EXPERT SYSTEM FOR HEATING EQUIPMENTS' MODELLING IN CLIM 2000

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ABSTRACT

The CLIM 2000 software proposes a host architecture for dynamic, modular building energy modelling. CLIM 2000 provides a library of basic models, which in particular allows simulation of hydraulic heating networks. Unlike those oriented towards simulation of the building envelope, these models pose specific resolution problems.

Owing to the modelling adopted, the elements making up the hydraulic networks require knowledge of the topology of the heating circuit. The choice of models depends on this topology.

This choice is made by an expert system, here produced with the GENESIA 2 generator, executed before the global model numerical solving phase, consisting of assembly of the various basic models. Here, we propose studying the method used to solve these problems inherent in this new type of model.

This approach enabled the field of application of CLIM 2000 to be broadened in relation to its initial design. Here, the modelling adopted demands pre-processing before the numerical solving phase. General modelling problems can therefore be processed independently of any numerical solving (processing of sequential data, choice of models dependent on the organisation of a graph, etc.). The solution proposed here will thus enable other problems we will encounter in the future to be answered on a case by case basis, further to specific adaptations.

1) INTRODUCTION

CLIM 2000 is a modular software environment for development of building energy numerical models, developed by the Département Applications De l'Electricité d'EDF. It has been operational since 1989 (Bonneau et al. 1989) and is built around an ordinary differential equations solver, and provides modellers with an open-ended library of modelling elements, which can be assembled to create a global building model.

These modelling elements are represented by a data structure combining:

- a schematic representation for handling,
- a mathematical representation corresponding to the equations associated with them,
- a numerical representation defining their parameters.

These elements reflect the main components of a building: envelope, heating systems, etc.

Some elements, in particular those allowing modelling of the various components of a hydraulic heating network, posed specific problems. The modelling adopted is such that the elements chosen are not governed by a numerically solved mass balance equation (Gautier 1990). On the contrary, the flowrates are considered to be information propagating through the network. In this case, two problems arise:

- propagation depends on the network topology,
- looping of the network introduces an additional constraint, which must be eliminated.

These points were solved by an expert system, interfaced with the application, and whose execution is completely transparent to the user (Covalet - Gautier 1990).

After describing more completely the two problems mentioned above, we will analyse how they were solved by the expert system, explaining the relevant facts and rules.

2) PROBLEMS LINKED TO THE MODELLING ADOPTED

2.1) Imposed flowrate in a hydraulic circuit

We will concern ourselves here with the modelling adopted for studying hydraulic heating networks. The elements modelled are radiators, pipes, programmable 3-way valves, boilers, stopcocks, T-couplings, circulation pumps, water tanks, etc.

These elements are crossed by a water flow and interconnect via this mass transfer. Assembly of two hydraulic elements thus implies a coupled heat exchange by enthalpic and mass flow. The enthalpic flow is directly linked to the direction of flow passing between the two elements:

$$\phi_h = \dot{m} \cdot h_a$$

where ϕ_h is the enthalpic flow
$\dot{m}$ is the mass flow
h_a is the enthalpy of the fluid upstream.

The distinction for each element between upstream and downstream therefore leads us to orient the elements.

The modelling hypothesis adopted for the water heating networks is the absence of pressure drops. Therefore, we don't calculate the pressures in the modelled elements (pipes, boilers, 3-way valves, etc.): the flowrates circulating through each branch of the hydraulic circuit are known through the mass conservation of each element:

$$\Sigma\, \dot{m}_s - \Sigma\, \dot{m}_e = 0$$

where $\dot{m}_e$ is the flowrate entering the element
$\dot{m}_s$ is the flowrate leaving the element.

Here, the circulation pumps provide a given water flowrate, which may be variable over a period of time, but which is independent of the geometry of the circuit.

The mass balance equation above does not require numerical solving, but can be transformed into an affectation of the following type:

$$\dot{m}_{si} = \sum_{i} \dot{m}_e - \sum_{j \neq i} \dot{m}_{sj}$$

where $\dot{m}_e$: flow entering the element
$\dot{m}_s$: flowrate leaving the element
($\dot{m}_{si}$: flowrate leaving No. i)

Therefore, the flowrate is not calculated by the solver, but is an imposed value, which must be propagated to all the elements in the circuit.

2.2) Propagation of flowrate through the circuit

In the case of a circuit only comprising elements such as one upstream inlet and one downstream outlet (pipes, radiators, boilers), propagation of the flowrate is easy since the same flowrate, imposed by a circulation pump, passes through each element.

However, in reality, this type of circuit is practically never encountered (see figure 1).

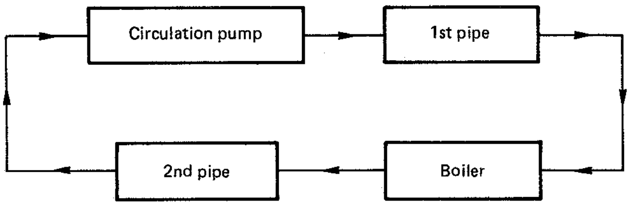


Fig. 1

Elements with more than two openings (generally three) are often encountered. Then, the problem is different, since the branches will appear in the circuit and the flowrate will have to be determined for them. There are two sorts of elements:

- those for which knowledge of one of the flowrates is sufficient to deduce the others in given branches. These elements always have a predetermined operating mode. For example, for a distributor cock (one upstream inlet, two downstream outlets), the user fixes the secondary/primary flow fraction. Determining the secondary flowrates from the primary flowrate is an integral part of the model and therefore poses no particular problems (see figure 2),

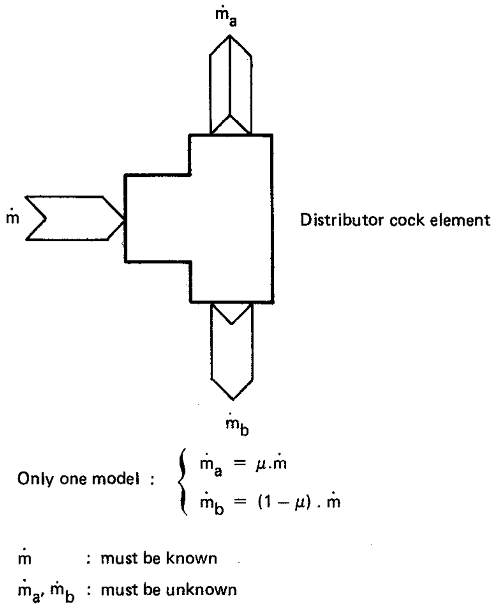
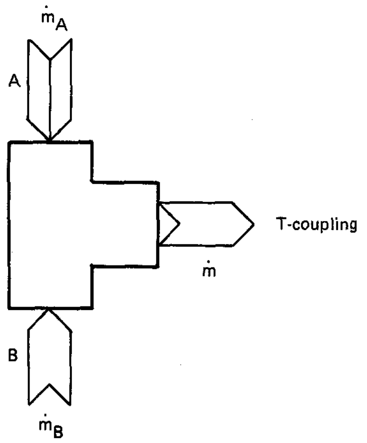


Fig. 2

- coupling type elements, performing a simple mass balance on the flowrates, allowing division or connection of the hydraulic network branches. Knowledge of the flowrates in any of the two branches enables the flowrate in the third to be obtained.

In this second case, it must be possible to identify the known and unknown flowrates in each of the branches in contact with the element. Determining the flowrates depends on the other elements in contact upstream and downstream and on the configuration of the circuit, in other words, its topology. The explicit mass balance is part of the model. For an element, we select a particular model from the three possible models (see figure 3).



The three possible models :

1) $\dot{m}_a = \dot{m} - \dot{m}_b$ if $\dot{m}$, $\dot{m}_b$ are known, $\dot{m}_a$ is unknown

2) $\dot{m}_b = \dot{m} - \dot{m}_a$ if $\dot{m}$, $\dot{m}_a$ are known, $\dot{m}_b$ is unknown

3) $\dot{m} = \dot{m}_a + \dot{m}_b$ if $\dot{m}_a$, $\dot{m}_b$ are known, $\dot{m}$ is unknown

Fig. 3

2.3) Redundant balance equation

When the entire circuit is looped, global conservation of mass leads to an additional balance equation, which is not independent since it is the result of the balances concerning each element. It must therefore be eliminated.

This requires removal of the connection between adjacent elements. The location of this redundant connection isn't known in principle, but depends on the topology of the circuit. It is therefore determined on a case by case basis.

3) TECHNICAL SOLUTION ADOPTED: AN EXPERT SYSTEM

3.1) Motivations

The problem with selecting models on the basis of the graph topology is in itself reason enough for choosing an expert system. For instance, let us consider that:

- we know the intrinsic behaviour of each hydraulic element through its associated model. From one or more known inlet (upstream or downstream) flowrates, we therefore know how to determine one or more outlet flowrates. We will thus have local rules specific to each model,

- the propagation of known or unknown flowrates takes place through the connections between the various occurrences of adjacent elements of the hydraulic circuit. Thus, we will have a global step by step propagation rule,

- the topology of the graph is described by symbolic facts.

This is a problem of data propagation via a graph, a problem directly handled by the inference engine, whereas it would have been far more cumbersome to have to handle it using a conventional procedural program.

It should be noted here that the numerical values of the flowrates do not concern us in determining whether or not the flowrates are known.

3.2) Propagation of flowrate and choice of models

The propagation of flow data in the graph takes place in two groups of rules:

- link propagation rules,

- rules of intrinsic propagation to each model.

The link propagation rules transfer the data between two adjacent occurrences of any elements:

"If the flowrate at the outlet of element X is known, if the outlet of element X is linked to the inlet of an element Y, then the flowrate at the inlet of element Y is known" (see figure 4).

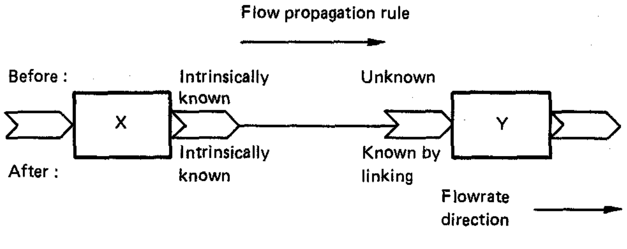


Fig. 4

A second symmetrical rule is used to process the case of a known downstream flowrate (upstream flowrate unknown):

"If the flowrate at the inlet of an element X is known, if the inlet of element X is linked to the outlet of an element Y, then the flowrate at the outlet of element Y is known" (see figure 5).

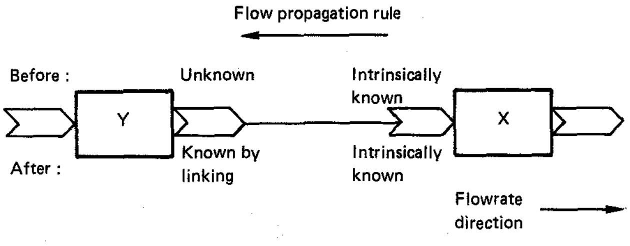


Fig. 5

The intrinsic propagation rules are specific to each model and do not depend on the assembly of the circuit. For example, for a boiler:

"If the upstream flowrate of the boiler is known, if the downstream flowrate of the boiler is unknown, then the upstream flowrate of the boiler becomes known" (see figure 6).

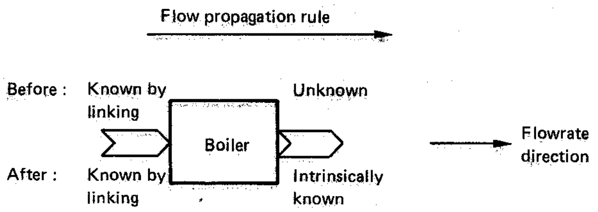


Fig. 6

Conversely, it should be possible to propagate the flowrate in the element in the downstream --> upstream direction:

"If the downstream flowrate of the boiler is known, if the upstream flowrate of the boiler is unknown, then the upstream flowrate of the boiler becomes known" (see figure 7).

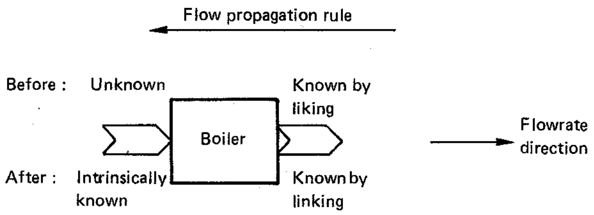
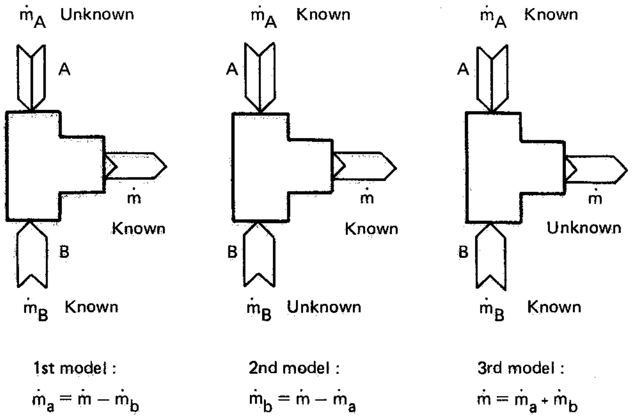


Fig. 7

Here, only one model is possible for the boiler element, and there is thus no ambiguity concerning the default choice.

The intrinsic propagation rules explicitly select the appropriate models when the elements concerned are couplings. For a manifold element, for example, there are 3 possible models. One of the possible cases is:

"If the upstream branch A flowrate of the manifold is known, if the upstream branch B flowrate of the manifold is unknown, and if the downstream flowrate of the manifold is known, then the upstream branch B flowrate of the manifold becomes known and the chosen model is No. 2" (see figure 8).



3 possible models for the same element

Fig. 8

3.3) Removal of the redundant balance equation

The redundant mass balance equation is due to the looping of the circuit, or of portions of the circuit with each other. On the one hand, the flow data propagation must be stopped, and on the other, the connection between adjacent elements (to be determined) must be removed, since this connection propagates the flow data.

Propagation is stopped naturally by the inference engine of the expert system, which stops examination of the rules once the knowledge base is saturated.

To determine the connection to be removed, two cases of looping are distinguished:

* when a link propagation rule is applied to an element whose flowrate is already known intrinsically: the connection carrying the flow data between the two elements is removed (see figure 9).

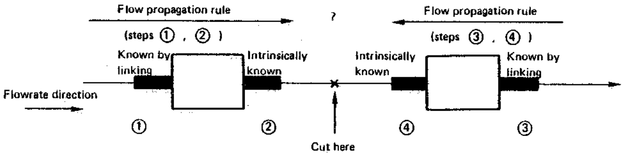


Fig. 9

* when an intrinsic propagation rule is applied to find out a flowrate already determined by a link propagation rule : all the element flowrates are already known by the link propagation rule. In this case, the connection with the adjacent element, for which the flowrate should have been unknown, is removed (see figure 10).

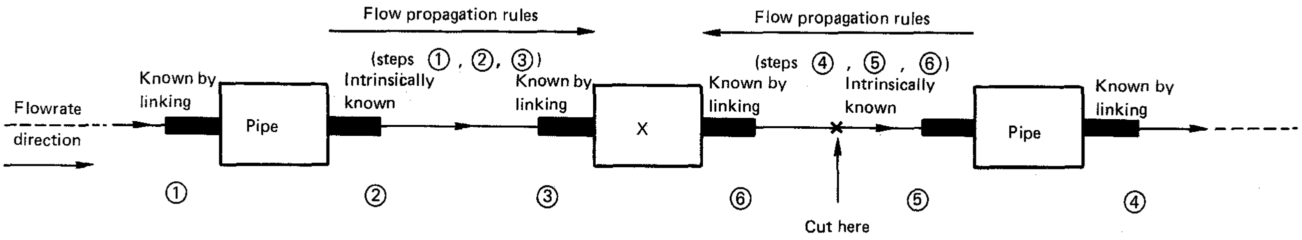


Fig. 10

It should be noted that here, there is no consistency check. At most, it is possible to check that no undetermined flowrates remain in one or more branches. A more detailed consistency check would demand knowledge of the numerical flow values, which is not the case here.

4) IMPLEMENTATION OF AN EXPERT SYSTEM

4.1) Architecture adopted

The expert system used here was designed using the GENESIA 2 expert systems generator (Steria 1987), whose inference engine runs with forward chaining using extended first order predicate logic (Gondran 1985).

First order predicate logic does indeed apply here since the reasoning, and therefore the writing of rules, is on generic elements (boilers, pipes, dividers, circulation pumps, etc.) and not on occurrences of elements in the circuit.

4.2) Facts base

The initial facts base can be broken down as follows:

- a fixed facts base which, for each element, associates the schematic representation handled by the modeller with its flow data representation. For example: "(entrée de tuyau) associe (débit_amont de tuyau)";

- a variable facts base describing the topology of the hydraulic circuit by element occurrence connections : this varies when the modeller changes the circuit to be examined. For example: "(entrée de (tuyau no 5)) relié_à (sortie de (circulateur no 2)".

We assume that the flowrates passing through all the occurrences of elements are unknown to start with. For example, here is a fact : "débit_amont de (tuyau no 5) 'inconnu".

Application of the rules should gradually lead to these facts becoming known.

4.3) Rules base

4.3.1) Link propagation rules

Any flowrate x known by intrinsic propagation in an element linked to another element makes flowrate y in this other element known through the following link:

```
REGLE CONNEXION _ALLER
SI          (x) 'connu_intr
            (x) relié_a (y)
            (y) 'inconnu
ALORS       (y)  'connu_lia

REGLE CONNEXION _RETOUR
SI          (x) 'connu_intr
            (y) relié_a (x)
            (y) 'inconnu
ALORS       (y)  'connu_lia
```

4.3.2) Intrinsic propagation rules

These are specific to each element. The inference engine starts up thanks to two intrinsic rules of the circulation pump:

```
REGLE PROPAGATION_CIRCULATEUR_ALLER
SI     débit_amont de (circulateur no (x))
       'inconnu
ALORS  débit_amont de (circulateur no (x))
       'connu_intr

REGLE PROPAGATION_CIRCULATEUR_RETOUR
SI     débit_aval de (circulateur no (x))
       'inconnu
ALORS  débit_aval de (circulateur no (x))
       'connu_intr
```

Here, x refers to any occurrence of the element in the circuit. These two rules are particular, since they enable the inference mechanism to be started. The rules specific to the elements with one inlet and one outlet are, for example :

```
REGLE PROPAGATION_TUYAU_ALLER
SI     débit_amont de (tuyau no (x))
       'connu_lia
       débit_aval de (tuyau no (x)) 'inconnu
ALORS  débit_aval de (tuyau no (x))
       'connu_intr

REGLE PROPAGATION_TUYAU_RETOUR
SI     débit_amont de (tuyau no (x))
       'connu_lia
       débit_aval de (tuyau no (x)) 'inconnu
```

```
ALORS  débit_aval de (tuyau no (x))
       'connu_intr
```

The principle is identical for those elements with several imposed inlets-outlets, except that there is no "retour" rule. For a 3-way manifold valve:

```
REGLE PROPAGATION_VAN3VCOLLECT
SI     débit_amontA de (van3collect no (x))
       'inconnu
       débit_amontB de (van3collect no (x))
       'inconnu
       débit_aval de (van3collect no (x))
       'connu_lia
ALORS  débit_amontA de (van3collect no (x))
       'connu_intr
       débit_amontB de (van3collect no (x))
       'connu_intr
```

The case of elements with several free inlets-outlets is more complex, since the model has to be chosen and the occurrences renumbered accordingly. The 1st step consists in generating the model from the element :

```
REGLE PROPAGATION1_DIVISEUR_MODELE1
SI     débit_amont de (diviseur no (x))
       'connu_lia
       débit_avalA de (diviseur no (x))
       'connu_lia
       débit_avalB de (diviseur no (x))
       'inconnu

ALORS
POUR_TOUT ((N))
TEL_QUE [occ_diviseur_mod1 = (N)]
DEDUIRE:
   [ (M) = ((N) + 1)
   occ_diviseur_mod1 = (M)
   (x) modele1_diviseur (M)
   débit_amont de (modele1_diviseur no (M))
   débit_avalA de (modele1_diviseur no (M))
   débit_avalB de (modele1_diviseur no (M)) ]
```

x represents an occurrence of the divider element, M the number of models No. 1 of the divider element encountered. The object occ_diviseur_mod1 is a counter set at 0 in the facts base. The 2nd step makes a correspondence between the flowrates of the element and those of the model, using the predicate "devient":

```
REGLE PROPAGATION2_DIVISEUR_MODELE1
SI     débit_amont de (diviseur no (x))
       'connu_lia
       débit_avalA de (diviseur no (x))
       'connu_lia
       débit_avalB de (diviseur no (x))
       'inconnu
           (x) modele1_diviseur (M)
ALORS  (débit_amont de (diviseur no (x))
       'connu_lia) devient
       (débit_amont de (modele1_diviseur
       no (M)) 'connu_lia)
       (débit_avalA de (diviseur no (x))
       'connu_lia) devient
       (débit_avalA de (modele1_diviseur
       no (M)) 'connu_lia)
       (débit_avalB de (diviseur no (x))
       'inconnu) devient
       (débit_avalB de (modele1_diviseur
       no (M)) 'inconnu)
```

For this model, the flowrate knowledge must then be propagated, in the same way as for any element:

```
REGLE PROPAGATION3_DIVISEUR_MODELE1
SI    débit_amont de (modele1_diviseur no (x))
      'connu_lia
      débit_avalA de (modele1_diviseur no (x))
      'connu_lia
      débit_avalB de (modele1_diviseur no (x))
      'inconnu
ALORS débit_avalB de (modele1_diviseur no (x))
      'connu_intr
```

Finally, the model must be substituted for the element. To do this, we generate the new flowrates link in the knowledge base and remove the old one with status INEXISTANT. A such rule depends on neither the element, nor the model:

```
REGLE SUBSTITUTION
SI        (old_x) relié_à (y)
          (old_x) devient (new_x)
ALORS     (old_x) relié_à (y) 'INEXISTANT
          (new_x) relié_à (y)
```

The above 3 propagation rules are to be repeated for all the possible models.

4.3.3) Circuit looping

In the case of link propagations, the circuit is opened when two opposing flowrates are known by respective intrinsic propagations:

```
REGLE BOUCLAGE_LIAISON
SI     ((x) 'connu_intr) relié_à ((y)
       'connu_intr)
ALORS  ((x) 'connu_intr) relié_à ((y)
       'connu_intr) 'INEXISTANT
```

In the case of intrinsic propagation specific to an element or model, the circuit is opened when all the flowrates are known by link propagation. Opening is applied to the flowrate(s) which should have been unknown. For example, for the radiator element:

```
REGLE BOUCLAGE_RADIATEUR_ALLER
SI     débit_amont de (radiateur no (x))
       'connu_lia
       débit_aval de (radiateur no (x))
       'connu_lia
       (débit_amont de (radiateur no (x)))
       relié_à
       ((débit_quelconque) de
       ((élément_quelconque) no (y)))
ALORS  (débit_amont de (radiateur no (x)))
       relié_à ((débit_quelconque) de
       ((élément_quelconque) no (y)))
        'INEXISTANT
```

There is a similar rule for the downstream side. This same type of reasoning can be transposed for elements with several imposed flowrate inlets-outlets. For elements with several free inlets-outlets, any model can be chosen.

5) INTERFACING WITH THE APPLICATION

The entry application is resident on a

UNIX workstation. When an user requests simulation, the entry software generates files which are then processed by a code generation program in the syntax of the numerical solver, which is itself executed on a more powerful computer.

The expert system is inserted between data entry and the code generation program. Interfacing uses the files produced by the entry phase, in particular that containing the description of the circuit entered by the user. At the end of execution of the expert system, new files are regenerated and replace those generated by the entry phase.

Interfacing is performed using the Shell command language and UNIX tools (chiefly substitution of character strings).

6) APPLICATION EXAMPLE

Here, we show the simplified circuit of a Sanitary Hot Water loop (see figure 11), modelled with CLIM 2000. The flowrates' orientation are shown on this figure:

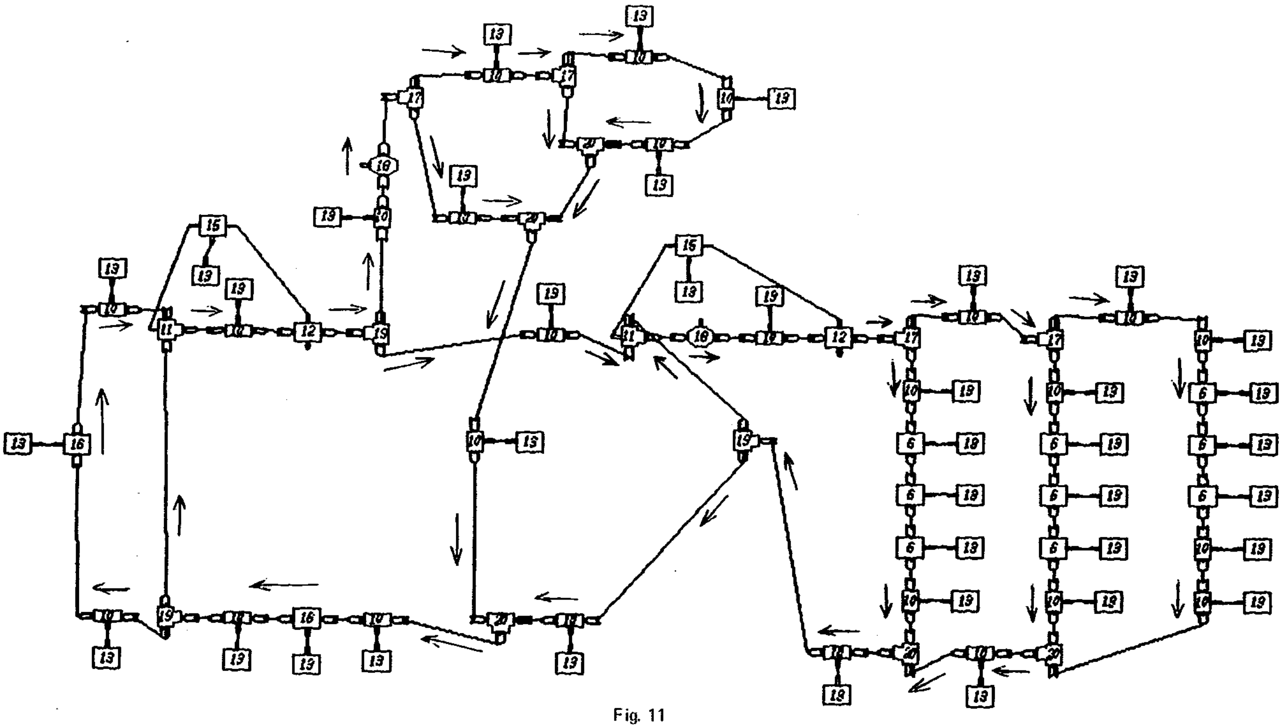


Fig. 11

7) CONCLUSION

This first experiment leads us to envisage the broadening of the CLIM 2000 applications scope in relation to its initial design. Generic modelling problems have however appeared:

- the exchanges between elements of a system are not necessarily symmetrical, but can be a sequential series of data, which it must be possible to determine according to the assembly proposed by the modeller,

- the data processing layout of the equations associated with the model is not always unique and can depend on the topology of the assembly graph.

The solution proposed here will thus enable us to deal with other problems we will encounter in the future, to be answered on a case by case basis, further to specific adaptations.

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