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Closing the "CIM GAP" in the Process Industries

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ABSTRACT

Vendors and consultants struggle to draw attention to their proven experience in discrete CIM in order to convince process manufacturers to adopt CIM technology. The analogy works very well at the periphery where an invoice is an invoice, but disintegrates at the core where modeling of the manufacturing "process" is required. Until recently, it has not been possible to completely and rigorously model entire process plants in real-time, and this missing core element has been called the "CIM GAP". With the recent introduction of the *concurrent resolution*™ kernel, the CIM GAP now is being closed in the process industries.

1. INTRODUCTION

The term, computer integrated manufacturing (CIM), arose a decade ago in discrete parts manufacture, and has more recently been extended to include process manufacturing even though there is great disparity between the two in modeling of the manufacturing "process". Information handling, on the other hand, bears greater similarity. In each case, information handling starts on the "plant floor" and extends throughout the enterprise and to suppliers and customers. Even though such information handling systems are tedious and costly to install, they have been well within the state of known practice for at least a decade. Modeling is another matter, however.

Unlike discrete manufacturing, process manufacturing involves changes at the atomic and molecular levels. Rather than by direct observation, the state of a process plant is determined by instruments measuring temperature, pressure, composition, flowrate, etc. At any moment, many of the instruments will be grossly incorrect, but taken as a whole, they provide essentially the only evidence about the state of a process plant. Modeling is required not only to determine the present state of the plant, but also to determine how to change conditions, feeds, etc. to improve manufacturing performance. Success in adequate modeling of entire plants in real-time has proven elusive over the past two decades, and such lack of success has given rise to the term, "CIM GAP", which is widely used to explain why CIM cannot be applied to process manufacturing.

Beginning in the mid 70's, a research program was started with the aim to develop methods for fast, complete and rigorous modeling of process plants. This research resulted in the *concurrent resolution*™ kernel which not only meets the objectives of the research, but also is easily configured for different process plants, much like traditional process simulators. With the development of the *concurrent resolution*™ kernel, a large step has been taken in closing the "CIM GAP" in process manufacturing.

2. PROCESS VS. DISCRETE CIM

In defining process CIM, it is worthwhile to consider a classical example of CIM in discrete manufacturing - automobiles. The main idea is to convert paper transactions to electronic transactions. Starting in the dealer showroom, a customer order specifying color, body style and options is transferred electronically to a manufacturing plant, and an estimated delivery date is returned to the dealer. Automobiles are partly assembled by robots and partly by hand so both an electronic record and a human-readable record are generated for each customer order. The electronic record, a machine-readable module, is placed on a chassis carrier, and the robotic part of the manufacturing process begins.

The electronic record instructs robots regarding body style, paint color, etc. When the robotic portion is completed, assembly is finished manually based on a human-readable record. The completed automobile enters a testing facility where its complete performance is recorded electronically. Records from assembly and testing become part of the manufacturer's permanent record for each automobile, and is available via network to its dealer's where any subsequent maintenance also is entered into the permanent record. Once the car is shipped, an electronic invoice is forwarded to the dealer. Suppliers also are integrated into the manufacturing process by direct access to the manufacturer's database. Thus, suppliers can gauge the ebb and flow of demand for their components as new automobile orders are placed with dealers.

This automobile manufacturing example makes it clear that discrete CIM methods, while useful as role models, cannot be directly applied to CIM for continuous processes: the consumer is too remote, process conditions are demand dependent, supplies are subject to "take or pay" conditions, etc. The business case and the interaction between the business case and the way products are manufactured are quite different. Process manufacturers may have a large number of possible suppliers willing to sell feedstocks of various qualities at various prices, and selection of suppliers may vary week to week and may be dependent upon how the manufacturing process is operated. Likewise, the manufacturer may sell products of varying quality to a diverse market at various prices, and the most profitable array of products may impact the way in which the products are manufactured.

So in process manufacturing there is much greater diversity in the way products can be manufactured in a given plant, and there is much greater interaction between the best mix of suppliers, the best mix of products, and the conditions under which supplies are converted to products. Fortunately, the laws of nature permit precise modeling of these interactions in continuous process plants, and such models can be made to provide great economic benefit which simply is unavailable to discrete manufacturers. Not only can the models be used online for CIM, but also they can be used offline in preliminary studies in order to be sure that a proposed CIM project will provide adequate return on investment.

3. COMPLETE AND RIGOROUS RECONCILIATION- FIRST STEP IN CLOSING THE CIM GAP

Let us imagine a plant with a state-of-the-art CIM system in place. All financial transactions between the plant, its suppliers and customers, and its owner are done via computers and networks in a fully automated system. Custody transfer meters, which are agreed to be correct by buyer and seller, are the foundation of the financial system and provide information directly and electronically from the distributed control system (DCS) to the financial system. Utilities and feedstock supplies are thereby paid, and customers thereby pay. Naturally the plant is equipped with state-of-the-art DCS and advanced control systems.

So what is missing? Data reconciliation. The entire operation is defined by instruments measuring temperature, pressure, composition, flow-rate, power consumption, etc. Yet at any moment, many of these instruments will be grossly inaccurate and each instrument is subject to failure without notice, and perhaps, without detection. Even custody transfer meters, although agreed correct between buyer and seller, may be incorrect in an absolute sense, or may become incorrect at any time.

Fortunately, the interdependence of process units and conditions within units makes detection of inconsistencies possible, at least in principle. For example, the overhead composition in a distillation tower is related to the top tray temperature and tower pressure. Or the flow rate of a heat pump fluid is related to its compressor power consumption And if the heat pump is driving the distillation column, then overhead composition, top tray temperature, tower pressure, heat pump fluid flow rate and compressor power consumption are all inter-related. One needs only to specify the inter-relationship in mathematical form in order to have precise standard against which to judge the correctness of the individual measurements.

A complete and rigorous model of the process, based upon all applicable laws of nature, is the ultimate standard that defines the necessary relationship between <u>all</u> measurements in a process. If more measurements are available than are required to completely specify the state of the plant in such a model, then opportunities for data reconciliation exist. It is fortunate that, in fact, a typical process plant will have several times as many measurements available as are required to mathematically define its state. In this case, some of the measurements are redundant; the redundancy ratio is defined as the total number of measurements divided by the degrees of freedom in the model plus the number of parameters, such as fouling factors, compressor efficiency and catalyst activity. Redundancy always is highest for a complete and rigorous model because the sum of degrees of freedom plus parameters is minimum.

Redundancy then permits both determination of parameters as well as analysis of measurement accuracy; a particularly lucid discourse on this topic has been given by Deming (1). For a typical process, thousands of measurements are available and the complete and rigorous model may comprise hundreds of thousands of non-linear equations, so a real example involves so much detail that an overview is difficult to obtain. To illustrate the usefulness of redundancy, let us consider a single model equation:

$$y = a x + b z$$

Here a and b are parameters like, say, fouling factors in a process model and the model has one degree of freedom, that is once a and b are known, one variable (x, y or z) must be specified in order to establish a definite relation between all other variables. x, y and z are akin to reflux ratio, condenser duty and reboiler duty in a process model.

When doing data reconciliation against a process model, we are not at liberty to fix any measurement as "true", but for purposes of illustration let us assume that we know that $z = 2$ exactly. Further suppose that measurements are available for x and y as shown in *Figure 1.* Here the redundancy ratio is $9/(2+1) = 3$. By fitting the model equation to the measurements, analytically or even graphically, we can determine a and b, and we can also judge the correctness of the measurements. For example, measurement number 7 seems to be incorrect. Thus, our model has provided a

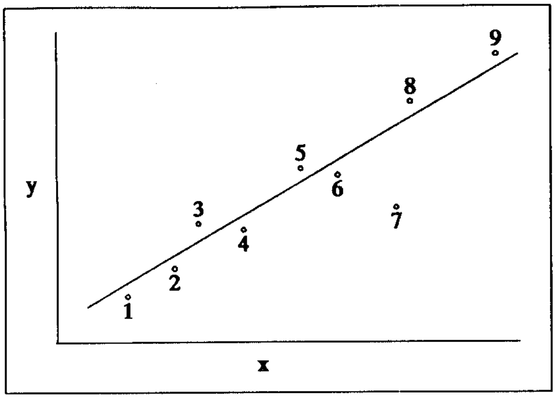


Figure 1. *Illustration of use of redundancy in measurements.*

standard against which the correctness of data can be judged. When the model is based upon all of the laws of nature applicable to a process, then such a standard is especially powerful in detecting incorrect measurements, and if redundancy is adequate, in detecting which measurements are incorrect.

Detecting that some process measurements are incorrect, based upon reconciliation with the laws of nature, does not require much redundancy; pinpointing which measurements are in error is where redundancy is of great value. For example, consider the natural gas liquids/nitrogen rejection unit (NGL/NRU) illustrated in *Figure 2.*

There are 10 components in the feed (N_2, C_1, C_2, C_3, nC_4, iC_4, nC_5, iC_5, C_6 and C_7^+). Since no chemical reactions occur in the plant, one law of nature (conservation of mass) provides 10 equations, one for each component, which any set of measurements must satisfy if they are correct. If we had a set of measurements that did not satisfy these equations, the measurements could be reconciled, or adjusted, for example, by least squares, to produce a set of reconciled measurements that exactly satisfy this law of nature. But that is not the main point at the moment.

The main point is that the mass balance alone does not provide a way to pin-point errors. For example, some ethane appears in the feed stream and all products streams. If the ethane mass balance is not satisfied for a set of flowrate and composition measurements, it can only be said that at least one of the measurements is in error; it is not possible through reconciliation to pin-point which one. Choices can be narrowed for components such as nitrogen which are not expected to occur in measurable amounts in some streams, but pin-pointing grossly incorrect measurements still is not possible. As illustrated in *Figure 1*, redundancy ratio is a good measure of pin-pointing ability. Let us examine the redundancy ratio in this case. Assume that flow-rates for each component in each stream are measured; fifty measured values, many of which are zero, are available. Clearly, there are ten equations, one for each component. There are no parameters in mass balance model. The number of variables in the model is 50; therefore, the number of variables that must be specified to define the model equals the total number of variables minus the number of model equations, i.e., 50-10 = 40. The redundancy ratio then is 50/40 = 1.25.

Now consider the redundancy ratio for the same plant, except now we will use a complete and rigorous model. For the whole plant, there are 550 measurements of temperature, pressure, composition, flowrate and compressor power consumption. In this model, 150 parameters and variables must be specified in order to completely define the model. Thus, the redundancy ratio is 550/150 = 3.7. With a much higher ratio, it can be expected that incorrect instruments can be pin-pointed, and actual experience over a two-year period at the plant has proven this to be true.

4. USES OF COMPLETE AND RIGOROUS RECONCILIATION

Although difficult computationally, complete and rigorous model reconciliation (CRMR) truly is the foundation of process CIM. In a simultaneous calculation, repeated automatically several times per day using online data, it uses all measurements to (1) arrive at a reconciled set of measurements which provide the best estimate of the state of the plant, (2) detect incorrect measurements and (3) determine equipment performance parameters, such as fouling factors. As shown in *Figure 3*, there are a number of practical uses of this information.

Knowing which measurements do not match the model provides information necessary for doing instrument maintenance by exception. The "Bad Instrument List" is produced for this purpose. Instruments fail frequently online, and as they are the only indication of what is happening in a plant, it is important to recognize and correct failures as quickly as possible. Not only must the state of a plant be correctly known in order to perform economic optimization, a plant with correct instruments is a safer plant.

Reconciliation also provides the best evidence of actual equipment performance. By monitoring equipment performance, maintenance can be more timely and reliability analysis can be more accurate.

Accounting for feed costs, product values and outside utility consumption is done by "custody transfer" meters, which by agreement between buyer and seller are defined

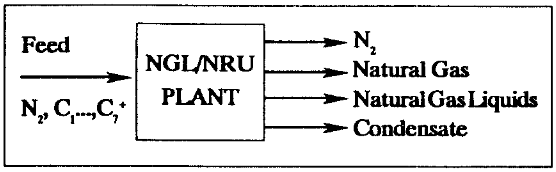


Figure 2. *Overview of NGL/NRU Plant.*

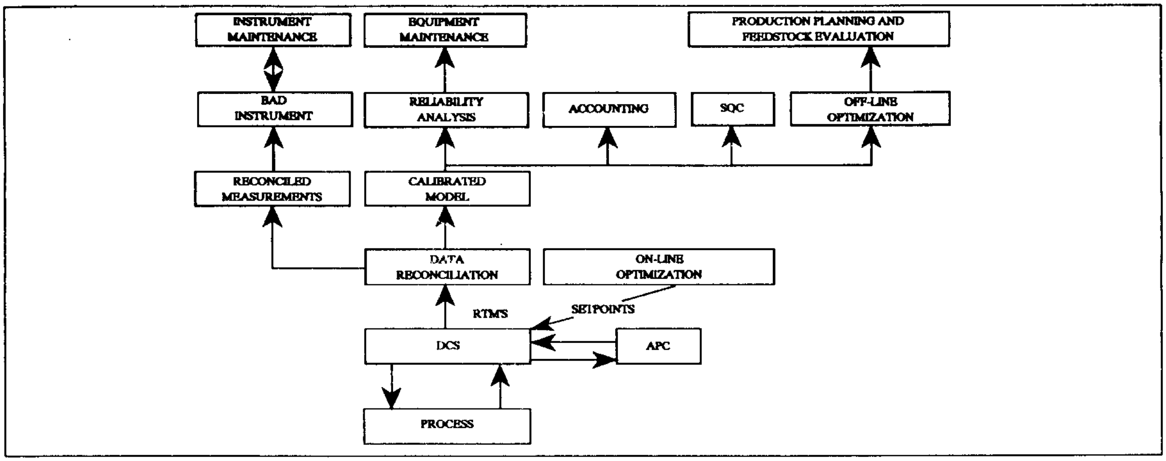


Figure 3. *Uses of CRMR.*

as being correct. Of course, often this is not the case in an absolute sense. Reconciliation uses information not only from custody transfer meters, but also are other temperatures, pressures, compositions, flowrates, wattages, etc. measured in the plant. In some cases, all of this information taken as a whole when reconciled against the complete and rigorous model shows custody transfer meters to be in error in an absolute sense. Then it is time for buyer and seller to find the cause of the error and to agree upon a course of action to correct it.

Statistical quality control (SQC) is useful for meeting quality specifications without undue give away. Reconciled measurements provide the most accurate input to SQC, and largely avoid the problem of applying SQC to measurements that are in gross error, an all too common occurrence.

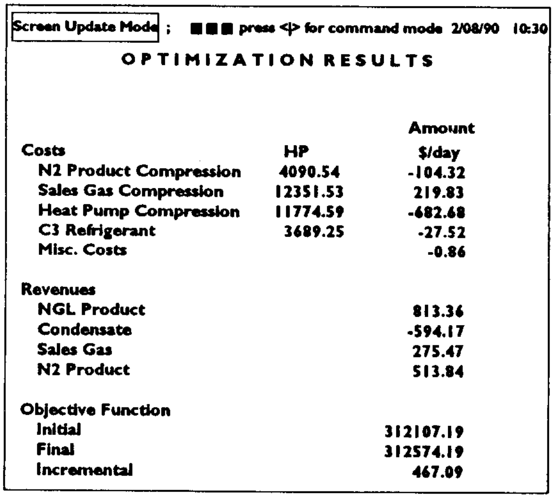
Offline optimization for production planning, feedstock evaluation , and even evaluation of process changes is one of the most valuable uses of the just reconciled and adapted model. The model shows exactly how the process is performing at the moment and is the best starting point for proposed changes.

5. OPTIMIZATION - SECOND STEP IN CLOSING THE CIM GAP

Just as complete and rigorous models provide a basis for data reconciliation, a procedure unknown in discrete CIM, they also provide the means for evaluating trade-offs in manufacturing in a way that must be the envy of discrete manufacturers. Although extensive calculations are required, the result from online optimization is just a few numbers that can easily be acted upon: the optimum setpoints and the financial tradeoffs. Many plants are operated based upon "cost minimization". Of course, complete and rigorous models through optimization allow calculation of the best trade off between costs and revenues to permit "profit maximization", a simple result. Still as shown in *Figure 4*, it may be important to understand how the tradeoffs actually occur. This is particularly important in convincing staff who do not understand economic optimization that increasing costs can, in fact, increase profits by providing a better yield of more valuable products, for example.

6. ACTUAL EXPERIENCES IN CLOSING THE CIM GAP

A natural gas liquids/nitrogen rejection plant operated by Amoco Production Company is the first plant to undergo data reconciliation, gross error detection and economic optimization using complete and rigorous models. Although the process is proprietary, a simplified schematic for one of two trains is shown in *Figure 5*. Both trains must be solved simultaneously because they share common methane heat pump and propane refrigeration systems. There



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                    OPTIMIZATION RESULTS


                                                  Amount
Costs                              HP             $/day
   N2 Product Compression        4090.54         -104.32
   Sales Gas Compression        12351.53          219.83
   Heat Pump Compression        11774.59         -682.68
   C3 Refrigerant                3689.25          -27.52
   Misc. Costs                                     -0.86

Revenues
   NGL Product                                    813.36
   Condensate                                    -594.17
   Sales Gas                                      275.47
   N2 Product                                     513.84

Objective Function
   Initial                                     312107.19
   Final                                       312574.19
   Incremental                                    467.09
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Figure 4. *Optimization Results.*

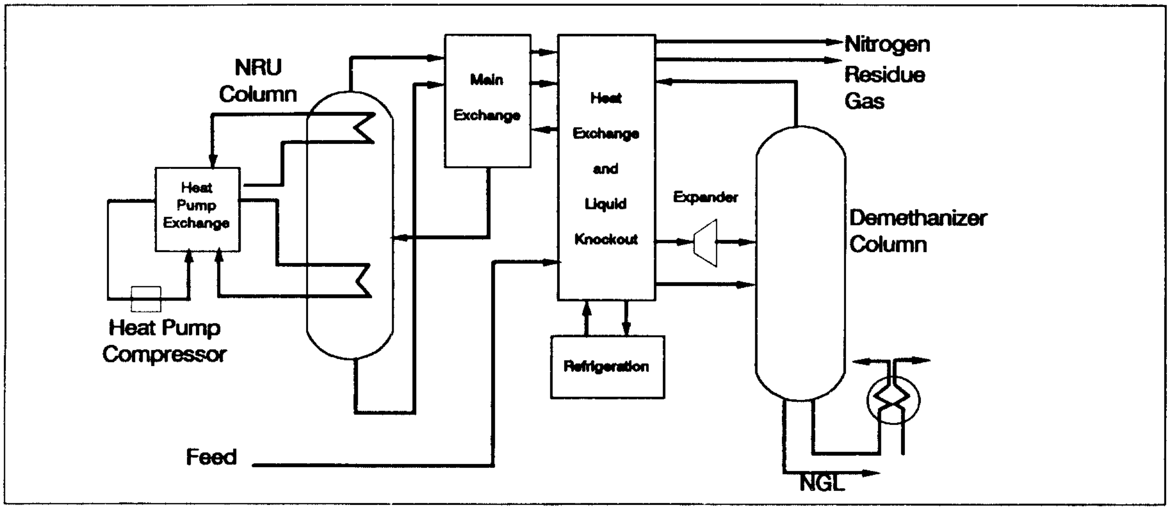

Figure 5. *NGL/NRU Process Schematic.*

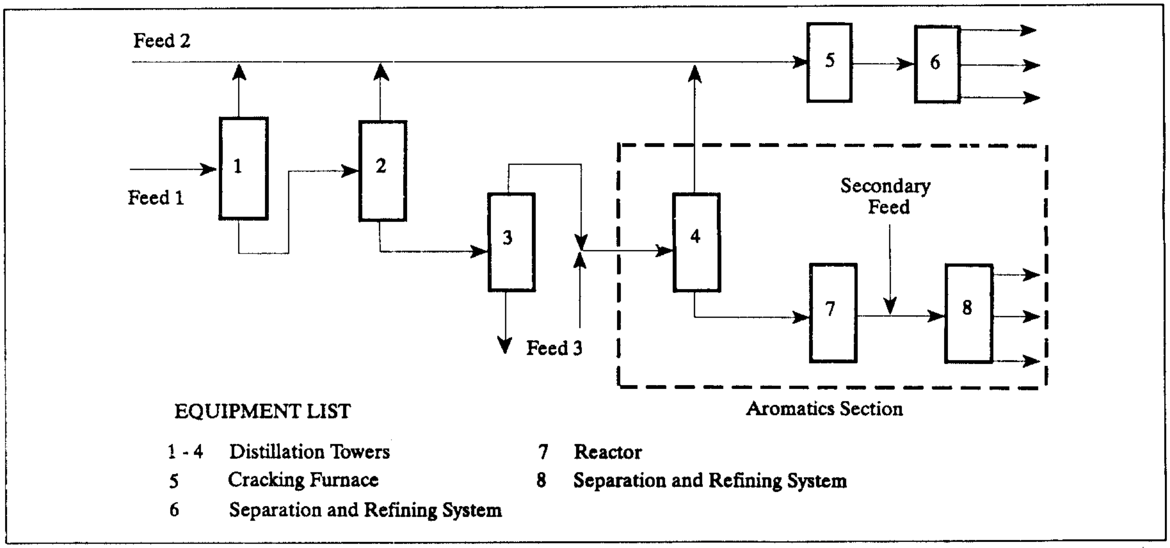

Figure 6. *Idemitsu Petrochemical Ethylene and Aromatics Supply System.*

are 550 measured variables, 40 independent setpoints and 170 pieces of equipment. Details of this installation have been published (2). The information in *Figure 4* is from an actual screen available at the operator's console for this plant. An installation on a similar but larger plant with three trains also has been completed.

CIM projects for two ethylene-aromatics plants owned by Idemitsu Petrochemical Company using complete and rigorous models has been described previously (3). A simplified schematic of one plant is shown in *Figure 6*. An interesting aspect to this project was that the feed preparation system (Units 1-4 in *Figure 6*), was modelled completely and rigorously, whereas client models in object code for Units 5-8 were interfaced to the *concurrent resolution*™ kernel.

An overview for the entire CIM system at Idemitsu Petrochemical is shown in *Figure 7*. Here it can be seen that a great deal of equipment and systems, other than complete and rigorous modeling capability, is needed for a complete CIM system. On the otherhand, all such equipment and systems is of limited demonstrable economic benefit without the modeling capability to answer "What if?" questions over a broad range of circumstances.

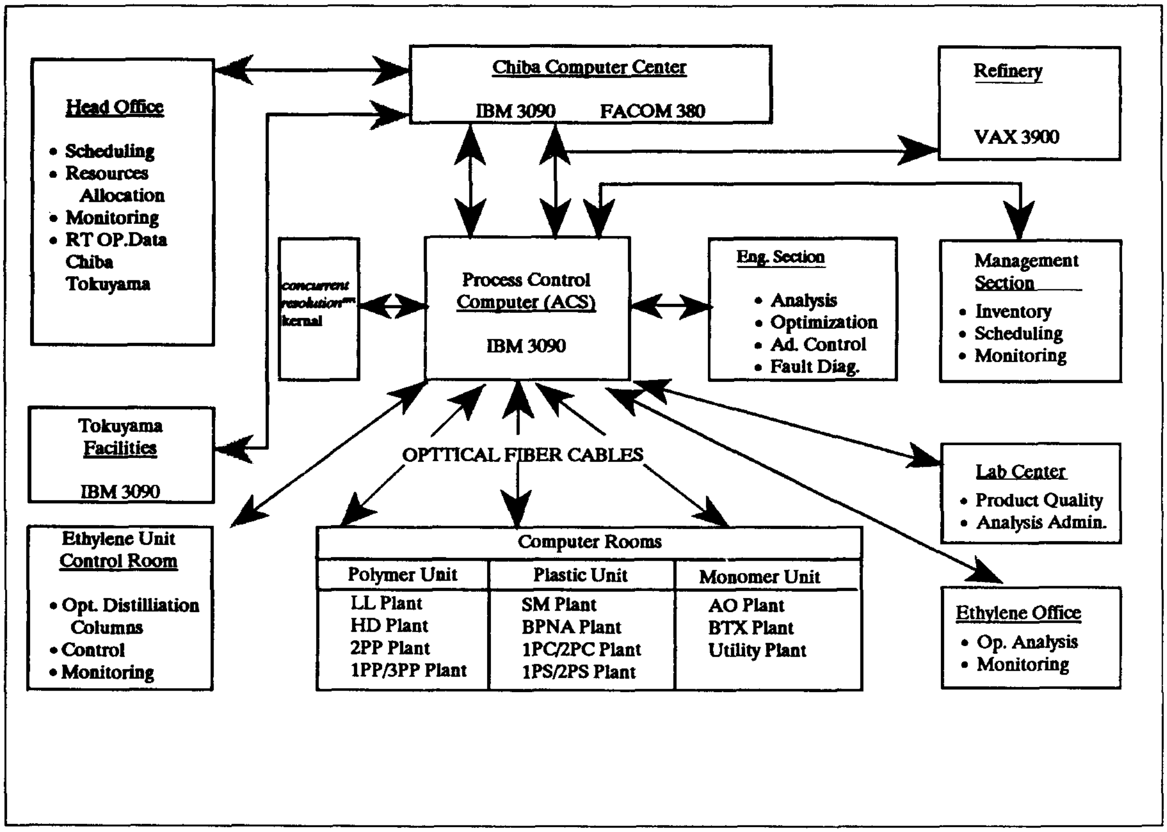

Figure 7. *Idemitsu Petrochemical ACS Network.*

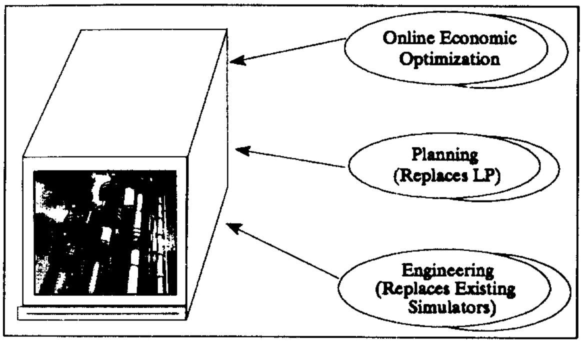

Figure 8. *All-In-One Modeling System.*

7. ALL-IN-ONE MODELING SYSTEMS

The importance of complete and rigorous models just begins with online data reconciliation, gross error detection and optimization. Once such a system is online, it becomes an all-in-one modeling system, *Figure 8*, replacing both linear programs for planning and tradition simulators for engineering.

8. EASE OF CONFIGURATION

For such a modeling system to be truly all-in-one, it must be readily configured to a specific plant just as are traditional simulators. It must also be generic, that is, applicable to a broad range of plants, and a thermophysical property system must be built in just as with traditional simulators. Each of these was a design objective satisfied by the *concurrent resolution*℠ kernel.

9. CONCLUSIONS

Complete and rigorous process models are the core element in CIM for the process industries. Such models allow the state of a process plant to be determined, allow detection of bad instruments and allow overall plant optimization, including feedstock selection, to be done; they close the "CIM GAP". Until recently such models could not be executed in real-time as required in CIM, but now the *concurrent resolution*℠ kernel provides a ready solution which has been proven in two plants in America and two in Japan.

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