FROM PROBLEM CONCEPTUALIZATION TO SIMULATION. THE APPLICATION OF THE SYSTEMS DYNAMICS TO WATER MANAGEMENT PROBLEM

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Abstrakt

The article continues previous text published in "Management Business Innovation" (no. 6, 2010) under the title Stock-And-Flow Thinking In Decision Making. Towards Systemic Procedure of Problem Solving. The methodology presented there is shown in the practical context of water supply management problem in one of the largest cities in Mexico. Basic methodological implications for computer supported problem modeling and simulation are shown, beginning with the Partitioning&Tearing Method, causal diagram of the problem as well as the computer simulation model structure drawn with the Vensim™ software.

Key words: *problem simulation, system dynamics, water management problem*

Introduction

There is an extensive number of different approaches to the modeling process and models (Wolstenholme 1994; Morecroft, Sterman 1994, 2000). Most of them emphasize internal nature of models and type of variables they involve. Others are based on physical features of means used in modeling process. In this study we use a different perspective. This text is a continuation to the one published under the title "Stock-and-Flow Thinking in Decision Making. Towards Systemic Procedure of Problem Solving" (see: Management Business Innovation, No 6, 2010). System methodology of problem solving is presented in two layers here: theory and practical application. This text is devoted to the latter stream.
Modeling is not only a means for predicting future but it could also be a powerful instrument for understanding the nature of the problem and learning from and about the problem. In fact, learning through testing difficult problems structures and behavior is a major advantage of problem solving process.

Common tradition in modeling practice is to acquire ready-to-go models from experts in the field and use them for selected problems. It seems that it has become dominant in the field of professional education; instead of learning "how to learn" we provide decision makers with the knowledge of "where to look for". Research works at the Tavistock Institute (Winnicott 1971 and Trygvar 1985) show that there is a remarkable relationship between playing, learning, and problem solving. Modeling contains all these activities; imported models can be replaced by authors' own experimental vision of the problem which can be then changed, re-arranged, and re-interpreted. While playing with the problem and its variables we acquire knowledge of the problem, verify learning through our intuitive process of evaluating its future behavior, and see into possible solutions. We can do that using formal approach

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consisting of a structured methodology imposing order upon our creativity and friendly computer simulation testing our understanding of a problem.

The paper presents such methodology, beginning with the problem conceptualization phase and ending with the construction of the problem's formal, computer-supported model. It is not only a theoretical essay; the paper results from many years of hands-on experience in modeling and simulation of real problems of which dynamic complexity was a trigger for accepting them as the analysis topic. Some of them were presented at international conferences, in many cases work results were adopted as official guidance for policing those problems. An incomplete list of those problems includes solid waste management, water management and policy, urban development, air pollution, urban logistics, and others.

It seems that proposed hereafter methodology and technology is of special importance in public administration. Most problems, especially in public administration, are solved on a very superficial and lineal knowledge base and emerging solutions results from existing budgetary constraints rather than from problems structure contents; frequently, reached solutions usually become counter-productive and short run fixes.

Cycle of Problem Structuring, Modeling, and Simulation

Problem modeling occurs in a broader intellectual setting which can be called problem solving. We always attempt to model a problem in order to understand and solve it. The term "model" and "modeling" refers, in this context, to a cycle of intellectual activities aiming at discovering problem structure, its codification in accepted language and symbols, and understanding present and future behavior of the problem and its variables. That cycle, therefore, is much more than a problem statement and simple algorithmic approach to its solving. For this reason we depart from the concept of problem solving, interpreting it as a sequence of three phases: structuring, modeling, and simulation. Each phase contributes to our problem knowledge and is linked with problem solving through some specific mental instruments. The exploration and use of those instruments is another objective of this study.

Problem Structuring

Problem structuring is oriented toward ordering of all internal elements contained within a problem. Problem exploration (such name assigned to this stage of problem solving M. Mazur - we follow his terminology hereafter - 1980) begins thus with a precise definition of problem boundaries; this separates the problem from its environment and defines its variables as controllable or independent. Exploration is intimately related with problem classification; we cannot define problem boundaries unless we possess the knowledge of the variables constituting that problem – to classify a problem means to make a list of all variables within and outside the analyzed problem relevant for its solution.

Problem structuring is aimed at specifying problem variables and their distribution in their logical space (which variable affects which other), physical space (spatial distribution), and time. Thus, a structured problem must contain:

- its boundaries (exploration),
- all involved variables (classification),
- relationships existing among variables (problem explanation).

Brainstorming is only one of many thinking tools we can use for this phase. If a problem remains in our domain, brainstorming allows us to make a preliminary list of variables. In most cases, however, the knowledge of a problem requires accessing information and knowledge depositories belonging to other parties and we need to seek relevant information. We can assist brainstorming with some simple instruments, like Variables Inventory List, Double-Q-Diagram (Fish-Bone Diagram) or similar.

It is also very helpful in the Structuring phase to think of the variables in terms of what type of behavior they may present (dynamic properties of variables). While analyzing possible behavior of a variable over time, only three distinguishable behavior patterns can be detected:

- variables with present states depending on their previous states; those variable show the accumulation or depletion of certain resources (tangible and/or intangible) important for the problem. Those variables are called stock, state or level variables: level variables represent resources within a problem,
- variables that take in the conversion of resources; level variables change over time according to a certain transformation rules contained in another variable, linked with level variable; those variables are called flow or rate variables and they directly increase or deplete resources level, thus absorbing their dynamics,
- variables that are neither level nor rate variables; they usually intervene between level and rate variables and/or between a problem and its environment; as those variables convert internal or external influences into a language understandable for level and state variables, they will be called conversion variables (converters).

The importance of attributing one of mentioned behavior patterns to problem variables stems from different contribution that level, rate, and conversion variables make to the problem structure and behavior. A link between structure and behavior is perhaps most important paradigm of the Systems Dynamics (Senge 1990). Any problem has a structure and the problem behavior is not dominated by its variables alone but it depends on a set of relationships existing among them. Therefore, the problem structure must be analyzed as a whole entity paying special attention to feedback loops existing among variables in the structure. Thus, it is not variables themselves but what occurs in and among variables that determines problem behavior (symptoms) and possible solutions of that problem. In other words, solving a problem implies our intervention in its structure, particularly in its feedback elements. No problem can be solved without purposefully changing its structure.

Another assistance to structuring a problem can be obtained from Dynamic Thinking. Dynamic Thinking attempts to identify all feedback loops included in a problem structure. We can perform it by drawing Causal Loop Diagrams or using more formal algorithm, e. g. Partitioning Method.

It is easy to draw Causal Loop Diagram in the case of simple problems. It becomes more challenging if the problem complexity increases. In such cases we may use the Partitioning Algorithm. The Partitioning Method, invented by Gerald Kron in 1963, was initially used to structuring (partition) complex and large equation systems. It allows us to group all problem variables into blocks where a block contains variables linked with a feedback and where there are no feedback loops between blocks. That means the Partitioning Algorithm locks in all feedback loops into structures called blocks, interpreting the block as a variable or set of variables not connected to other variables (other blocks) with the feedback links. Thus, feedback can exist only within a block (unless block contains one single variable) and never between them.

This phase of problem structuring moves us closer to dynamic properties of the problem and its variables. To get an insight into dynamic behavior of the problem variables, we can use other tools, e. g. Behavior Over Time Diagram and Graphical Function Diagram. Behavior Over Time Diagram presents changes in variable values over time, taking into account any inter-relatedness in their behavior. This gives us a reference mode for capturing relationships between variables in a more detailed way (Graphical Function Diagram).

Problem Modeling

Problem modeling is interpreted here as the conversion of our visual version of a problem into a formal model enabling us to simulate a problem. During problem structuring, central focus is on information available from our knowledge and other information sources and we try to determine most probable behavior of problem variables. This is only the beginning of the modeling process. As problem structure influences upon its behavior, we must adjust problem structure to behavior requirements and to facilitate our interaction with the problem structure and behavior.

We can use for that purpose Basic Feedback Loop and Policy Structure Diagrams accompanied by the analysis of available systems archetypes. Systems archetypes are common patterns persisting in many problems; they are recurring structures that lead to similar behaviors. That similarity of distant structures and behaviors (thus similarity of otherwise distant problems) is a very interesting feature. If we possess some basic knowledge of archetypes and of feedback-based behavior, the modeling task is not that difficult. Once a problem structure is determined, we can make many interesting observations regarding its behavior, we do not need any practical knowledge of that problem but rather information of all feedback loops underpinning its structure. Systemic analysis and inference substitutes empirical observation.

Based on this we are now able to design a model of the problem containing all feedback loops. Feedback loops can also be considered basic decision making loops. They contain, at least, one stock variable and one flow variable, though in most real cases they are accompanied by a number of conversion variables. Having such a picture of the problem, we can pass to the next phase of the process.

Simulation

Simulation is an invaluable tool for problem solving. Its history has been marked by decreasing cost, increasing availability and applicability. Decades ago it was a sophisticated instrument accessible only to selected and trained specialists, now it is a common tool used in "soft" sciences and for solving less tangible social problems. With computer tools that have recently become available, we can model, understand, and re-interpret many important concepts that habitually have had descriptive form. Simulation has been losing its traditionally "hard" predictive rationale and it becomes a way of modeling and playing with problems. This is fundamentally due to new, emerging kind of computer software. Though called "simulation software", it is more a "thinking tool" than computational technique for predicting future states of the problem. We refer here to packages like STELLA®, ithink® , POWERSIM®, or VENSIM®.

Computer Simulation is becoming a learning framework where problems can be tested, variables can be altered or eliminated, and the simulation process, through experimentation with the problem, leads to qualitatively new insight and reflection on the problem under analysis. Presented approach, in addition to its technical efficiency and effectiveness, is an easy to understand and attractive to accept platform for all people involved in problem solving processes; curiosity and interest of people not familiar with this way of modeling and solving problems is a typical and highly motivated reaction.

Having completed the process of problem structuring and modeling, it is easy to translate the model of the problem into a language understandable for each of previously mentioned simulation environments (software). In the next part of the paper we will show briefly the application of presented "in-use" methodology to a concrete problem. We select water management problem in a city of approximately 2 million inhabitants, located in central plateau in Mexico where the author was involved in water policy design in mid 1990's.

Water Management. Problem Structuring in Practice

We will go through all phases of the problem solving process presented in the first part of the paper. We start with the Exploration Stage requiring problem boundaries to be defined. There could be many motives of dealing with a problem. It is critical, however, to know exactly why people are willing to solve it. In our case, we detected a number of different justifications, beginning with "care about citizens" through "budgetary and political reasons". After a careful investigation we came to a conclusion that real motives of people responsible for water problem in the city were:

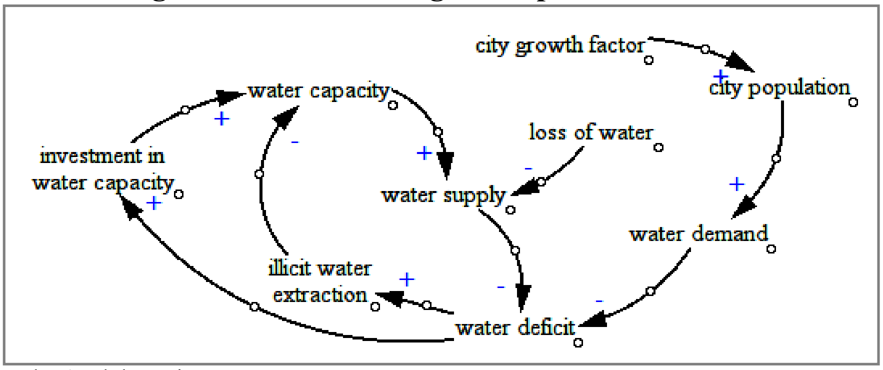
- responsibility for water supply to inhabitants, provoking (in some cases) unfavorable social reactions and political consequences,
- budget constraints resulting in perceived impossibility to solve water problem, thus leading to high costs for the city hall,
- recent decision on water supply privatization and uncertainty caused by this.
- Therefore, we had to mount into the problem all variables related with the cash flow caused by water service. In addition, given claimed rationale for water supply privatization, the problem has to include variables corresponding to its present state (with future extrapolation) and to it future states (what would happen, if we do not privatize but modify existing water policy).

Brainstorming and more formal investigation of the problem components led the research team to constructing the list of involved variables:

- Water Availability (Wav)
- Water Demand (Wdem)
- Water Planned Demand (Wpd)
- Demand Error (Der)
- City Growth (Cg)
- Population Growth (Pg)
- Water Deficit (Wdef)
- Illegal Extraction (Iextr)
- Water Loss (Wl)
- * Water Capacity (Wcap)
- Water lnvestment (Winv)
- Water Provided (Wpr)
- Water Income (Winc)
- Water Recuperation (Wrec)
- Water Extraction (Wextr)

Various sessions with specialists and groups of citizen led to the elaboration of a basic causal diagram representing overall structure of the water management problem (Fig. 1). It became clear that two feedback loops were embedded into its structure: first, beginning with the water supply and leading through water supply and water deficit to the increase (social and political pressure) in water capacity investment which – in turn – increase the city water capacity; second loop also begins with the water capacity and supply – insufficient supply results in common practice of extracting illicitly water from existing water supply aqueducts. Both feedback loops follow water demand increasing in function of the city growth and population size.

Fig. 1. Causal diagram of water management problem



Source: author's elaboration

These 15 initial variables of the water management problem were gathered through internal discussion in the research team and external consultation with water management professionals grouped in the City Council as well as groups of water system customers. According to presented methodology, variables inventory is only the first step towards problem structuring and modeling enabling us to design the initial structure of the problem (obtained through the Partitioning Method - see: Tab. 1).

With Partitioning algorithm we moved from a chaotic, initial list of problem variables towards its structural representation. We can now re-read the problem semantics and verify the viability of previous hypotheses on internal relationships of the problem. We can get closer to feedback loops within blocks and analyze their dynamics. Internal dynamics of blocks containing two or more variables is a critical factor for the dynamics of the problem as a whole and for thinking of its solutions. Even if we stop modeling process and decide to analyze the problem intuitively, our intuition will be assisted with more solid fundament helping to understand the problem. Initial structure, however, is a cornerstone for further work and the construction of the simulation model of the problem.

Tab. 1. Water Management Problem (initial and final matrix)

PROBLEM VARIABLES	Water Availability	Water Loss	Water Demand	Water Capacity	Water Planned Demand	Water Investment	Water Provided	City Growth	Water Income	Population Growth	Water Recuperation	Water Deficit	Illegal extraction	Water Extraction
Water Availability				X							X			
Water Loss				X		X					X			
Water Demand										X				
Water Capacity						X					X			
Water Planned										X				
Water Investment												X		
Water Provided		X											X	
City Growth														
Water Income							X							
Population Growth								X						
Water						X								
Water Deficit														
Illegal Extraction												X		
Water Extraction			X	X										

PROBLEM VARIABLES	City Growth	Illegal extraction	Population Growth	Water Demand	Water Planned Demand	Water Investment	Water Recuperation	Water Deficit	Water Capacity	Water Availability	Water Loss	Water Extraction	Water Provided	Water Income
City Growth														
Illegal extraction														
Population Growth	X													
Water Demand			X											
Water Planned Demand			X											
Water Investment								X						
Water Recuperation						X								
Water Deficit							X		X					
Water Capacity						X	X				X			
Water Availability													X	
Water Loss						X	X	X				X		
Water Extraction														
Water Provided											X	X		
Water Income													X	

Note: a rectangle in final matrix shows block of feedback variables
Source: author's elaboration.

Water Management. Problem Modeling

To solve a problem implies to control it. The advantage of the Partitioning Method is the division of problem structure in blocks of variables between which no feedback loops exist. In that perspective we can see the water management problem as "linear" in form and subject to cause-effect relationship existing between (author's underline) blocks. Therefore:

1) if we control Population and City Growth,
2) we control Water Demand and can easily plan it;
3) by controlling Water Demand we are able to determine the scope of water supply with its all variables (large block in the matrix).

The scope of the water supply is yet much more complicated. Figure 3 shows what form analyzed problem takes while converting its structure into a formal, computer model (Vensim^{TM} was used). We call its diagram "policy structure" as it allows to discover structures influencing possible policies for solving water management problem. Reading through the model we can discern. The city growth represented by its population is not depending upon assumed policy and should be considered independent variable (changeable only in a very long run). It affects water demand and open three large feedback loops.

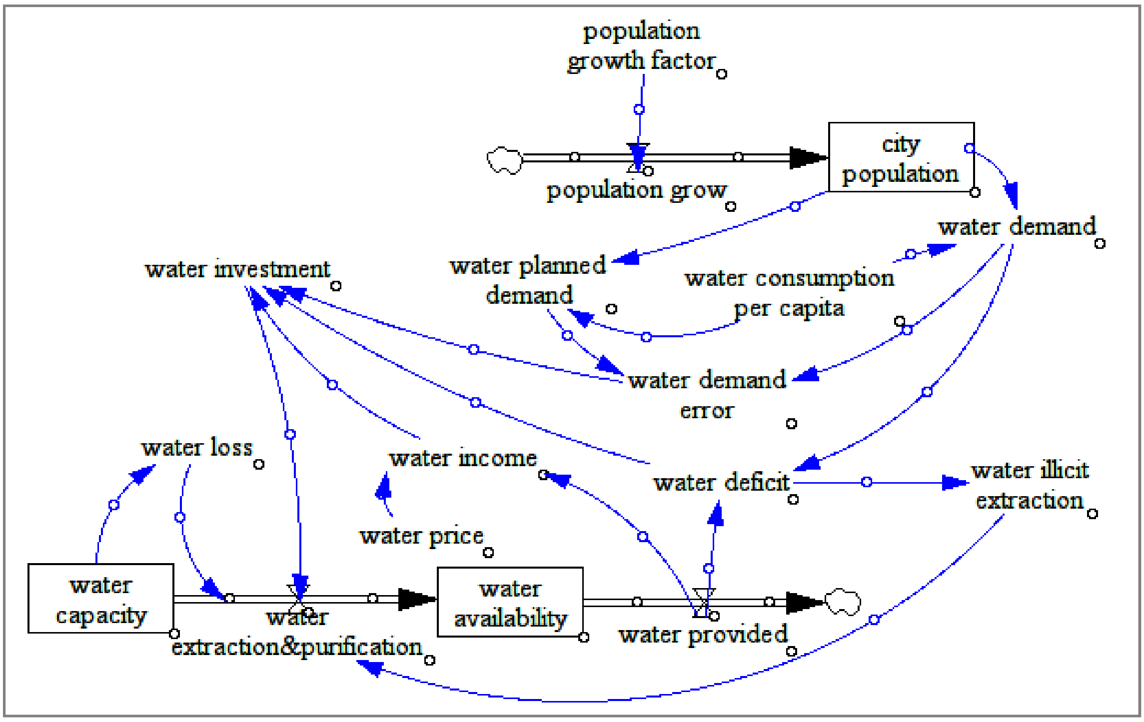
All those loops begin with "Water extraction&purification". The first loop leads to "Water availability", then to "Water provided", "Water income", and "Water investment", closing the loop again in "Water extraction&purification". This part of the problem structure reflects simple fact that water provided to households affects funds devoted to enhancements and improvements in the city water system. The loop is positive (strengthening).

The other two feedback loops point to the variable "Water deficit" linking both into a vicious part of the problem structure. First, when the amount of water is not sufficient ("Water deficit"), pressure towards increasing water supply raises, increasing the perception of urgency in "Water investment" and pressure towards receiving external (federal) funding.

This loop is also strengthening and it closes in "Water extraction&purification").

Third loop is quite different. When water deficit takes place, illicit water extraction by underserved households perplexes the city water supply system, decreasing the extraction and purification of water that – in turn – activates the first two positive feedback loops.

Fig. 2. Policy Structure Diagram for Water Management Problem



Source: author's elaboration (in Vensim™)

Each of involved variables has a positive reactivity (increase/decrease in affecting variable causes increase/decrease in affected variable, respectively). Whenever all relationships existing between variables have positive reactivities, then the whole block must also possess positive reactivity. Its value may either increase or decrease but increase and decrease cannot happen at the same time. Any reaction causes another reaction in the same direction. Therefore, if we can control any variable of this block, we control the whole block.
Modeling, as a stage preceding computer simulation, requires a careful consideration of each block and its internal dynamics. Understanding blocks is fundamental for converting initial structure of the problem into Policy Structure Diagram. As it was mentioned, Policy Structure Diagram presents decision-making properties of the problem and emphasizes the role of variables reaction to the behavior of other linked variables. Although nothing can substitute our systemic intuition, it is possible to use some rules of thumb:

- within each block there must be at one level variable and one rate variable,
- number of rate variables cannot be lower than a total number of level variables.

Water management. Problem simulation

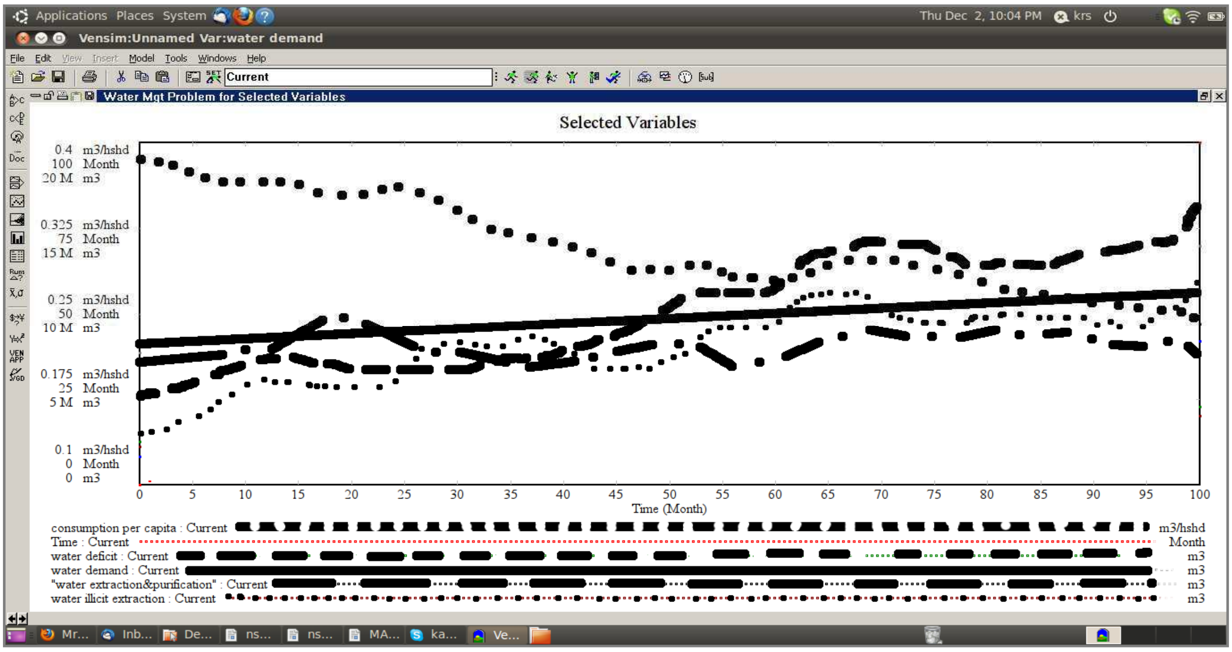
The Policy Structure Diagram is a good starting point for developing it into a plain simulation model. A specific model of the water management problem is not important here, however. The purpose of this paper is to present a road leading from the initial, intuition-based vision of the problem to its more formal representation and, at the final stage of system approach to problem solving, to testing problem policies through a friendly, computer-based simulation. What was in the past the domain of few versed specialists, now is becoming a tool accessible for decision-makers, enhancing their intellectual potential.

Contrary to classical justification of computer simulation, system procedure of problem solving sees computer simulation as an instrument for learning, particularly learning about systemic (dynamic) structures of social problems. These problems possess some peculiar characteristics that arise due to the nonlinear behavior of stock variables, dynamics of flow variables, and feedback structures included in their structure. Among these characteristics we have:

- symptoms of a problem are often separated from it in time and space;
- they often behave contrary to human intuition;
- our intervention in those problems frequently yields short-term successes but long-term failure, or vice versa;
- feedback loops in their internal structure often counteract external policy intervention;
- it is better to see problem structure to absorb and withstand uncertain external shocks than to predict those shocks;
- real-world dynamic problems are not in equilibrium but rather are continually changing.

System Dynamics offers several tools for accessing problem structure through computer simulation. Some of them rely in using simple mathematical methods for presenting and interpreting internal relationships. Behavior over Time Diagrams (BOT) and Graphical Function Diagram (GFD) are good examples of them. BOT Diagram is a simple graphical presentation of a variable behavior over time. "X" axis denotes "time" and "Y" axis is reserved to a variable in consideration. BOT is especially important in building computer simulation models; if a model is to mimic a real problem, then its structure must generate behavior of problem variable that is equivalent or close to its real behavior (validity of initial model structure). BOT is also an invaluable tool for the analysis of possible relationships existing between variables that otherwise could be considered separated from each other. In this case we use BOT diagram for showing behavior of several variables and the diagram suggests further analysis of variables behavior in connection to each other. Figure 3 presents the BOT diagram for water management problem (note: original variables' behavior graphs have been replicated due to printing color policy).

Fig. 3. BOT Diagram for water management problem (selected variables)



Source: author's elaboration

Presented BOT diagram of selected variables shows surprising relationship between "Water Extraction & Purification" and "Water Illicit Extraction". Contrary to common sense, when water extraction (city supply of households) grows, the illicit water extraction also grows. That is only one of four unexpected outcomes in used city water supply policy. As our aim is not to propose a solution to analyzed problem, so that no implications of those counterintuitive relations will be shown here. Nevertheless, it is worth mentioning how discovered feedback pattern affected the understanding of the problem. The variable "Water Extraction & Purification" represents mainly territorial expansion of the city water supply system, giving more opportunities to the households willing to illegally connect to that system. Such a vicious mechanism works until the city supplies all households with required amount of water – mission that was and is impossible.

Conclusions

The argument that most of public management policy makers (and implementers) are distant from understanding the dynamic nature of problems being solved by them is supported by many empirical researches. Problems having dynamic, feedback based structure require quite a different approach. In this study we have attempted to prove that we can assist complex problem solving with computer modeling and simulation; there are tools and methodologies showing us how to handle dynamic problems and convert them into simpler ones without losing their systemic properties. Proper modeling leads to problem solution.

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Abstrakt

Artykuł przedstawia systemową metodologię rozwiązywania problemów i podejmowania decyzji rozwinietą w poprzednim tekście (Stock-And-Flow Thinking In Decision Making. Towards Systemic Procedure Of Problem Solving) zamieszczonym w poprzednim numerze "Management Business Innovation" (no. 6, 2010). Metodologia ta, przedstawiona w zarysie w cytowanym artykule, jest tu uzupełniona przez praktyczne przedstawienie jej zastosowania w rozwiązaniu bardzo złożonego problemu zarządzania systemem zaopatrzenia w wodę w jednym z 5 głównych miast w Meksyku. Artykuł dyskutuje podstawowe zasady systemowego rozwiązywania problemów i przedstawia ich praktyczne implikacje.