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Modeling Techniques to Support Abnormal Situation Management in the Petrochemical Processing Industry

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ABSTRACT

We describe the use of the Abstraction Hierarchy framework to model a petrochemical system. The framework provides a description of the physical and functional relationships within the plant which reveal opportunities for operator action in both normal and abnormal situations. We demonstrate that the Abstraction Hierarchy can be meaningfully applied to petrochemical systems as it has been in other domains and we discuss some implications for future research.

1. INTRODUCTION

The inability to effectively manage abnormal situations exacts an annual $20 billion toll from the U.S. petrochemical industry [1]. This occurs despite continual technological developments in advanced control systems and training of operational personnel. Many of these developments have been based on an implicit assumption: that the range of representative events considered by designers are sufficient to cover all possible contingencies. However, experience with large industrial systems inevitably leads to the conclusion that unanticipated events will occur regardless of the extent of engineering analysis and planning. Further, it is that very unanticipated variability which represents the greatest threat to plant safety and productivity [2]. How does one model a plant so that the representation is both useful and meaningful to operators forced to contend with unanticipated events?

The Abstraction Hierarchy Representation

The Abstraction Hierarchy [3] is a multi-level representation of the structure of a plant. Although the number and nature of levels are not fixed, in the process control domain we have found it useful to include models of production and safety goals, first principles, general functions, plant equipment, and equipment location and appearance. Each level of the Abstraction Hierarchy constitutes a complete system model and is distinguished by a specific language employed at that level.

Individual levels of the Abstraction Hierarchy (AH) are related to adjacent levels by a means/ends relationship. When transitioning between levels, an operator can exploit these relationships to ask three crucial questions (see Figure 1). By entering any level of abstraction operators are implicitly asking themselves the question, “What?” More specifically, “What is the form, function, or purpose that I am interested in?” When traversing up the levels of abstraction, the operator can ask the question “Why?”. That is, “Why does the structural description of the plant include equipment X or function Y at this level?” At the adjacent level above, the operator should find the answer to that question in a more abstract function or purpose. Similarly, when stepping down to lower levels of abstraction, the operator can ask the question, “How?” For example, “How can function Y or purpose Z be realised?” The adjacent level below should denote the functions or equipment that are pertinent to answering such questions. The WHY:WHAT:HOW questions form a window that can be vertically translated through the levels of abstraction. That which constitutes a WHY in one window can serve as the WHAT if the frame is moved up one level of abstraction.

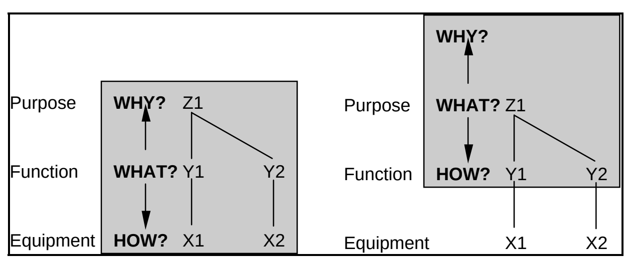

Figure 1: The shifting WHY:WHAT:HOW window in the Abstraction Hierarchy.

The AH can be complemented by a second dimension to describe the physical aggregation of components at various levels of resolution. However, the nature of the relationship described along the aggregation dimension is conceptually distinct from the means/ends relationship described along the abstraction dimension. The various levels of aggregation are ordered by a part/whole relationship. For example, a casing, impeller and a motor might be aggregated to form a pump. The individual components can be treated separately or they can be treated at a lower level of physical resolution (i.e., higher aggregation) as a pump.

These orthogonal dimensions of abstraction and aggregation define an area over which a number of different plant models are described (see Figure 2). Although each of these models reveals a unique set of information about the modeled system, we emphasize that each is a complete model within its particular cell in the full abstraction/aggregation area. Navigation through this area facilitates an understanding of both the physical and functional relationships between plant elements.

Finally, it is often helpful to specify what an abstraction hierarchy is *not*. The AH is not a specification of events, situations, or plant states. These concepts are temporally restricted whereas the structural representation provided by the AH is relatively invariant over time. That is to say, the AH is *event-independent* [4]. The model content is not specified via a finite set of abnormal events which are anticipated by designers. Further, the AH does not specify operator tasks or goals. While such a specification can be useful, tasks and goals can vary while structure remains constant.

The McFarlane et al. FCCU Model

The Abstraction Hierarchy has been employed previously to model a simulated thermal-hydraulic process [5], a simulation based on an existing pasteurisation process [6], aircraft engineering systems [7], a power plant feedwater system [8], and conventional [9] and nuclear [10] power production. In order to test the feasibility of employing the AH in the petrochemical domain, we have employed a partial plant simulation described by McFarlane, Reineman, Bartee, and Georgakis [11]. Henceforth we will refer to the simulation as the McFarlane et al. model. This simulation focuses on the reactor/regenerator section of a Fluid Catalytic Cracking Unit (FCCU). Within a refinery, an FCCU breaks down high boiling point input feeds and separates valuable products from waste products. Within the FCCU, the reactor breaks up the hydrocarbon chains by combusting input feed with the help of a catalyst. The regenerator serves to clean the catalyst used in the reactor. The FCCU is the economic heart of a refinery. To a large extent, its successful operation determines whether or not the refinery will be profitable [12]. The critical nature of its employment makes the FCCU an ideal candidate for exploring the techniques described in this report.

The McFarlane et al. model is a highly simplified model of an FCCU. However, it is designed to capture major system dynamics in order to explore various control configurations [11]. The important criterion in this case is the degree to which the model is representative of the complexities of existing FCCUs. The McFarlane et al. model is multivariable, nonlinear, and features strong interactions between sub-systems. Further, it imposes both mechanical and operational constraints that would be found in actual applications [11]. Given these characteristics, the McFarlane et al. model seems to strike a good balance between representativeness and simplicity.

A major advantage of the McFarlane et al. [11] model is that a full description of the model equations is provided. The modeling techniques described here can only yield models as precise as the engineering process models on which they are based. Our goal is to transform the algebraic and differential equations that engineers use to describe the plant into a model that is psychologically relevant to operators challenged with controlling these processes [2].

2. MODELING THE STRUCTURE OF THE FCCU

In this section we apply the AH modeling framework to the McFarlane et al. model of the FCCU. In the following section, we highlight some lessons learned from the application of the framework to this novel domain.

The McFarlane et al. Abstraction Hierarchy Space

Figure 2 provides an overview of the regions in the abstraction/aggregation space which have been defined for the McFarlane et al. FCCU. Eight cells in the space have been found to be useful in describing the plant. The arrow between the Physical Function and Generalized Function levels at the Component level of aggregation indicates that we have constructed a diagram detailing the transition between these cells.

Aggregation

Abstraction	System (S)	Sub-system (SS)	Unit (U)	Component (C)
Functional Purpose (FP)	$$			
Abstract Function (AF)		AF-SS	AF-U	AF-C (mass) AF-C (energy)
Generalized Function (GF)		GF-SS	GF-U	GF-C ↕
Physical Function (PFn)				PFn-C
Physical Form (PFo)				

Figure 2: The abstraction/aggregation topography for the McFarlane et al. [11] model FCCU.

In reviewing Figure 2, the reader might question why only 8 of 20 cells in the AH space have been described. We emphasize that all cells of the AH are valid and potentially useful representations of the plant. However, in constructing an AH we must evaluate which cells are likely to be most useful to operators. Each cell has been evaluated in terms of what information is added/lost when transitioning from one cell to another. When a representation is constructed for a given cell, we evaluate what information is contained therein which is not contained in other cells. If there is little or none, we sacrifice use of that cell. Through this evaluation process we can limit the presence of marginally useful information that might drain the limited cognitive resources of the operator.

Experimental observations of problem solving behavior (from which the AH concept was initially formulated) have shown that such behavior typically falls along the diagonal from the Physical Function/Component cell to the Functional Purpose/System cell [3]. Not surprisingly, the evaluation process described in the preceding paragraphs frequently yields a set of representations that fall along the same diagonal. When operators think about the purposes and functions of a plant, they tend to adopt a coarse unit of analysis (e.g., system, subsystem); when operators think about physical properties of a plant they tend to adopt a fine unit of analysis (e.g., component).

Levels of Aggregation

Figure 3 provides a representation of the levels of aggregation. It emphasizes the manner in which lower level nodes are aggregated to form higher level nodes. We give the levels of aggregation a cursory treatment in this paper because part/whole hierarchies are common in system descriptions. What is important at this stage is that the reader recognize that the four levels of aggregation cut across the five levels of abstraction (see Figure 2). Thus, at each level of abstraction there are four possible complete descriptions of the plant.

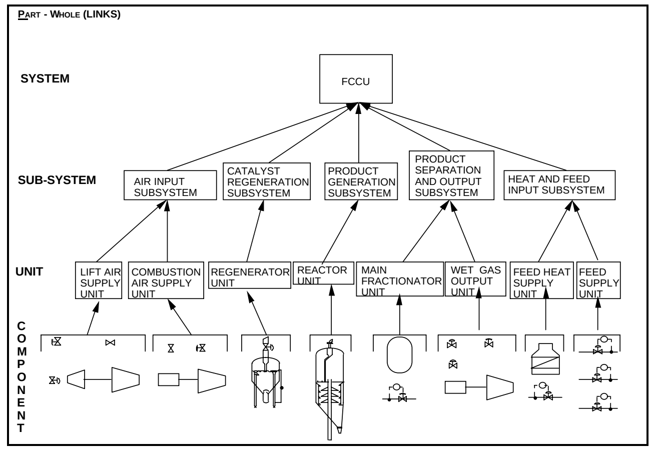

Figure 3: Levels of Aggregation with emphasis on relationships between levels.

The Level of Physical Form

The reader will likely notice that no cells at the Physical Form level are defined in Figure 2. This is because there is no physical instantiation of the McFarlane et al. FCCU. The plant is exclusively simulated and thus has no Physical Form to model. In an operational plant this level would be filled with representations of the location and appearance of the physical components.

The Level of Physical Function

The Physical Function (PFn) representation resembles a traditional piping and instrumentation diagram except that instrumentation is not specified by the AH (see Figure 4). Also absent from this representation are the various controllers employed in the FCCU model. In constructing an AH, we pay particular attention to restricting our descriptions to the means/ends structure of the plant elements. While control systems are crucial to the successful operation of a modern petrochemical plant, they do not lend themselves to characterisation by means/ends descriptions. In our work, we employ a different framework (not described in this paper) to model the behaviour of control systems.

The lines connecting the nodes at the PFn level represent physical relationships between the structural components. For example, the two Ubend lines connecting the reactor and regenerator imply that there is a direct physical connection between these units. While this statement may strike the reader as being obvious, higher levels of abstraction do not follow this rule. The reader should be careful to understand the meaning of connections between nodes at each level.

The Level of Generalized Function

The level of Generalized Function (GF) reveals information about heat transfers and flows of commodities (e.g., catalyst, feed, products). We have found it useful to discuss chemical reactions at this level also. The primary reason for including reactions at the GF level is that the language typically employed here lends itself well to discussing reacting commodities. Further, chemical reactions are equally subject to the mass and energy first principles that are described at the Abstract Function level (see below). In other words, we can talk about chemical reactions at the GF level and emphasize which commodities are reacting, in what proportions, with certain products and heat transfers. At the Abstract Function level we can talk about relevant mass and energy relations. Thus, the same chemical reaction can be treated at two levels of abstraction, each complete yet unique in the type of information it provides.

Figure 5 details the transition between the cells of the PFn and GF levels at the Component level of aggregation. It is the manifestation of the arrow between the cells visible in Figure 2. Such a representation is not typical of AHs and was initially constructed as a memory aid for the authors. In review, however, we realised that it was a valuable explanatory tool and we have continued to find it useful. This representation provides a very detailed explanation of how each node at the PFn level is related to its associated end(s) at the GF level. Conversely, each node at the GF level is connected to its mean(s) at the PFn level. Thus, a given node can have a single or multiple means and ends, emphasizing the homomorphic nature of the AH representation.

There are a couple of noteworthy features in Figure 5. One is the empty node at the PFn level which is connected to the Gas Oil Flow node at the GF level. This flow is different from other flows in this simulation in that it has no regulating valve. Our conversations with process engineers indicate that it is not uncommon for flowrates in FCCUs to be determined by upstream processes over which the FCCU operators have no control. This lack of

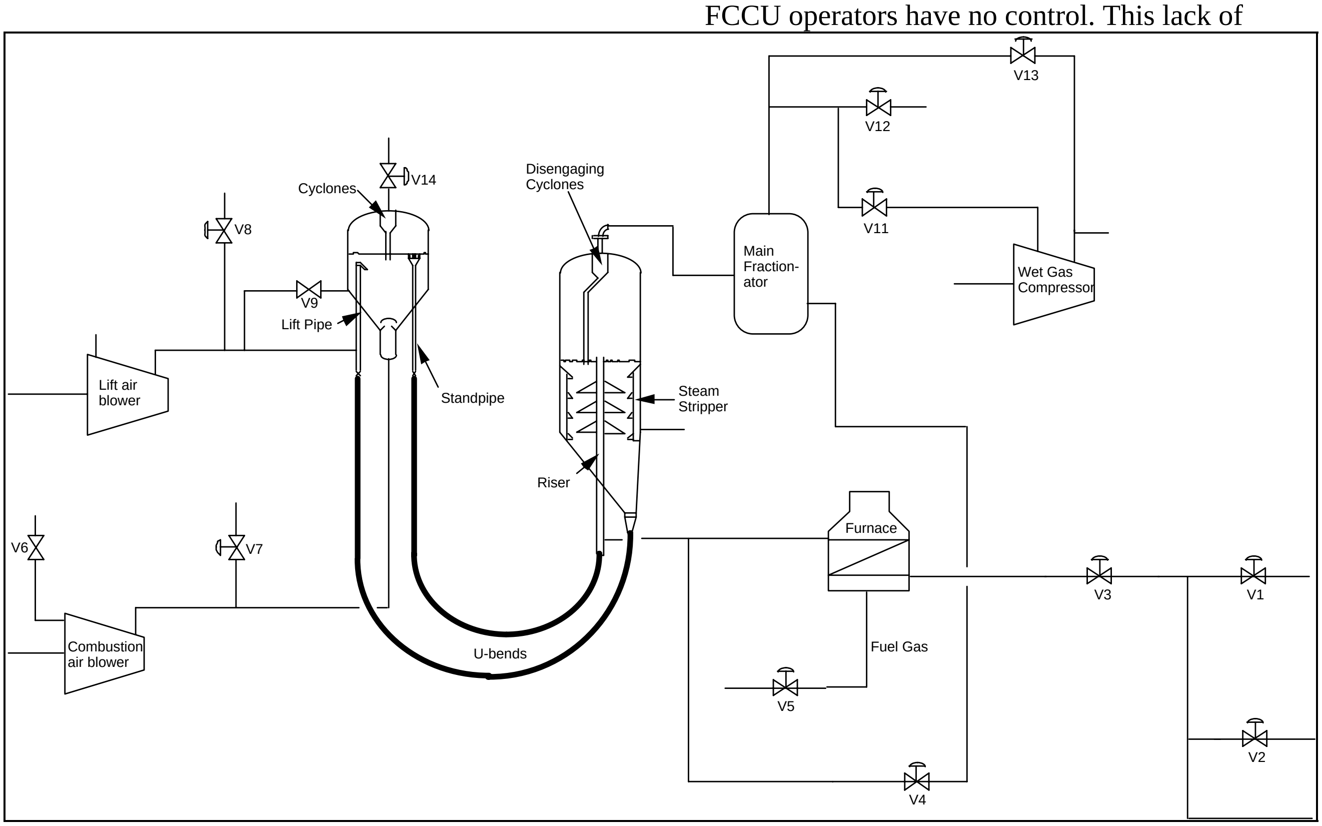

Figure 4: The Physical Function level at the Component level of aggregation.

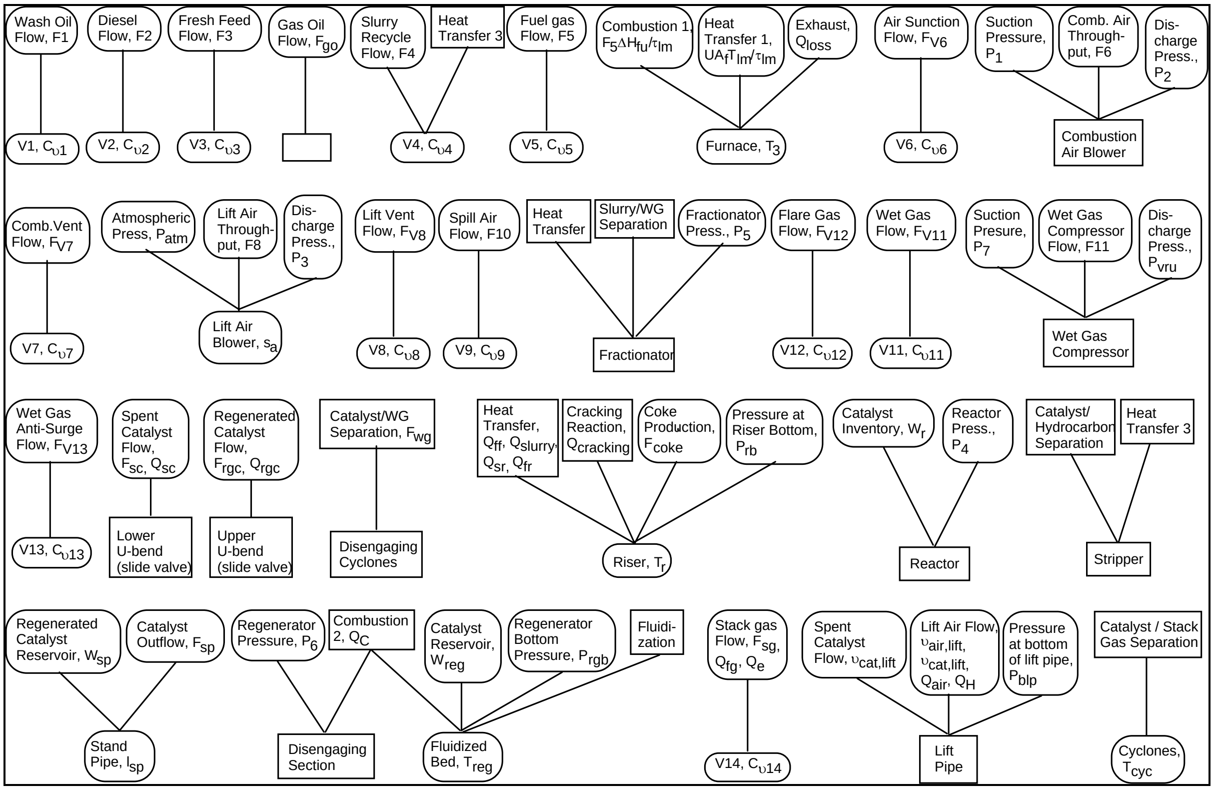

Figure 5: Detail of transition from the Physical Function to Generalized Function level.

opportunity for action is clearly reflected in the AH. In a fault management situation involving this flow, a well designed interface should make it clear to the operator that he has no capability to affect this flow. A second point of interest is that many nodes at the PFn level have multiple ends. Changes in the state of the equipment will lead to multiple changes in flows and heat transfers.

The GF-Component cell representation is shown in Figure 6. The nodes at this level represent general functions of the plant, e.g. flows, heat transfers. The connections between these nodes represent causal relationships. Note that

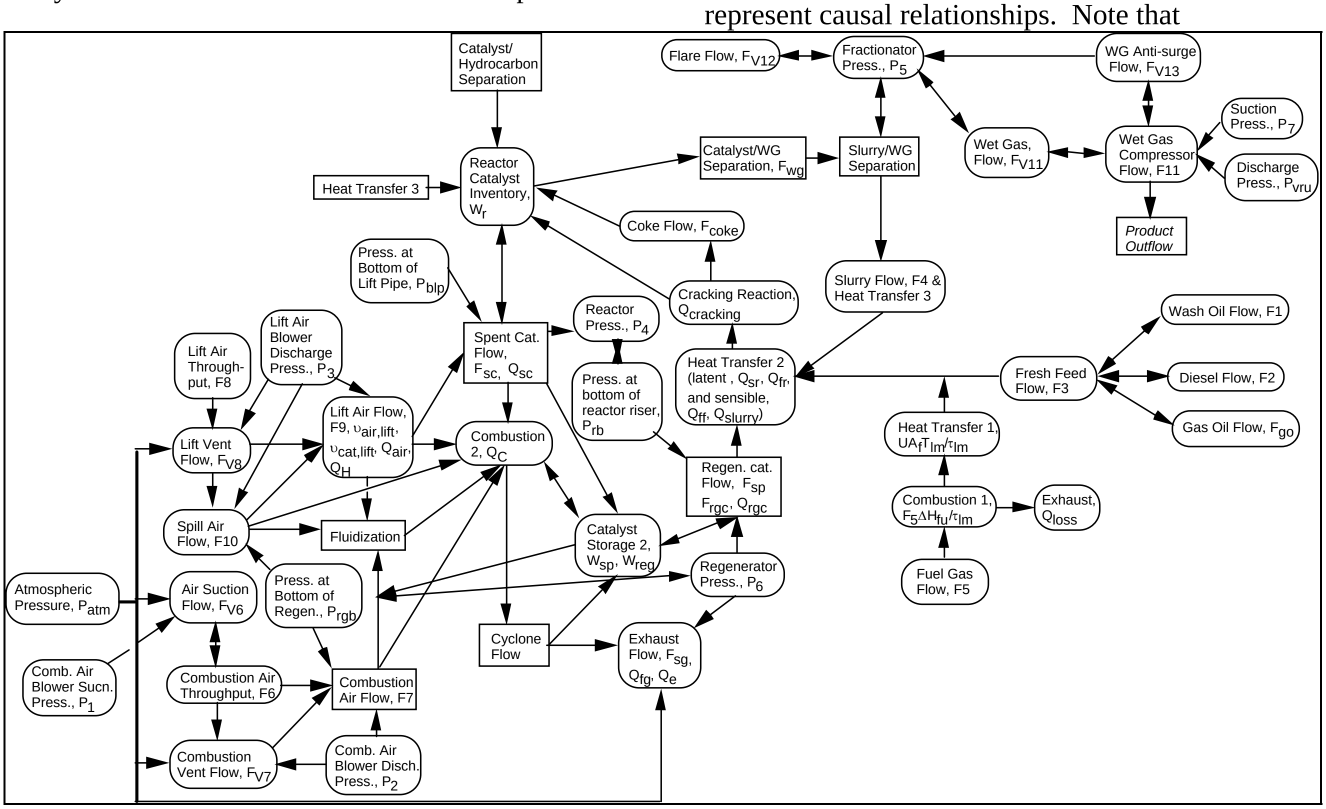

Figure 6: The Generalized Function level at the Component Level of Aggregation.

causal relationships need not be coupled with physical relationships such as those described by the connections between nodes at the PFn level. The GF-Component cell is quite complicated. The extensive connections between the nodes reflects the high degree of interaction between plant functions. The influence of pressure propagations is a major driver of this inter-dependency. Note that the complexity increases around those nodes related to the reactor and regenerator units. Whereas the functionality around the Feed Input and Heat Transfer Units is essentially sequential (which is typical of AHs we have dealt with previously), the functionality in the reactor and regenerator is circular.

The GF level at the Unit and Subsystem levels of aggregation are shown in Figure 7. Note that we employ the same language to describe the functions at these levels. Thus, units and subsystems are discussed in terms of their functions as flows, reactions, and heat transfers. Note how much simpler these representations are compared to the GF-Component level. Moving up a level of aggregation allows the operator to think about the same system in fewer terms, exploiting hierarchy to reduce memory demands.

The Level of Abstract Function

The Abstract Function (AF) level reveals information about mass and energy relationships in the plant. Connections between nodes at this level again reflect causality. Note that at this level of abstraction the various commodities are no longer distinguishable, they are all represented as masses. Further, different types of heat transfer are treated as energy exchanges.

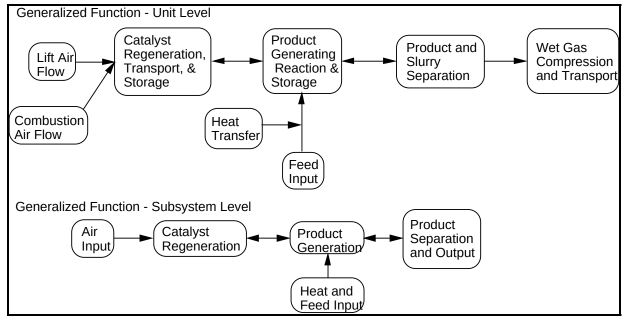

Figure 7: The Generalized Function Level at the Unit and Subsystem levels of Aggregation

The representations employed in the AF level are adapted from Multi-level Flow Modeling (MFM) [14]. We should clearly note, however, that we do not adopt all of the MFM rules of syntax. Thus, we do not claim that these representations are examples of MFM.

MFM prescribes six types of functions; *source*, *sink*, *store*, *balance*, *transport*, and *barrier* (see Figure 8). A *source* occurs when mass or energy crosses a system boundary into the system. Similarly, a *sink* occurs when mass or energy crosses a system boundary away from the system. A *store* represents a point in the system at which mass or energy can accumulate. A *balance* describes a conservation of mass or energy without

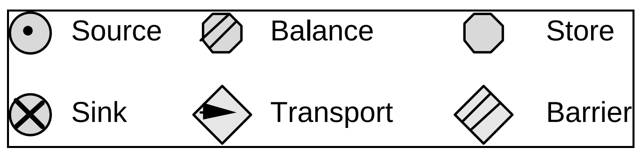

Figure 8: The functions of MFM employed in the Abstract Function Level of the AH.

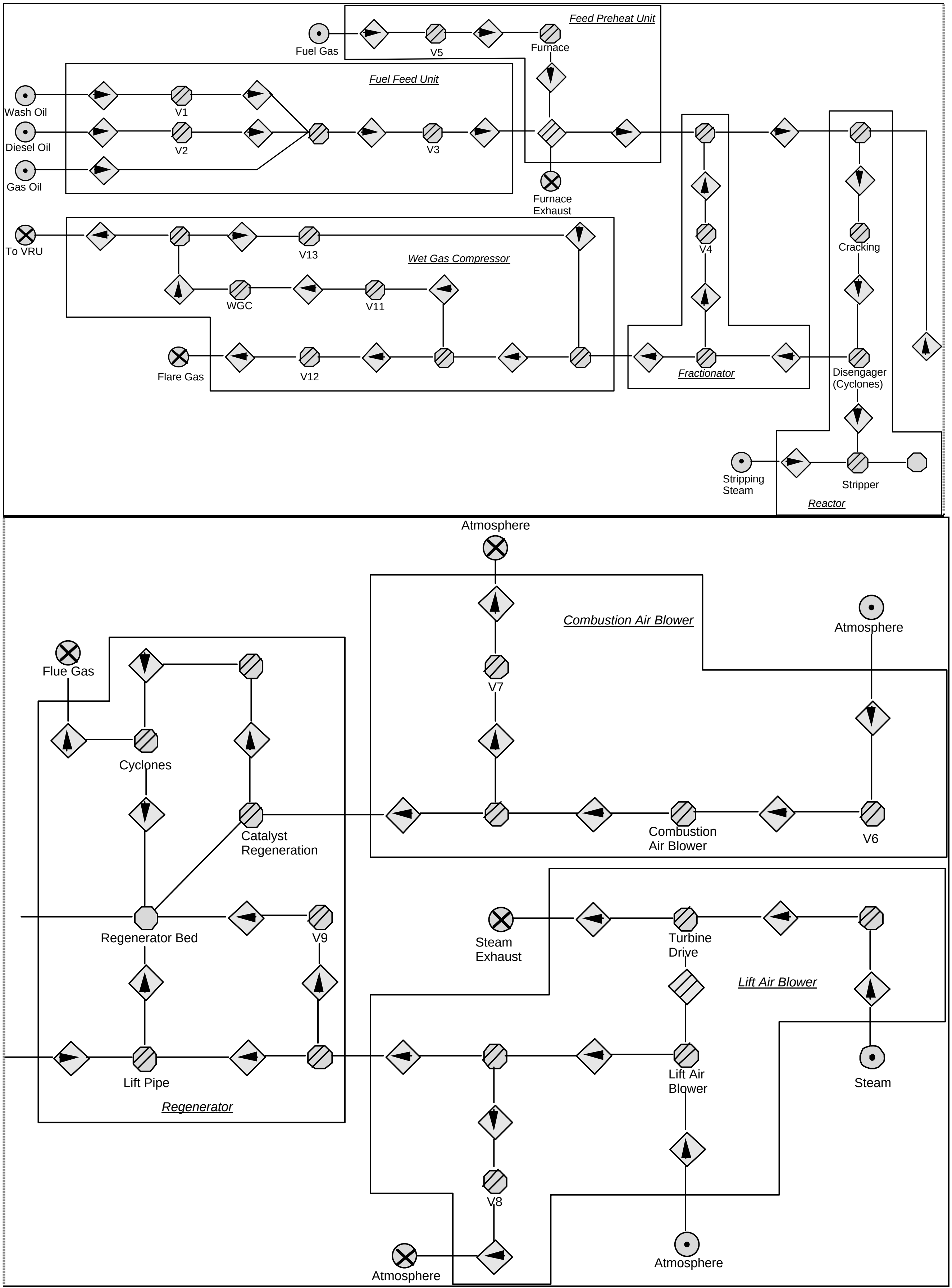

Figure 9: The Abstract Function level for mass relationships at the Component level of aggregation (figure split due to size and resolution limitations).

the use of a store, usually in the form of an exchange. A *transport* function indicates that mass or energy has been moved from one physical location to another. A *barrier* is used to indicate a prevention of mass or energy transport.

The functions at the AF level most likely to be confused are *barrier* and *balance*. A heat exchanger is an example of a common piece of process equipment that serves to exemplify and distinguish between these two functions. In a typical shell and tube heat exchanger, energy is transferred from the hot side flow to the cold side flow. As such, the heat exchanger acts as a *balance* to energy because the energy is conserved without being stored. In contrast, the two flows never come into contact with each other (a major advantage in nuclear systems). Thus, the heat exchanger acts as a *barrier* to mass because it prevents physical contact between the commodities.

The AF level at the Component level of aggregation for mass representations is shown in Figure 9. The parallel representation for energy relationships has not been included due to space limitations.

Figure 10 shows the separate mass and energy portions of the AF level at the Unit level of aggregation. Corresponding representations for the AF level at the Sub-system level of aggregation are not provided.

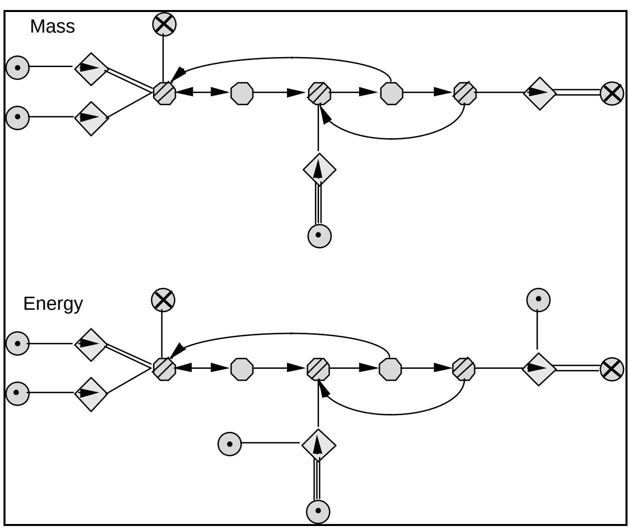

Figure 10: The Abstract Function Level at the Unit Level of Aggregation (mass and energy treated separately).

The Level of Functional Purpose

The overview of the AH space (Figure 2) has a pair of dollar signs in the Functional Purpose-System cell. The overall purpose of an FCCU is to contribute to the financial viability of the installation as a whole. This may appear to be a simplistic statement, but the rest of the AH demonstrates that, in order to achieve this purpose, an extensive range of functions must be properly arrayed. We have experimented with including a couple of other purposes for the FCCU. The most prevalent among these were safety-related. However, out conversations with process engineers have convinced us that these concerns are either coincident with production interests or not worthy of mention.

3. DISCUSSION

Prior to this exercise, the Abstraction Hierarchy had not been employed to model petrochemical processes. The results of our efforts shown here indicate that it is indeed feasible to extend the AH to this domain. While the transition has necessitated some modifications and extensions of the AH concepts, it has not posed any insurmountable obstacles or demanded any changes in philosophy. In the following paragraphs, we will discuss some of the peculiarities associated with employing the AH in the petrochemical domain.

Dealing with advances in technology.

In reviewing the AH described here, two process engineers noted that advances in FCCU technology are manifested at the Physical Function level of Abstraction. In other words, the higher level functions which comprise an FCCU are seldom modified by new technology. This observation has strong implications for employing an AH throughout the life cycle of a plant. Modifications of plant equipment are to be expected, although their actual form cannot be anticipated far in advance. If the immediate effects of those changes are manifested in a single level of abstraction, modifications could be restricted to that level. Information systems and displays could be designed flexibly in areas where changes are likely. Such an approach would alleviate the need to overhaul the AH when slight (but influential) process modifications are introduced.

This observation can also be extended to creating AHs for other FCCUs. If differences between multiple plants also lie primarily at the PFn level of abstraction then it is likely that higher levels of abstraction will be relatively consistent between plants. This suggests that once an AH has been created for a full scale FCCU, it can be adapted to other FCCUs with modifications to low levels of abstraction only. If this extension holds then it has strong implications for the flexible application of a particular AH modeling effort.

New developments in AH methodology.

Extending the AH to the petrochemical domain has challenged our understanding and appreciation for the modeling technique itself. Two particular principles have evolved from this application. First, we have concluded that not every node in the AH needs to have an associated quantitative variable. Previously we had assumed that each node could be quantified in some manner. Our experience with the FCCU has convinced us that this is not necessary. Qualitative labels can be employed as place holders as long as the distinction is clearly drawn. For example, the cyclones in the reactor and regenerator clearly serve the function of separating commodities (see Figure 6). However, there is no model variable that characterizes this function. Despite our inability to attach a quantitative parameter to this function it is still important that it be spelled out in the plant model. Operators can still use the qualitative concept (i.e., the object) in their reasoning processes, even though there is no quantitative value for it.

The second principle is that not all higher level functions must be connected to lower level nodes. In other words, not all ends have means which can be efficiently described at the adjacent lower level. The introduction of pressures to the GF level provides a good case in point (see earlier discussion). In this case, there is frequently no node at the PFn which acts and a means for the pressure. In previous applications of the AH this problem was not encountered. We elected to allow nodes at functional levels to remain unconnected because it would be misleading to suggest to operators that a node at a lower level could be employed to affect a higher level function. In other words, we opted for no information over misleading information.

4. CONCLUSIONS

We stated earlier than the greatest threat to plant productivity and safety is the reality of unanticipated variability. Because all events cannot be foreseen by plant designers, event-based responses to abnormal situations must eventually fail to encompass the range of situations operators will face. This statistical fact need not lead to the conclusion that there is nothing that we, as engineers, can do to support operators faced with abnormal plant situations. The Abstraction Hierarchy is a framework which allows a description of opportunities for acting on the plant which is independent of transient states. The model formed by the AH is applicable in all situations, anticipated and unanticipated. Because the Abstraction Hierarchy is event-independent, it accommodates unanticipated variability by describing the invariant relations [15] of the plant that constrain both operator and control system behaviour.

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