System Dynamics Concepts Applied to the Development and Quality Assurance of Environmental Information Systems

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Abstract

At RIVM environmental models are not only used for exploration but also for production, whereby environmental reports are provided on a yearly base. Using models in a production situation raises the demands on quality to which models must comply. A robust "multiuser, multipurpose information system" is needed rather than a set of separate models. The demands on quality include:

- full reproducibility of results
- high performance (speed, reliability, uniform user interface)
- complete documentation to assure ease in maintenance
- explicit regulation of responsibility for and access to data.

These demands have called for a method of software development that can assure the quality of the resulting information system. This paper describes the method which RIVM's Laboratory for Waste Materials and Emissions has developed. Important elements are:

- Development of information systems in a cyclic, "evolutionary" process, consisting of a number of stages, as opposed to a linear succession of steps. The end-users (environmental specialists) participate in all stages. The development cycles can also be considered as feedback loops. The quality of specifications appears to be a key factor in the behaviour of the system.
- Management and modelling of data preceding the modelling of functional relations.
- Facilitating the testing of the resulting, complex information system by creating a description in the form of adapted causal loop diagrams.

The laboratory is now in the process of obtaining ISO 9001 certification for its information management based on this method of software development.

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1. INTRODUCTION

System dynamics principles have often been used in the development of environmental models, not only as guidance for the models themselves, but also for the modelling process., The resulting models, could often be categorised as "single user, single purpose". The main purpose for many of them was to gain understanding and explore future developments. Many of those models declined after being developed, tested and published. This article focuses on a type of models which come into bloom just at this very point, emphasizing three aspects:

- what special part do models play in our situation?
- what are the consequences for the infrastructure, organisation of work and the development of models?
- how do system dynamics principles help to improve the quality of our work?

This article will only discuss the situation in one specific laboratory of RIVM. A further delimitation is that we abstain from the environmental research itself and only deal with the models that are being used. And even these models will not be described in detail. Instead the focus will be on the construction of the models (or information systems), the cooperation of many contributors in fulfilling the communal purpose, and -last but not least- the quality assurance of this whole process. Section 2 will sketch the organisation in which we build and use our models. Section 3 discusses the functions models have in our organisation and the consequences for the modelling process and the working with models. Section 4 continues with the cyclic development of models and the way of testing.

2. THE ORGANISATION

2.1 RIVM

RIVM, the National Institute of Public Health and Environmental Protection is a leading research institute in The Netherlands. It has two complementary fields of interest that sometimes cross-pollinate. It employs almost 1600 people; some 500 participate in environmental research. Together they take into consideration the whole environmental "chain": from the emission of contaminants into air, soil or water, via transport processes to effects on ecosystems and man. The institute is divided up into a number of laboratories.

In 1988 the cooperation of many researchers resulted in the publication of the report *"Concern for tomorrow"* (Langeweg, 1988). In this report a coherent and comprehensive analysis of environmental problems each on its own scale and in its own time - place frame was presented. This had a major impact on environmental policy in the Netherlands. A National Environmental Policy Plan (NEPP, followed up by the NEPP+) describing definite objectives (like emission reductions up to 50% in 2010) has been adopted by the Dutch Government and Parliament.

This environmental policy in its turn invoked more environmental research. One line of research still aims at better in-depth insight in separate environmental problems.
However, a major task of RIVM has become the production -on a yearly basis- of a "National Environmental Balance Report" and a "National Environmental Outlook" every four years. The former will present the current status of the environment - thus monitoring the effects of environmental measures. The latter will provide an outlook on future environmental situations, based on different economic and demographic scenarios, and explore the effects of measures that have been agreed upon or announced by Government and Parliament.

This task urges not only the coverage of the whole range of environmental problems, but the provision of very detailed and precise figures for environmental parameters. Providing these reports can be designated as an "industrial production process" in which a complex "web" of models is applied.

2.2. The Laboratory for Waste Materials and Emissions.

The Laboratory for Waste Materials and Emissions (LAE) is concerned with the first link in the environmental chain as described above.

Fig. 1 The scope of study at the Laboratory for Waste Materials and Emissions.

Objects of study are all industrial, human and natural processes which emit compounds into the air or water and produce waste (see Fig. 1). Examples of processes are traffic, house-holds and agriculture. Both the present situation (diagnosis) and the projected future situation (prognosis) of these processes are investigated. Besides studies on the origin and amount of wastes and emissions, special emphasis is laid on the effects of preventive and abatement measures for different scenarios.

3. DEVELOPMENT OF ENVIRONMENTAL INFORMATION SYSTEMS

3.1. History of Modelling at the Laboratory for Waste Materials and Emissions

Models have always played an important role in the work of LAE. In the beginning these could be categorised as "single user, single purpose". Also, the main purpose of many of these models was to gain understanding and to explore future developments. Then each investigator had his or her own model for each process under study: an agricultural model, models for passenger traffic and freight traffic each, a model for waste management et cetera.

In an early stage an attempt was made to construct an integrated model based on a large database of environmental data called RIM, Dutch acronym for the Environmental Information and Planning Model. This model was applied in some studies but appeared unsuitable for further development for the following reasons:

- performance of the hardware and software. The large database systems had a slow performance rate, building a user interface was cumbersome,
- expertise in the building of scientific models but insufficient training for the professional development of complex information systems,
- the lack of an explicit need for integrated tools, as the emphasis in research was on gaining understanding of individual environmental problems.
- the complexity and variety of models.

By 1991 many of these conditions had changed. There was an explicit need for an integrated model. Not only had the need for integration grown, but external and internal demands for the quality of the model (or information system) were even more of an item. New staff members with more expertise in information systems development were employed, and powerful hardware and software were available. However, the models in use by environmental specialists were still complex and varied.

Under these circumstances a large project was started to achieve not merely an integrated *model*, but an *infrastructure* which could provide environmental emission calculations of high quality.

3.1. From Models to Information Systems

It was clear from the beginning that the infrastructure needed would demand the cooperation of many specialists. Each of them would have to put in and maintain his/her own specific data and carry out calculations to realise his/her own purpose. For instance, one specialist is only collecting and maintaining data on actual emissions from one target group, like agriculture or traffic. A second specialist develops scenarios and evaluates future trends, and a third is responsible for the costing of environmental measures. In this way, the model would be *"multipurpose"*.

More important, the environmental specialists would have to contribute to the final result simultaneously. It was not acceptable for them to deliver their contributions in a series, they would have to work parallel with each other. So the model would have to be *"multiuser"*.

It is striking that - as far as we know - no dedicated simulation or modelling software is on the market that will facilitate building, running and maintaining data for multiuser models. So we concluded that we would have to use a general purpose programming and development environment, which was flexible, userfriendly, and guaranteed data integrity in the multiuser mode. So, from now on we will no longer speak of models but of information systems. The main difference is that in an information system not only the hard/software and data are part of the system, but also the people that work with it.

The quality demands on the system invoked certain limiting conditions:

- Every calculation had to be reproducible.
- Data used for calculations would have to be stamped "approved" by a specialist before other specialists were allowed to use it. All final calculations had to be based only on approved data.
- The whole RIVM and thus the laboratory was required to obtain a quality certificate. It was chosen to aim at ISO 9001 certification, so the utilization and construction of the information system would have to comply to the ISO standards. This encouraged for a complete description of procedures and the establishment of strict regulations and authorization.

3.2. The RIM$^+$ Project

Under the limiting conditions mentioned above, the RIM$^+$ project was started (Fig. 2). To assure the realization of a high-quality information system which would suit its demands, the following choices were made:

- All data necessary for and produced by all models should be based on one common data model. Each data element was to be described thoroughly and stored only once in the database
- The environmental modelling specialists were not supposed to do any programming themselves. Professional programmers were to be hired within funding limits.

Fig. 2 The RIM$^+$ logo.

- From the beginning specific responsibilities for data and for the model structure were to be laid down and an attempt should be made to put these responsibilities on specific staff members.
- "Keep It Simple". The system developers should be reluctant to add complexities and details if not absolutely necessary. This produced interesting interactions with the end users.
- The information system would be developed incrementally. This means that in an early stage a prototype is constructed, which is evaluated with the end users. Then this prototype is gradually

improved and adapted within an "evolutionary process", until approved. Serious testing still has to be carried out after that.

- All meta information (data dictionary, definitions, program structure, cross references) was stored in the repository of one CASE tool.

- All applications would have the same userinterface. It was decided to use Ingres Windows 4GL, a relational database with a graphical userinterface running under X-windows. C with embedded SQL was used for complex calculations and ARC/INFO for spatial manipulations and presentation. In a "Style guide" (Van der Maas et al., 1993) the rules to which the programmers will have to conform are established.

Based on these starting-points several applications have been produced: a process model (PROMO), an environmental costs model (MKM), a global emissions database (EDGAR) and an application for evaluation emissions to water (PROMISE, in cooperation with the Institute for Inland Water, RIZA). Details of these can be found in Laan and Bruinsma (1993) and Laan (1994).

4. QUALITY ASSURANCE OF ENVIRONMENTAL INFORMATION SYSTEMS

This section will describe two elements that contribute to the quality of information systems: evolutionary system development and testing. Both of them are linked to system dynamics principles.

4.1. Evolutionary System Development

An important technique used is the evolutionary (synonym: incremental) system development. It is very useful in situations where neither the end user, nor the system development team knows exactly the functionality to build beforehand. In other words the specifications are not known in detail. This technique can be applied successfully only if three conditions haven been fulfilled :

- A flexible development environment has to be available and hence,
- A stable data model of the system must be previously established, and
- Cutting up both the functionality to build and the time to spend for building into slices that are not too large. Hence the information system will consists of separate applications.

Figure 3 outlines the stages of evolutionary development as implemented at LAE. It shows two cycles. The outer one represents the production process of a whole application. A prototyping loop is contained inside this production process. In the prototyping loop a working prototype is created, which is evaluated by a team of system developers and end users. In this way they experience by hands-on demonstration what the application does and does not do correctly. Next, the specifications can be refined and the prototype improved.

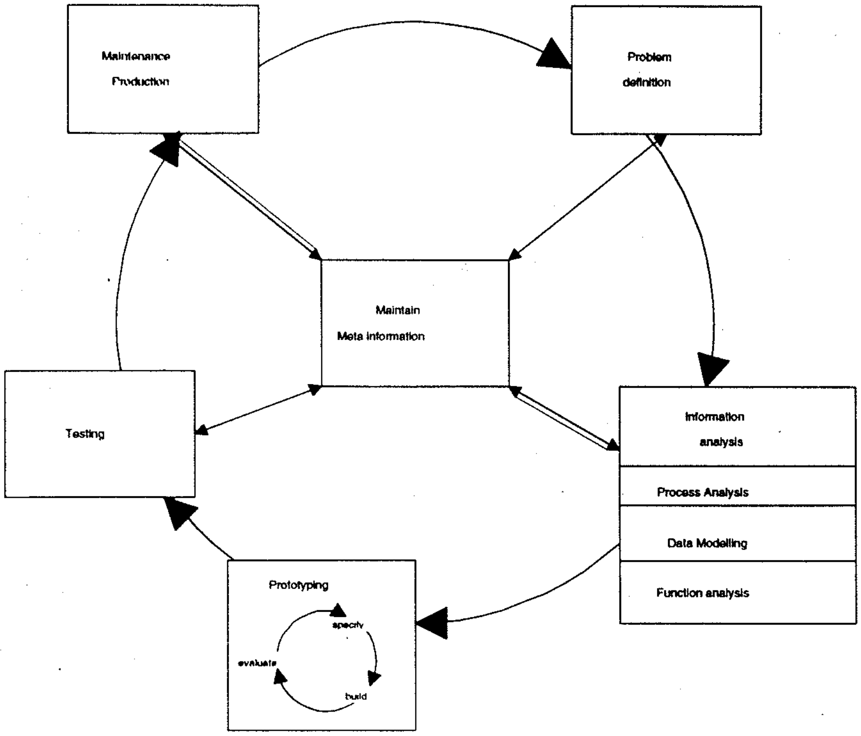

Fig. 3 The stages of evolutionary system development

The inner circle will probably be recognised by many who have built models themselves. It is a necessary learning process which must not and can not be formalised by the strict regulations of a quality system. The power of the approach chosen is that this process is embedded in a larger circle of which the quality can be assessed. The quality control system assures that in all stages discrete products are delivered and approved. For instance, a application may not be taken into production before it is adequately tested. A prototyping cycle may not start before the underlying data model is approved. And the development of an application can not start unless a detailed project plan is provided and accorded.

Fig. 4 Causal loop diagram of the evolutionary system development process.

It is interesting to take a look at the development process from a system dynamics point of view. A very simple causal loop diagram is shown in figure 4. In the beginning, the end users are not satisfied with the system and willing to spend time in discussing with the system development team, evaluating prototypes etc. This effort results in a (prototype of an) information system. The quality of this system also depends on other factors. One is the collective understanding of end users and development team of the desired functionality. This we express as *quality of specifications*. This quality increases gradually with the number of prototyping cycles that the team has gone through. However other factors are of influence here too:

- The quality of the analysis at the startingpoint,
- The experience of system developers with the problem area,
- The experience of end users with information modelling concepts,
- The willingness to share a learning process,

It appears that these factors also determine how the development process behaves. The desired behaviour is completing the application after a number of the prototyping cycles and taken it into production. However, if the initial quality of specifications is poor, more cycles will be needed (with an intense learning process will taking place). This has the undesired side-effect of a large deviation from the conceived functionality. This will cause the process to last longer than planned and may require adaptations to the project plan. In the worst case the application will never reach the production stage. Here we run into a paradox. The evolutionary development approach is most useful when initial specifications are hard to formulate, yet the success of the process largely depends on the quality of these specifications.

4.2. Testing guided by influence diagrams.

In any quality system, testing is an essential element. The testing of large information systems is time-consuming and constructing an optimal set of test-cases (highest chance of fault detection with minimal effort) is difficult. In fact, finding the last bug is almost impossible.

There are formal techniques for constructing test sets, but we found them not suitable to our needs. An example is a technique known as *decision analysis*. It concentrates on detecting the branching points (like "IF","CASE" and "WHILE") in the program code, and prescribes that test-cases should be chosen so that every branch is touched at least once. This level of detail makes it suitable for the programmers, but less so for the end users. Besides, it produces an overload of combinations to be tested.
Endusers are willing to carry out a limited number of test runs to verify the results with the outcome of other calculations. Their interest is to evaluate the system at a more concrete level of abstraction. However, there was no recipe to help them create an adequate test plan.

As represented in figure 3, formal testing is an element of the outer cycle, and part of the quality system. How can one assure that a whole information system is ready for production? And how can one convince an auditor that the system has been tested adequately? At this moment, we have had no experience yet with auditors questioning this. But we think that an adapted form of causal loop diagrams could be very helpful. These express how each variable in the system affects other variables. We speak of *"influence diagrams"*, because the information system concerned contains little loops. The diagrams are constructed by abusing an element of our CASE tool which was originally meant to create Data Flow Diagrams (DFDs). Figure 5 shows an example.

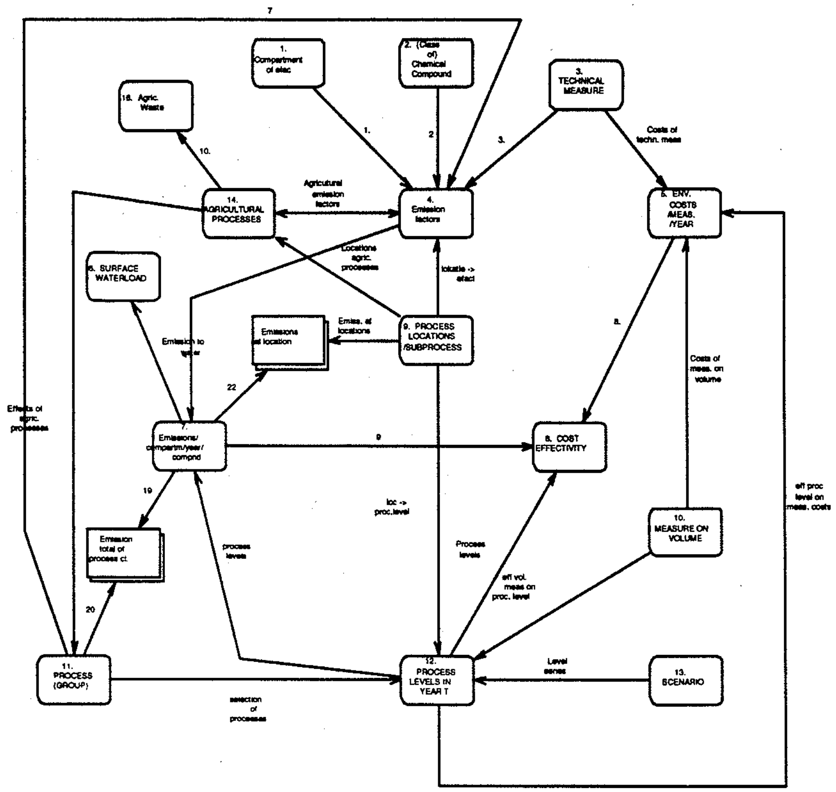

Fig. 5. Example of an influence diagram of an environmental information system (top level). The rectangles with round corners represent variables that influence other elements of the system. The rectangles with sharp corners are results; they do not affect other factors.

An interesting feature is that using the CASE tool opens the possibility of applying the hierarchy concept to the influence diagrams, which makes them easier to understand. We have adopted the convention that when a variable is written in capitals it can be "exploded" or "zoomed in to" to reveal more detail. To illustrate this we will zoom in on the variable ENV. COSTS /MEAS/YEAR (Fig. 6).

The use of influence diagrams not only has the benefit of clarifying the relations in an information system visually, but the case-tool contains a script language which can flexibly produce reports.

So, from the diagram it is possible to create a table with influencing and influenced factors (Table 1). These can provide substantial support in testing. When an end user makes changes to a variable, he/she knows exactly what other elements in the system have to be checked to verify the correctness. Note that the diagrams are constructed independently of the actual program code. They express the system as the end users expect it to function. So a test based on these diagrams also verifies if the system development team has built the system as the end users expect it to be.

Factor	**Influenced factors**
Energy costs	**Costs per Branch of industry** **Costs per NMP action** **Netto Costs per branch of ind** **Costs per compartment** **Costs per process** **Transfer (bruto)** **Costs per alt proc class /year**
Interest rate	**Electro-mechanical Investments** **Civil investments** **Costs per Branch of industry** **Costs per NMP action** **Netto Costs per branch of ind** **Costs per compartment** **Costs per process** **Transfer (bruto)** **Costs per alt proc class /year**

Table 1. Example of Influencing and influenced factors to be checked.

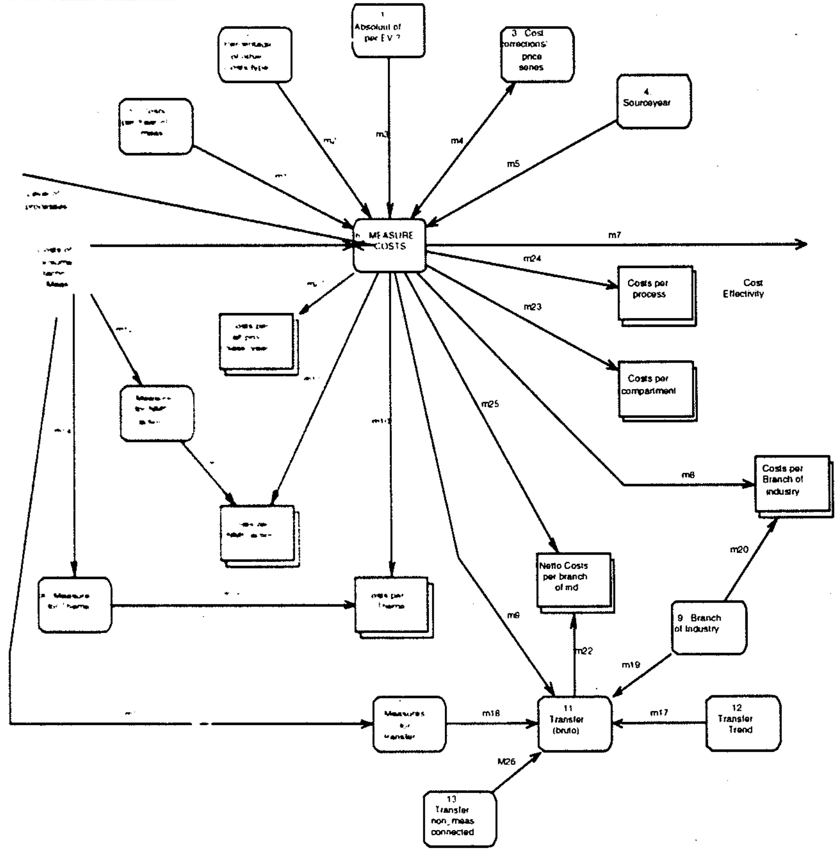

Fig. 7 Example of a more detailed Influence Diagram, zoomed in to show relations refering to environmental measure costs.

5. CONCLUSION

The transition from a situation where models are used with the aim of exploration to an almost industrial production situation is not easy. It demands multiuser, multipurpose information systems instead of single-user, single-purpose models. Also other skills, other methods of system development and emphasis on quality assurance are needed.

Both evolutionary system development and testing guided by influence diagrams appear to contribute to this quality assurance. Evaluating the evolutionary approach from a system dynamics point of view reveals that the quality of specifications is a key factor.

Our organisation is now in the middle of transition process mentioned above and still learning every day. We think we have achieved a system development method that is able to stand the quality trial of ISO 9001 certification. A pre-audit has shown that we are on the right road but still have some way to go.

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