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A graph-theory-based approach to the analysis of large-scale plants

Heinz A. Preisig*

Chemical Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

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ABSTRACT

On-line balancing of mass and energy in a large-scale plant is today an absolutely feasible operation given the development state of the current data-acquisition systems. However, whilst the computing power is available, not all stream data are available in real-time and the programmed version of the instrumentation flow sheets in form of a graph cannot be used directly. They need to be modified so as to match the available information.

Two cases are discussed: the dynamic case, where all units are seen as dynamic components and the steady-state case, where each unit is assumed to operate at steady-state.

The analysis is done purely on a graph basis. The resulting algorithms are extremely simple and only require a depth-first path search algorithm. The idea is the essential part. Applying the algorithms yields simplified graphs, which contain in the dynamic case only computable quantities and the computation sequence. In the steady-state case one obtains a set of over-determined or dynamic nodes and a set of nodes that can be computed following sequence of computing computable unknown connections.

1. Background

1.1. The origin of the problem

Today's large-scale plants, such as the one of Statoil's refineries that we are currently analysing, are equipped with plant-wide data acquisition equipment, which log a large amount of process data as part of the plant's operation. This data can be used for various purposes but data-acquisition was largely implemented for the purpose of planning, thus a high-level control action. In many cases the collected information is also used for plant-wide control and safety supervisory systems, scheduling of maintenance, fault detection and simply to keep a statistic of the operations.

In our case we are interested in assessing the plant's operations in terms of mass and energy of parts of the plant, preferably to the detail possible. This requires closing the mass and energy balances over parts of the plant. In a large plant, where one has hundreds of streams and correspondingly many measurements, it is not trivial to identify the parts for which balances can be drawn up thereby also identifying what type of quantity can be balanced in the respective case. Thus our first effort was to work on a method to systematically determine on what balances we can actually draw up in the plant. Only afterwards the plant description is ready for the implementation of data reconciliation. Once the data have been reconciled, the extracted information can be used for different control and planning related operations. The problem of not having enough information to compute all streams in the plant has been given little attention in the literature. A search revealed little. Joris and Kalitventzeff (1987) mention the issue but no solution is being offered. The problem is nearly always present, which implies that it is resolved ad hoc when ever it arises. In the case we have explored closing the balances on-line and to the extent possible is simply not done.

1.2. Network modelling: basics

The approach that will be taken builds on network modelling to which this group is dedicated. Network modelling represents the plant as a network of primitive capacities that communicate mass and energy (Westerweele, 2003). We first map the physical containment of the plant into a network of control volumes and communications of material and energy between them. Each control volume represents a capacity for mass and energy and each connection represents a flow of mass or energy. The result is a directed graph with the nodes representing the different control volumes and the edges representing the connections between connected pairs of control volumes. Arcs can thus not split or join as this is the case in a flow sheet. Instead capacity elements must be introduced for each split and each joint. Both, the vertices, as well as the arcs can be typed. For example one distinguishes between mass transfer and conductive heat transfer as well as mechanical work.

* Tel.: +47 735 92807.
E-mail address: Heinz.Preisig@chemeng.ntnu.no.

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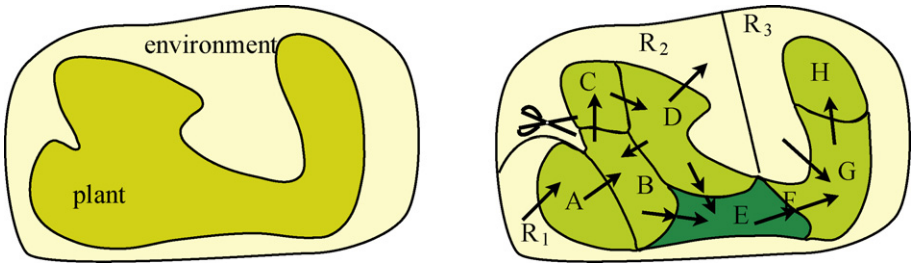

Fig. 1. The process-relevant part of the Universe and its dissection into control volumes. System labelled with E represents a different phase.

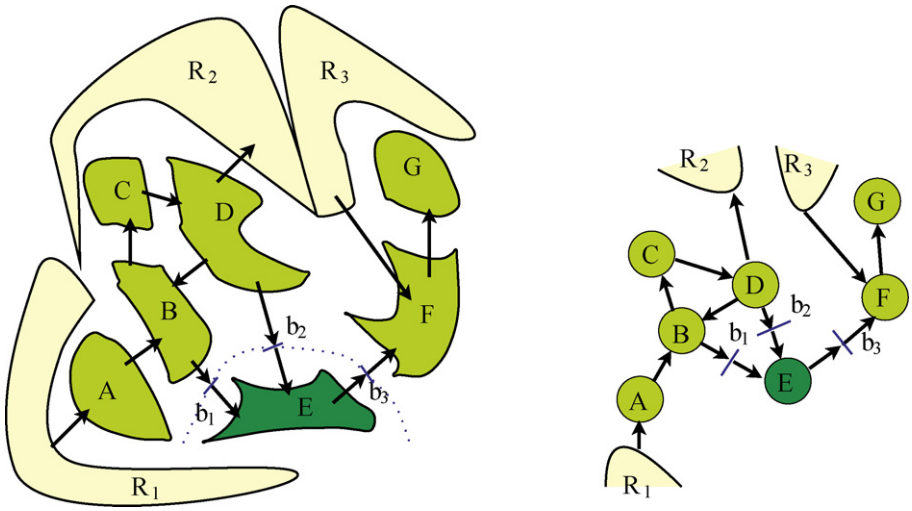

Fig. 2. Pulling apart makes the interfaces more visible; then the abstraction is extended to a set of connected systems. The phase boundary encloses system E.

In order to illustrate the concept, let us first look at an example that demonstrates the generation of a graph. A plant is seen as an entity being embedded in its environment as shown in Fig. 1. Keeping the purpose of the model in mind, one splits it into spatial sub-domains, which are chosen such that one obtains easily describable parts of the plant and the relevant environment. This sectioning of the plant and its environment is the most essential step of the modelling process, because it determines the maximum information contents being captured. The decisions on how to sub-divide is often based on physical units, phases or other spatial entities for which primitive descriptions are available. Once one introduces this subdivision, one also introduces flows of extensive quantities, thus flows of mass, energy and momentum. These are introduced as entities that, whilst in fact being bound to a physical transfer system, are simplified to flows, thus only the conductivity property of the underlying transfer system is being considered but no capacity effects are included. Otherwise these parts of the systems must be identifiable sub-domains. Once this subdivision has been made, the plant is abstracted in two steps. First one "pulls" the individual sub-domains apart, which makes them a separate entity. Next one abstracts the sub-domains into either uniform entities, referred to as lumps, or gradually changing entities, referred to as spatially distributed systems. Phase surfaces are lifted out and modelled as sub-domains without capacity.

Fig. 2 shows the capacities and the phase boundaries as nodes in a graph, which are connected with each other by arcs representing the flows of extensive quantities: the base physical topology has been generated.

The resulting graph is a directed one: the direction, indicated by showing arcs as arrows, defines a reference co-ordinate for each stream, thus taking care of assigning the transfer a proper sign in each of the balance equations, one in each of the connected systems.[1]

For the purpose of discussing the problem approached in this paper, we do not need any further details on how to handle for example complexity and the details on how to automatically generate the equations. It shall though be mentioned that these issues are rather complex but also have been finding solutions over the past years,[2] and need to be reported separately.

1.3. Problem formulation

We start with a network representation of the type introduced above that represents a large-scale plant such as a refinery. How one generates this network representation is of secondary importance. We require only a node/arc graph representation such as an adjacency matrix, an incidence list or an incidence matrix representing the graph (Bondy & Murty, 1982; Diestel, 2005). We are currently using a new generation of the MODELLER (Westerweele, 2003), our first commercialised version of a high-level modeling tool. The new version carries a new name: ProcessModeller. It has the ability to easily generate network models for large-scale sys-

[1] For the notation the reader is referred to Wikipedia-Graph-Theory (2008), Bondy and Murty (1982), and Diestel (2005) and for some typical chemical engineering applications of graph-theory the reader is referred to Mah (1990) and Friedler, Tarjan, Huang, and Fan (1992).

[2] See MODELLER project: Preisig (2004), Westerweele (2003), Mehrabani (1995), and Lee (1991), the RWTH project: for example Theissen and Marquardt (2007) and as a third project with similar objectives: Linninger (2000).