Eisley

After quite debate on environmental effects of hydropower, the inhabitants of Mos Eisley have just built their first dam in the near mountain range. The dam is situated in a narrow valley with reasonable large river flowing through it. The technicians are letting water in the dam for the first time and want to test the valves of the dam. In order to test the flow they need an expert to describe the dynamic of inflow and outflow of water through the dam. Create a CLD and RBP of the water level in the dam when the lake is at full capacity.

3. Mining minerals on Antarctic

Antarctic Mining Corporation Inc. (AMC) has bought the mining right on a huge land are near the Drottning Maud land in Antarctic. Mining in a polar region is still new method but only partially successful due to the thick glacier covering the continent. Since so little is known about the geology of the Antarctic, AMC has undertaken basic mineral exploration of the area. It is suspected that when the mining starts that the easy accessible minerals will be exploited first and mineral exploration has to be undertaken to locate further resources. Create a CLD and RBP (of minerals availability) of the problem.

4. Mars, the next frontier

Mars in the year 2046, the first settlers have arrived to the new world with hopes and dreams of a better life. They have brought a lot of equipment to transform the environment that will in the distant future change the Martian surface toward more Earth-like conditions. The process of creating an atmosphere and cultivatable land is long and, if successful, the colonists can progress into new areas. Create a CLD and RBP (population) of the situation.

5. The island Gaia and the climate change
The island Gaia near Tonga in the Pacific is a peaceful place. The inhabitants have flourished on the island through the centuries on old farming traditions, growing the main food source, the Slartibastfast coconut. Cultural traditions on Gaia have created a balance between the population size and the yearly crop yield. The inhabitants are pretty well off. In recent years the climate change issue has created a problem on Gaia. Due to the low topography, rising sea levels threatens to submerge large areas of agricultural land and limit the available resources. Create a CLD and RBP (resources) of the problem on Gaia.

Following two examples are more extensive problems that are optimise for group work. Team up 2-3 persons per group. Remember to define the system boundaries and ask the questions, before venturing into the CLD. The optimum time allocation for each of these tasks is a whole afternoon, where it is possible to refine and redefine the CLD several iterations.

The traffic problem in Malmö City

The Malmö city has been experiencing massive traffic gridlocks (traffic not moving for hours) during weekdays. This happens during rush hours when people drive to, and from work. The problem has always been there in some form, but increased after the appearance of the new bridge over to Denmark. Real-estate prices are cheaper in Scania so some Danes see the opportunity to live in Sweden and commute to Copenhagen for work. The traffic jam is becoming part of the commuter's everyday run-arounds. What used to take ½ hour is now a major undertaking. When the first signs of traffic problem arose, the approach to this problem was to increase the road space within the city, enlarging existing roads (more lanes, single → double road), and building more highways. This strategy has worked in the past but now it seems there are just too many cars around.

On top of that, air and noise pollution is increasing, new road and rail network is noisy. People are not happy and many are starting to move to other communities around Malmö for quietness and cleaner air. "It's better to take an extra hour to work every day than listen to the highway around the clock," said one unhappy inhabitant. This results in the loss of tax revenues for the city since people are not living in Malmö but only working there. There is a public transport system in place, but it has not got the necessary attention needed. Busses are late and not on schedule, the ride is expensive and routes are few. Many people just consider it more profitable to use the private car; it takes about the same time to commute, and costs about the same as public transport. "I have to take three buses just to get to work; I would rather sit in the car instead," said one commuter.

Politicians are desperate and need assistance to tackle this problem. They are not sure how to approach the problem, if there is just one thing causing the whole problem, or if it is a combination of action that creates it. They are asking you to help them to define the problem and confine the core issue within the problem. You have the authority to come up with one or several long-term scenarios that make the city attractive for people to live in.

You are a consultant and have been assigned to the city expert team. Identify for the team what are the main issues at stake and what is the root of the traffic problem, how extensive it is, and what should be the main focus for the city to revert the situation. Your task as an expert is to present your analysis by constructing a CLD and a RBP/OBP, explaining for the city council how the problem has evolved from the beginning. Create alternative scenarios how the problem should be solved, both short term and long term using a combination of CLD and RBP/OBP.

The polluted lake in Duncan

Duncan is situated up in the mountains where people enjoy fine outdoor sports, hiking, hunting and fishing. Duncan is situated by the fine Lake Tranquillity. The lake is famous for its big salmon that migrates up every year from the ocean through the Tranquillity River. In combination of the nice natural landscape and salmon fishing, Duncan is a tourist attraction. They have enjoyed fishing from the lake and the tourism is flourishing and is becoming an important part. The chemical manufacturer ZorChem™ has for many years provided the livelihood and work for inhabitants in Duncan. Due to ZorChem™, Duncan has risen from being a small village to a Town (with a capital T). More than half of Duncan's inhabitants work at ZorChem™. For 20 years ZorChem™ has dumped its waste chemicals products directly into the large Lake Tranquillity.

Recently the inhabitants have started to experience health problems related to the fish catches in the lake. This has also started to affect some of the salmon tourism who have complained about the fish. An environmental representative working at the city council has determined that the fish contain mercury that have levels that are 100 times higher than the normal background level in nature. He has confronted the board at ZorChem™ who are reluctant to take actions. Now there is a large ongoing protest by the inhabitants of Duncan, which want something done. Closing down the plant is not feasible option, according to some, since most of the people work at ZorChem™. But something has to be done.

Your have been given the task to assist the community council on defining the problem, explaining for the city council how the problem have evolved from the start. Is it possible to keep the factory and preserve nature or do you have to choose one over the other? Your task as an expert is to present your analysis by constructing a CLD and a RBP/OBP. Create alternative scenarios how the problem should be solved, both short term and long term using a combination of CLD and RBP/OBP.

Good luck with your modelling!

10.0 References

Capra, F., 1997. The web of life, A new synthesis of mind and matter. Flamingo Publishers, New York, 288 pp.

Cover, M.J., 1996. Introduction to System Dynamics. Powersim Press, Reston, 44 pp.

Dörner, D., 1996. The Logic of Failure, Recognizing and Avoiding Error in Complex Situations. Perseus Books, Reading, 222 pp.

Forrester, J., 1961. Industrial Dynamics. MIT press, Boston, 464 pp

Grant, E., Pedersen, E.K. and Marin, S.L., 1997. Ecology and Natural Resource Management: System Analysis and Simulation. Wiley, 373 pp.

Haraldsson, H.V. and Sverdrup, H.U., 2003. Finding Simplicity in complexity in biogeochemical modelling. In: J. Wainwright and M. Mulligan (Editors), Environmental Modelling: Finding Simplicity in Complexity. Wiley, New York, pp. 211-223.

Lagerroth, E., 1994. Världen och Vetandet Sjunger På Nytt: Från en Mekanisk Värld till ett Kreativt Universum. Korpen, Stockholm, 250 pp.

Mitchell, B., 1997. Resource and Environmental Management. Longman, Ontario, 298 pp.

Richardson, P.G. and Pugh III, A., 1981. Introduction to system dynamics modeling. Productivity Press, Portland, 413 pp.

Roberts, N., Anderssen, D.F., Deal, R.M., Garet, M.S. and Shaffer, W.A., 1983. Introduction to Computer Simulation. Productivity Press, Portland, 562 pp.

Rosnay, J., 1979. The Macroscope: A new world scientific system. Harper & Row Publishers, New York, 247 pp.

Senge, P., 1990. The fifth discipline, The art and practice of the learning organisation. Century Business, New York.

Senge, P., 1994. The fith discipline fieldbook, strategies and tools for building a learning organisation. Currency Books, New York, 593 pp.

Sterman, J.D., 2000. Business Dynamics, System Thinking and Modeling for a Complex World. Irwin McGraw-Hill, New York, 982 pp.