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SCENARIO DEVELOPMENT, QUALITATIVE CAUSAL ANALYSIS AND SYSTEM DYNAMICS*

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Abstract

The aim of this article is to demonstrate that technology assessments can be supported by methods such as scenario modeling and qualitative causal analysis. At Siemens, these techniques are used to develop preliminary purely qualitative models. These or parts of these comprehensive models may be extended to system dynamics models.

While it is currently not possible to automatically generate a system dynamics model from a qualitative model (or vice versa, obtain a qualitative simulation model from a system dynamics model), the two techniques scenario development and qualitative causal analysis provide valuable indications on how to proceed towards a system dynamics model. For the qualitative analysis phase, the Siemens-proprietary prototype Computer-Aided Technology Assessment Software (CATS) supportes complete cycle and submodel analysis.

Keywords: Health care, telecommunications, qualitative model, sensitivity analysis, system dynamics.

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Resumen

El propósito de este artículo es demostrar que avalúos tecnológicos pueden ser apoyados por métodos tales como la modelación de escenarios y el anlisis causal cualitatativo. En Siemens, estas técnicas se usan para desarrollar modelos preliminares puramente cualitativos. Estos modelos comprensivos o partes de ellos, pueden ser extendidos a modelos de sistemas dinámicos.

Aún si no es posible en este momento generara automáticamente un modelo de sistemas dinámicos a partir de un modelo cualitativo (o vice-versa, obtener un modelo de simulación cualitativo a partir de un modelo de sistemas dinámicos), las dos técnicas de desarrollo de escenarios y análisis cualitativo causal, proveen información valiosa sobre cómo proceder para obtener un modelo de sistemas dinámicos. Para la fase de análisis cualitativo, el prototipo propiedad de Siemens *Computer-Aided Technology Assessment Software* CATS provee un análisis completo de ciclos y submodelos.

Palabras-clave: cuidados en salud, telecomunicaciones, modelo cualitativo, análisis de sensibilidad, sistemas dinámicos.

AMS Subject Classification: 62N99

1 Introduction

When looking at a process in a comprehensive manner - the precise German word would be 'ganzheitlich"-, all relevant parts of this process are considered with equal weight. This does imply that functional relationships need to be built among all components in any model for this process. The result will be a highly interactive feedback system.

In our context, feedback systems consist of a relatively small number of basic elements which are commonly referred to as stocks and flows within the system dynamics notation. Auxiliary variables are used to describe the functional relationships among various system components; thereby assuring that a comprehensive approach is utilized to describe the process in question.

Feedback systems may be qualitative or quantitative in nature. Examples for the first kind are scenario development and qualitative causal analysis, for the second kind, system dynamics could serve as an example.

In the sixties, the first description language for feedback systems was system dynamics. This simulation language can be used for the description of purely technical as well as technical-economic and socio-economic systems. Newly developed qualitative methods may assist in modeling complex technical-economic situations in which not all variables and relationships are known from the beginning.

The method presented in this report originates from work done at the Massachusetts Institute of Technology in the chemical engineering field. The algorithm QUAF (Qualitative Analysis of Causal Feedback) was adapted to the field of technical-economic systems. The main goal of the qualitative analysis is the identification of important feedback loops and the further investigation of that using system dynamics. The formal integration of this qualitative modeling technique with system dynamics remains as a possible future goal.

2 Scenario development

Scenario development (5) is a prognosis method where the present data is used to develop various possible, often alternative future scenarios (Figure 1). These scenarios demonstrate how a future situation can be regarded as a logical consequence of possible events occurring in the future.

One distinguishes trend and extreme scenarios. Extreme scenarios represent the framework for developing several trend scenarios. In this context, a trend scenario means the description of a likely future situation as well as the description of consequences leading to opportunities for today to achieve the goals determined by this particular trend scenario. If so desired, one may complement this step by performing a preliminary market analysis and/or a first sensitivity analysis.

Figure 1: Alternative scenarios and their consequences for today

2.1 Preliminary market analysis

Exploratory research is conducted in order to clarify opinions and attitudes of potential customers and special interest groups and in order to obtain insight and identify relationships among determining factors. This includes experience/attitude surveys and pilot studies.

Typically, a survey is a research technique in which information is gathered from a sample of people by use of a questionnaire. The questionnaire consists of either openended response or fixed alternative questions, i.e. interviews with experts from different areas of interest. Pilot studies involve focus-group discussions usually with six to ten participants.

2.2 Sensitivity analysis

Sensitivity analysis is an assessment method with emphasis on the observation of large effects caused by minor impacts to the system. This is done by evaluating system parts against each other and against a pre-defined set of criteria.

Sensitivity analysis may thus be undertaken after the preliminary market analysis phase providing qualitative answers, e.g. the biocybernetic approach [10], or during system

Figure 2: Causal model with cycle analysis completed

dynamics in determining quantifiable effects of certain system parameters to the overall system behavior [9].

3 Qualitative causal modeling

The qualitative model is used to formally analyze the causal feedback structure resulting from the scenario development phase. Typically, a simple structural network comes first and is refined into a comprehensive model which can be simulated qualitatively. Qualitative causal analysis determines system behavior, short-term and in the long-run, with respect to changes in characteristic system variables.

The qualitative algorithm is realized in the Siemens-proprietary Computer-Aided Technology Assessment Software CATS. This software enables the user to display system changes graphically on-screen.

Let us provide some background information on the history of the qualitative simulation technique applied here. Other qualitative simulation methodologies are briefly discussed in [8].

3.1 Background

The basis of the qualitative simulation in CATS was laid down by the Massachusetts Institute of Technology [3][4]. There, a tool was needed to describe process malfunctions of large systems in chemical engineering. Qualitative simulation was considered as the only suitable way to do so since other simulation methods are often not very informative regarding trend analysis and too time-consuming: time being critical in discovering faults in these process systems.

It should be noted that the Siemens prototype CATS uses a cause-effect graph for its qualitative modeling approach. Such graphs may be associated with Forrester schematics [1] and thus with system dynamics, and qualitative models be developed from system dynamics [2]. On the one hand, qualitative modeling (and simulation) with CATS can be seen as a first step in obtaining system dynamics models; on the other, it is possible to verify certain parts of a system dynamics model with the qualitative simulation tool in CATS. This is why a rudimentary system dynamics ansatz is integrated into CATS.

We will not discuss any technical details in this report. For algorithmic details of CATS, see [6]; the mathematical background is described in [7]. Instead, we will describe the qualitative techniques applied for performing a detailed causal analysis as a possible means in obtaining system dynamics models. To do so, we will consider the preliminary causal model of Figure 2, an example from the telecommunications field.

3.2 Strong components and self-regulating variables

The graph in Figure 2 consists of approximately 30 variables. The relationships among the variables are of type "increasing" and "decreasing" and indicated by arcs. In our diagram, a filled arrowhead $\rightarrow$ of such an arc indicates a positive (+) influence, while an unfilled arrowhead ($- >$) marks a negative ($-$) influence.

Some of the variables have a circle inside their boxes. Such a circle describes a self-regulating variable-candidates for state variables (stocks) in system dynamics models. They are chosen in such a way that they indicate cumulative effects or have regulatory impact on the system. Self-regulating variables have a decisive role in qualitative simulation. In particular, each so-called strong component must have at least one such state variable.

A strong component is a subgraph in which each variable can be reached from each other. In Figure 2, all variables of the strong component *Society* are indicated in lightly dashed borderlines with the variable Prestige in its center. The model in Figure 2 consists of three strong components as can easily be verified: *Society* and two other components referred to as *Manufacturing* and *Economy*.

By definition, no mutual feedback may exist between any two strong components. Thus number and type of components are an indication of the type of feedback occurring in the system. The computation of strong components may therefore help in evaluating whether any feedback should be added or eliminated. This represents one of the main advantages of qualitative causal modeling as a tool to obtain reasonably networked quantitative models.

Some variables point towards these components. As an example, consider the variable Digitalization (box in the upper left-hand corner of Figure 2) which points towards *ECONOMY* and *MANUFACTURING* alike. These variables - technically referred to as impact variables - play an important role during qualitative causal analysis.

3.3 Balancing and reinforcing loops

For any graph associated with the system model, CATS determines all cycles including their signs and displays them on screen (Figure 2, right side). The sign of any such cycle is simply computed as the product of the signs of all arcs in the cycle. In system dinamics, loops with a positive sign are called reinforcing, those with a negative sign balancing. The number and type of cycles and strong components therefore characterize a feedback system. It would be interesting to find a refinement hereof by considering the number of strong components, their sizes, and the signs of the cycles in an appropriate manner.

Two factors encompass the type of feedback to any state variable during simulation: the number of cycles this variable is contained in and the proximity to a self-regulating variable. Let us now see what this means for qualitative causal analysis.

3.4 Qualitative causal analysis

After determining the feedback structure of the model, we are ready to start qualitative causal analysis with CATS. CATS enables the designer to simulate short - and long - term changes in state variables with respect to impact variables acting upon the system. Incidentally, no quantitative data is needed to perform a qualitative simulation.

For the qualitative simulation considered here, it is not of primary importance how many positive or negative arcs point to any variable. (There is no “local” computation of the signs of these arcs performed at any time - this would almost certainly have no meaning.) Instead, it is merely necessary to realize in which component a variable is contained in and how the feedback structure in this component looks like.

This information suffices for the analysis of short - and long - term changes in state variables with respect to external impacts acting upon the system. An impact variable is assigned a positive (+) value for a (sudden) increase of its original value, and a negative value (−) for a decrease of its value.

Short-term changes for any state variable with respect to the impact variable’s new value are computed by the shortest path from the impact variable to the state variable: the signs of the path’s arcs are multiplied with each other, and then with the impact variable’s new value being (+) or (−). Thus, in Figure 2, an increase in Age Pyramid (box in upper right-hand corner of Figure 2) has a short-term positive impact on Immigration, but a negative impact on Sales Possibilities and Prestige. Short-term impacts are therefore always of positive or negative nature, and are assumed not to occur from any strong component towards any other one.

The long-term impacts to some state variable or stock are computed by considering the feedback structure and the self-regulating variables which are contained in the same component as the state variable. Again, it is important to note that this is not done by considering local impacts, i.e. by counting the number of positive or negative arcs pointing towards the state variable or “weighing” the arcs in any way. Instead, a very complex algorithm is enacted which recursively considers the complements to all cycles in this component [6].

Therefore, it is not surprising that long-term simulation results are not provided as positive or negative, but instead as “monotone”, “compensatory” or “inverse”. A typical behavior of an “inverse” state variable with a negative short-term change to some impact is indicated in Figure 3. Note that as time passes by, the variable becomes more and more “fuzzy” and that, here, in the inverse case, it can not be determined for certain whether the final long-term value will be above the “zero-line” or not.

Figure 3: Time progression of inverse state variable

4 System dynamics

System dynamics is a quantitative method for modeling and simulation of comprehensive systems. The qualitative causal model is extended using the information gathered during scenario development. All variables are supplied with initial values, and quantitative algebraic or functional relationships need to be found. A system of differential equations is generated from this input and solved using standard methods.

Results are typically provided in form of tables, bar charts and two-dimensional time or phase diagrams. In addition, a sensitivity analysis provides helpful hints on the importance of values of certain descriptive variables or parameters [9]. This enables the user to develop and assess marketing alternatives needed for the thorough development of a business plan.

For the system indicated in Figure 2 above, modifications were undertaken to first obtain a better qualitative model consisting of a single component, and all important feedback loops were specified and analyzed. Parts of this new model were finally extended to system dynamics.

5 Application to the health care field

A simulation model has been devised which analyzes feedback processes typically being present at various levels in the radiology department of a hospital when new or returning clients require medical attention. Patients enter the hospital on a pre-determined or random basis and are distinguished as new or returning clients. Aspects such as time of day, reason form hospital visit, type of diagnosis by diagnostic related group (DRG) as well as hospital personel and equipment needed for administering any treatment are considered. In particular, the model takes standard wait times and different types of resources available at the time of visit into account.

A financial score-keeping piece in the model determines any cost associated with diagnostic and administrative processes in the radiology department. All relevant subprocesses such as diagnosis, therapy, equipment and personnel are considered with equal weight. This does mean that functional relationships needed to be built among all subprocesses. The result therefore is a highly interactive feedback system.

A cost accounting component of the model determines any associated costs within the diagnostic subsystem (consultations, unexpected procedures, and complications resulting in a new diagnosis, co-morbid conditions requiring medical intervention) and identifies any bottlenecks within the system/departament operations.

The mathematical modeling using existing data sets determines costs and impact on length of stay associated with different assumptions for these parameters in a comprehensive fashion, including expected, adverse and unanticipated activities. The model can accommodate changes in any of the measured parameters. These scenarios enable the health care delivery system to optimize medical delivery as patient profiles and circumstances change.

In summary, mathematical modeling can offer suggestions to improve current facility processes by recommending alterations in the work force, additions or replacement of current equipment. The model can also account for variations in diagnostic and treatment options. Optimization of workflow, cost accounting and process improvement are the measured benefits of this intervention.

6 Conclusion

Qualitative analysis provides a means to structure purely verbal (qualitative and quantitative) statements and enables the designer to improve upon his model by analyzing the causal feedback in great length before any variables need to be quantified. This qualitative model or parts of it may be used as a starting point for system dynamics. Thus a qualitative approach may prevent modeling errors in complex feedback models, i.e. in system dynamics.

Therefore, certain principal modeling difficulties of qualitative nature are spotted which, within conventional quantitative models, may disguise through improper choice of parameters or functional relationships among variables. Qualitative simulation here should be understood as a means to develop good feedback models from the scenario development phase, simulate them quickly and use them in order to build up complex quantitative (system dynamics) models.

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