Synthesis in Engineering Design

by

Arthur W. Westerberg

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by
Arthur W. Westerberg
Engineering Design Research Center
Chemical Engineering Department
Carnegie Mellon University
Pittsburgh, PA 15213
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ABSTRACT

This paper describes the complex activities involved in engineering design. Next it reviews the chemical engineering literature on synthesis, looking particularly heat flows in processes. It concludes by looking at some illustrative design synthesis literature in electrical, mechanical and civil engineering.

SCOPE

Engineering design is a complex activity. The purpose of this paper is to present a broader view of the design activity than is generally done within the chemical engineering literature. This paper first describes several key issues in design. It examines how one might create tools to support this activity.

We summarize much of the chemical engineering literature which covers the synthesis of heat exchanger networks. The main results here are based on our ability to set targets for the design and the use of heat flow representations, both of which can be used to discover good designs quickly. Even in this area, where over 200 papers exist, much work remains to be done. When design targets do not exist, other approaches are used that are closer to those that exist in other disciplines. We examine cases of this type in chemical engineering, finishing with a look at a few design papers in other engineering disciplines.

SIGNIFICANCE AND CONCLUSIONS

This paper has discussed the complex activity involved in engineering design. We conclude that a major approach to -automating this activity involves partitioning a problem into several levels of abstraction and into several different views (representations), each of which is needed to reason about a design. Major issues are creating the views and then the operators and the control strategies for the propagation of decisions and the maintenance of consistency among these different levels and views.

1. INTRODUCTION

In the last two years, the author has been the director of a National Science Foundation funded Engineering Research Center - the Engineering Design Research Center (EDRC). The EDRC is one of fourteen such centers started in the last three years in the United States as a part of a national plan to improve US competitiveness. The vision for our center is to provide leadership in the *development* and *integration* of design methodologies that will make U.S. industry preeminent in design practice.

For administrative purposes the center is partitioned into three laboratories. Projects in each laboratory typically deal with several research issues; however, each laboratory emphasizes one key research thrust.

- The **Design for Manufacturability Laboratory [DFM]** is developing ways of bringing life cycle concerns (e.g., manufacturability, flexibility, safety) back to the early design stages.
- The **Synthesis Laboratory [SY]** is building methods for the automatic generation and selection of design alternatives based on incomplete information at the preliminary design stages.
- The **Design Environments Laboratory [DE]** is creating significantly improved next generation design environments as opposed to incrementally improving current environments.

We are examining design issues in and across several engineering disciplines. This paper is based on this experience and looks at design quite generally as an activity.

2. DESIGN

We shall choose a quite broad definition for design. It is the activity of gathering together and generating the information needed to create a new artifact or modify an existing one.

2.1. The Importance of Design

Several industrial studies have shown that design typically consumes about 10 to 15 percent of the resources used to create a new product, but the decisions made in this step generally fix 70 to 80 percent of the final product costs. Trying to correct the mistakes made in the design step is costly and often cannot have a profound impact on final costs; one is stuck with the earlier decisions. They had better be made well. Any company which wishes to remain competitive today has to upgrade its design capabilities continually.

2.2. The Pervasiveness of Design

Design is an activity which is done frequently by almost everyone. When we write an article, we first design it typically by listing all possible topics that might be in it, organizing these into some proposed sequence, etc.

A board of directors for a company is involved in design. They have to choose what types of activities the company should embark on and how to create an organization that can accomplish these activities effectively and efficiently. The objective function they use may be to increase the present worth of the company. They may select alternatives from the many which are provided, but they should generate alternatives too, possibly in some systematic fashion. They then have to decide which projects to choose, based on incomplete information. Heuristics, such as avoiding projects for which the company has little experience, play a role in this decision making.

2.3. The Steps in Design

Design is an activity which we might break into several parts: (a) conceptualization, (b) generation of alternative solutions and selection of a few of these based on our best guesses as to suitability, and (c) detailed analysis and evaluation. Iteration of these steps is always required to improve the resulting designs.

2.4. Computer Aids for Design

Step (a) above has the fewest computer aids to support it, whereas (c) is the best supported in all engineering disciplines. Analysis tools include flowsheeting systems and pipe stress analysis packages, for example, in chemical engineering. Finite element packages are used extensively in mechanical and structural design. VLSI circuit simulation packages at various levels of detail are in use (from logic descriptions to models based on partial differential equations).

With the development of tools to support the encoding and using of qualitative information (artificial intelligence, expert systems technology), we can see the development of aids for part (b). Aiding conceptualization is more difficult. Of course it will be done indirectly if we aid parts (b) and (c) as one can then develop the consequences of a new concept much more rapidly.

2.5. Multiple Objectives for Design

If design is done well, it will not only consider the functional requirements of the artifact under consideration but also how it is to be manufactured or constructed, the range of conditions under which it will likely have to operate, its safety and so forth. Each of these measures is quite different in nature. Each requires a very different view of the design both to evaluate it and to be able to suggest design alternatives to improve it. We do not have ability at this time to evaluate a design against most of the measures of interest. For example, how does one assess the controllability of a process or the lifetime of a mechanical part? For these measures we have to use design reviews and subjective evaluations. For others, we need to predict the future to assess them; an example is whether a supplier and his favorable price will be around in two years.

2.6. Hierarchical Nature of Design

Design is typically done is several levels of detail. We might consider the design of an automobile to appreciate the levels. At the highest level the design team will first develop the concept for the car. They may choose to produce a car that will appeal to the "yuppie" generation, have four wheel drive, accelerate rapidly, etc. They are designing at a high level and making decisions that will fix the boundaries for any subsequent more detailed decisions. At the next step they will make decisions about the sound and feel of the car; should it be soft or firm in cornering, should it be harsh or soft in its sound, and so forth. Next these decisions have to be translated into technical measures that can be used to judge the success of the design to meet these goals for it. Often such technical measures are difficult to quantify, analyze and/or test. At the grossest level of detail about the structure for the frame of the automobile, design can attempt to account for low frequencies that will be felt by the driver and will affect her/his impression of the solidness of the car, provided there is a known relationship between feel and the vibrations at these frequencies.

2.7. Concurrent Design/Simultaneous Engineering

Designs for large artifacts such as an automobile or a new 450 passenger airplane or the major equipment for a chemical process are never done by a single team of designers working together in a single room, except at the earliest stages of conceptual design. Rather the design is partitioned into subsystems, each of which requires significant effort by a team which is expert in that subsystem. Large design projects require coordination. Even the door in an automobile is designed by a team of people who are different from those who will design the window regulator mechanism within the door to raise and lower the window. These two teams must always be aware of each other if a successful design is to result. A change in the layout of the door may cause the current window regulator to collide with a part of the modified door, and this change in the door may make it impossible to design a regulator with sufficient strength, a fact that will only become apparent if both teams are aware of each other.

2.8. Routine versus Original Design

Design can be categorized into two quite different types: routine and original. In routine design, the concepts on which the design will be based and the methodology for carrying out the design are well understood. Tools are more readily created to support this type of design. Original design is where the team first has to create the concepts and very likely also the methodology for the design.

There are those who argue that only this latter constitutes design. We do not adopt this restricted view here but rather suggest there are two types of design, both of which offer interesting research issues to study. We claim here that a person is designing if she/he is gathering together and generating the information needed to create a new or modify an existing artifact, whether there is creativity in the activity or not. Thus using a methodology which uses operation research tools to select among a plethora of well understood alternatives is designing. Most of the results in design research in chemical engineering fall into this latter class.

2.9. A Theory of Design

There are many differing views as to whether there is a theory of design. Simon (Simon, 1968) develops a theory based on the idea that design is a set of processes for solving ill-structured problems by heuristic search. This form for a theory of design is appropriate. It suggests that the activity of design is a particular kind of human activity.

There is obviously a science base useful for design. The developments in operations research, computer languages, geometric representations, etc. are all important to design. They do not constitute a theory for design, however.

Some have suggested that we can state fundamental principles upon which to base design decisions. It should be evident that we cannot find *fundamental* principles as virtually any solution to a design problem can be the best one in a very particular situation. There are good heuristics that can indeed be developed to handle most cases for a particular type of design, but there cannot be fundamental principles. In terms of good heuristics, it is reasonable to design heat exchanger networks to minimize the use of utilities for most designs, subject to some minimum approach temperature in any exchanger. However, if the solution requires the matching of two streams which will lead to an explosion if there is a leak, the design has to be rejected.

3. COMPUTER AIDS FOR THE DESIGN ACTIVITY

Existing computer tools for design are typically very complex and difficult to learn. Many are complex analysis tools. Flowsheeting systems are an example, as stated earlier. Several support the construction of geometric models for a mechanical part or the layout of a building from which a finite element model is generated. The thrust is again analysis. Some do support the automatic generation of design alternatives, particularly in VLSI design. A designer may take as much as six months to a year to learn a new tool, and, as a result, she/he may have only about four or five such tools which he/she knows how to use effectively. New tools are very difficult to introduce into an organization for this reason.

In this section we look at how we might develop computer aids to support the design activity. We need to develop a model of that activity on which to base the structure of the aids.

3.1. The TAO Model

One such model, called a Test, Aspect, Operator (TAO) Model, has been presented in Talukdar and Westerberg (Talukdar and Westerberg, 1988). In it design is the iterative moving among many different *aspects* for the artifact being designed. Each aspect provides a different view of the artifact and includes information in a form needed by the designer or a tool to reason about it with respect to one or more given measures. Each aspect can be very different in the way it represents the information; in some the information might be graphical, in others as a set of equations or in tables of information and in yet others as a set of production rules.

Figure 1 illustrates a TAO diagram for the design of a chemical process. The highest level aspect shown is that used by the board of directors who have opted to start an activity to improve the net present worth of the company. The next aspect for the design is the specification for the scope of a process that might accomplish this goal - namely, to produce chemical A for sale in the U.S.A. and Europe. This aspect represents the result of generating alternatives to the first level goal and selecting what is thought to be a good candidate from among them.

It is not evident the first time an aspect is filled in that it is consistent with the higher level aspect from which it was derived. Until the process is studied in some detail, no one will really be able to assess if it will increase the net present worth of the company. However, it was generated in response to this goal.

In Figure 1 we show the creation of the process flow diagram (PFD) for the process as a next aspect; several ancillary aspects that are used to assess preliminarily the safety, control and flexibility of the process; and finally the expansion of the PFD into another aspect, a piping and instrumentation diagram (P&ID).

To connect aspects we show arrows in Figure 1. These are the *operators* used to convert the information in one or more source aspects into the information residing in the target aspect. An operator can be a very complex activity.

If the target aspect is a refinement of the information , the step is a *synthesis* step accomplished by generating alternatives and selecting among them. In a strict mathematical sense, a refinement will contain all the information in the source aspect plus added information. Seldom is there only one target refinement that will meet the requirements of the source aspect. Thus the mapping is typically one-to-many.

To make the mapping one-to-one, a criterion is needed for selecting among the alternatives that one generates. For example one will typically choose the target aspect which gives the best economic evaluation. Evaluating the economics can obviously be difficult.

The target aspect may be an abstraction of the source aspect, as for example the aspect labeled control in Figure 1 might be with respect to the PFD. In a strict mathematical sense, an abstraction is the opposite of a refinement - it contains a subset of the information in the source aspect(s). This type of mapping is more difficult than the refinement mapping in practice. It is like asking what the question was for which the source aspect is the answer. A temperature value of 275 K in the source aspect could be the result of selecting a temperature greater that 250 K or in the range 200 K to 300 K or equal to 275 K. The latter are how it might be stated in the abstract target aspect. This mapping is also one-to-many, even though it is the reverse of a refinement.

To make this abstraction mapping one-to-one, again some criterion is needed to select among the alternative abstractions possible. Suppose the abstraction already exists from an earlier pass through the design. One might be propagating a change made to a more refined aspect back to a more abstract one. Then the abstraction selected could be that which is closest by some metric to the one already there. And/or it might be selected to stop changes from propagating to other aspects connected to the target aspect.

Two aspects may contain exactly the same information, in which case the operator is a translation - rather like changing a document from one language to another. Translations will typically be used to convert an internal representation to one the user can interact with on the computer screen.

Most operators will likely be combinations of refinements, abstractions and translations. Part of the mapping will be less detailed, part will be more, and part the same.

The final notion expressed in this earlier work is that of a *test* A test is required to determine if two aspects are consistent with each other. A test may itself involve the development of many other aspects. It is an *analysis* activity. An example is to develop the information needed to see if a proposed chemical process will indeed lead to an increase in the net present worth of the company. The analysis requires considerable modeling and cost estimation to carry out this test. A less difficult test is to see if a distillation column will in fact function correctly for separating a given mixture.

With this view of how a design proceeds, one is concentrating first on the various forms of information that one wants to see when designing an artifact. Then one can concentrate on the operators to connect these aspects. In the early stages of creating a set of aids to support the design activity, most of the operators will be done manually by the designer. As a design becomes more routine, the operators can be implemented as computer aids.

Returning to the example discussed earlier on the design of a car door and the window regulator mechanism inside it, one of these aspects needed is the information to connect the door design to the window regulator design. By designing these aspects first, one is sure to allow for this type of information exchange.

Control of the Design Activity

The TAO model for creating a suite of integrated design tools is incomplete without considering how the design activity itself is to be controlled using these tools. Here all kinds of possibilities exist. We might consider how the tools would be used. Generally the aspects are filled in by starting from the specifications. However, they may be filled in by starting from a earlier but similar design.

The operation to move from specifications to a more refined definition of the problem generally is, as stated above, a synthesis operation. The checking of the suitability of the design from different perspectives will typically involve moving to more abstract representations where the information is presented in a form that the designer or a program can reason with it. For example, the design of a window regulator can proceed from a specification to a stick diagram to a solid model. From the solid model, features have to be extracted if one is to reason about how readily it can be manufactured by any of a number of different processes but most probably by stamping it. This feature extraction is an abstraction; feature extraction is a major research problem in solid modeling at this time.

To move among the aspects requires that operators exist from where information exists to where it is desired. Often the operators will be the designer doing the step manually, especially for nonroutine designs.

The design system will create the design by filling in an appropriate set of aspects. If the information in one aspect is complete enough, the operators leading from it to other aspects can be executed to propagate the design information. Tests executed at appropriate times indicate if the specifications found in one aspect are consistent with those in another. The design will likely be quite different depending on the sequence the aspects are created.

Analogy with Equation Solving

Solving complex problems has several analogies with the solving of nonlinear equations. If one has n equations in m+n unknowns, m of the variables have to be given values independently. One has to select a set so the equations are nonsingular. If the n nonlinear equations fully precedence order in the remaining n equations, then soJving them involves simply stepping through them one at a time, solving for a new variable with each equation as one proceeds. Generally, however, one must solve several of the equations as a block on k simultaneous equations in k unknowns. Solving by *tearing* methods require that one guess a subset of t of the variables in the block, step in sequence through k-t of the equations to establish values for the k-t remaining variables. The t unused equations are evaluated as error functions. If they are not zero in value, the original t tear variable values are adjusted and the process iterated.

In information space where qualitative or symbolic information is being processed to develop a consistency for it, one may first have to make some assertions which are never to be verified - these are the independent variables. In solving for the consequences, one will often find the information cannot be processed in a precedence order. One will have to guess values for some of the qualitative information (make t assumptions). Based on these assumptions, one can develop the consequences (analogous to solving in precedence order the k-t variables using k-t of the remaining equations). Some form of t error functions (expectations) will have to exist to check the validity of the assumptions. If not met, the one will have to alter the assumptions and iterate.

This form of control will exist, for example, when the designer is trying to propagate changes from a target aspect to a source aspect when no operator exists for this propagation. The designer will have to assume values for the source aspect, map the results into the target, compare with the desired target and iterate if necessary.

Use of Expert System Concepts for Control

Control in this environment can of course be at the discretion of the designer. It can also itself be automated if the reasoning that the designer uses can be captured and used. Clearly expert system concepts play a role here.

Lien (Lien, 988a, Lien, 988b) is presenting a paper on the use of expert systems in design. There are broad implications of his work on the control of systems of design tools, as we shall now discuss. Expert systems to solve design problems can have two quite different views for how to decide what to do next: data driven vs goal driven control. Lien has developed a data driven architecture. It offers some very interesting advantages over a purely goal driven approach.

A goal driven strategy is where one posts a goal to be accomplished. All of the "knowledge sources" in the system which can contribute to the solving of this goal bid for attention. The executive system selects one, usually based on a scoring function that indicates how well the knowledge source is expected to do toward solving the goal. If the knowledge source needs added information during its execution, it suspends its operation, posts a subgoal, and waits for the subgoal to be accomplished or for a notification indicating it has cannot be accomplished. This subgoal becomes the next activity for the system.

A data driven strategy is one where all knowledge sources continually watch the data being created as the problem is being solved. Any time a pattern exists within the data which a knowledge source needs to execute, it bids to carry out its action, irrespective of whether the action seems to contribute to the design goal or not.

The arguments for a goal driven strategy for design are that, if the design goal can be stated, it is more effective to concentrate ones efforts on accomplishing that goal. The design problem is too large to permit one to waste time on side activities which a data driven strategy may easily lead one to do. The argument for the data driven strategy is that the system only gets stuck in solving the problem when there is absolutely nothing more that can be done.

The weighting function used by the system to decide what to do next can allow one to get the benefits of both approaches while in fact using a data driven approach. As the problem solution progresses, knowledge sources which worry about what goals should be important at the present time can post them. All knowledge sources which can contribute still bid. Those which work toward satisfying the goals thought to be important at the present time will generally win if any of them bid. However, if none do, the system will still select something to do next. Also if a knowledge source screams loudly enough, it can in theory win and start a new line of activity or point out the folly of the current one even if it does not explicitly contribute to the goal posted.

In the TAO environment, the operators could in principle bid for attention to develop their target aspects.

3.2. Modeling TAO'S

Talukdar and Westerberg (Talukdar and Westerberg, 1988) present a discussion on how one might create a tool that will allow a designer to create TAO's quickly and accurately. TAO models will obviously be evolving with time, even for routine design situations. They discuss the features of a language that could support this activity, bringing up many features that exist in object oriented programming - but with a difference.

3.3. Integrating Existing Tools

The use of a TAO (Test, Aspect, Operator) model is the ideal way to view the creation of aids. However, the real world seldom allows one the luxury of working in an ideal situation. One usually has a suite of tools already available that one has to accommodate when creating design aids. For example, our Electrical and Computer Engineering Department has catalogued 92 tools to aid in the design of VLSI chips. No one today would attempt to design a VLSI chip without the use of such tools. The problem with the existing tools is that one can seldom get inside them to find all the information needed to wire them together effectively. Each will have its own interface and, especially if it is proprietary, each will have information inside it that is needed but inaccessible.

Within this environment, the creation of design aids that are truly integrated is difficult. Efforts are underway in academia and in industry to solve this problem.

4. SYNTHESIS

With the above discussion about the design process and how one might create tools to support it, we have set the stage to discuss the synthesis activity. A definition of the synthesis activity is as follows:

> *the automatic generation of design alternatives and the selection of the better ones based on incomplete information.*

In our earlier discussion, it was a method to move us from a more abstract representation to a more refined one. Because of the recursive nature of the design problem, synthesis appears repeatedly throughout a design. Synthesis is the activity of generating alternatives to increase the net present worth of the company. It is the activity of generating a process flow diagram. In this latter case, this activity may itself have embedded synthesis activities such as the synthesis of separation subsystems or the synthesis of heat exchanger networks.

We stress that synthesis is the generation step. It is also the act of selecting the better alternatives based on assessing the value of the design before one can prove it is one of the better ones. One is caught in the dilemma that the assessment requires information that does not exist until the details of the design are completed. However, one cannot complete the details for all the alternatives that one can generate; there are too many. So the decision as to which will be best has to be based on incomplete information.

There have been three issues listed as being significant in synthesis: representation, evaluation and search. The representation issue is related to the notion of aspects discussed earlier. As Simon (Simon, 1968) stated, the correct representation is extremely important as it can often allow one to "see" the solution or how to generate alternative solutions to problems that otherwise look very difficult to solve. In the solid modeling area, a correct representation is needed if one would like to know where features are located relative to each other without having to do extensive computations; for example, one would like to know if a feature sticking onto a cylinder is inside the cylinder or outside it. In chemical process design, using a heat flow representation allows one to understand how to design refrigeration processes.

4.1. Representation

The right representation will allow one to generate easily all the alternatives that are of interest. There can be an enormous set of alternatives for synthesis problems, as many earlier papers have demonstrated. Douglas (Douglas, 1988) notes that the search space for a flowsheet has millions of alternatives in it. Retrofit design can be explosively larger than grassroots design. For example, there are potentially over 4.5 million alternative distillation column sequences for a retrofit design of a separation sequence (a) to split seven components into relatively pure single component product, (b) using any of six existing columns, and where (c) one additional column can be purchased. If purchased, it can be used either to replace an existing column or to allow two columns to be placed in parallel or series (Grossmann et al, 1987).

4.2. Evaluation of an Explosive Number of Alternatives

With such a large potential search space, detailed evaluation can only be done after the number of alternatives is pruned to down by other means to just a few. Only approximate or heuristic evaluations are in fact possible to do the pruning.

4.3. Search

As we saw earlier one approach to this pruning is done by designing at several levels of abstraction. A high level decision will eliminate large numbers of alternatives at a lower level. With the automobile design example, the first set of design decisions are at a very high level of abstraction - create a car that appeals to the "yuppie" generation, that has four wheel drive, etc.

Many search approaches are algorithmic. For example if the design can be created by setting up and searching a tree of decisions (make a first decision, based on it make a second, etc.) and if it is possible to place a minimum cost on any branch without traversing it, then one can use a branch and bound search method that is generally effective. Alternatively one might set up a superstructure within which are embedded numerous alternatives and use optimization to find the best one.

Another approach advocated is to set targets for the design and only accept designs which can come close to those targets. This approach is applicable to only a few types of design problems at this time, but, where it is applicable, it is reduces the design alternative space dramatically.

4.4. Reviews of Process Synthesis

There are several reviews already in the literature covering the topic of process synthesis. These include Hendry et al. (Hendry et al, 1973), Hlavacek (Hlavacek, 1978), Westerberg (Westerberg, 1980), Nishida (Nishida et al, 1981), Stephanopoulos (Stephanopoulos, 1981) and Umeda (Umeda, 1982). Westerberg (Westerberg, 1987) presented a general discussion, as opposed to a review, of process synthesis along with a discussion about understanding the heat flows in processes. Westerberg (Westerberg, 1985) also reviewed the literature on the synthesis of distillation based separation processes and Gundersen and Naess (Gundersen and Naess, 1988) the synthesis of heat exchanger networks. By 1980 about 200 references existed for the total process synthesis literature; by 1988 that number exists for the heat exchanger network synthesis literature alone.

4.5. Heat Exchanger Networks

Clearly the area with the largest coverage is the synthesis of heat exchanger networks. Interestingly enough this problem is still far from being solved so the literature here will continue to grow, probably rapidly. We will spend some time here looking at this problem as it is a special problem rich with synthesis results.

Summarizing the key ideas and without giving full attributions as they are available in the above reviews, Rudd and coworkers started this literature by posing the problem in the late 1960s. In a landmark work in 1971, Hohmann, working with Lockhart, showed that one could predict the minimum heating and cooling utility requirements when heat integrating a set of hot and cold streams whose heating and cooling curves are assumed to be known. This work also noted that one could estimate the fewest number of heat exchanges (i.e., number of stream/stream matches) required by counting the number of process and utility streams and subtracting one. These results lay dormant until they were independently rediscovered and extended in the late 1970's by Linnhoff in his PhD work with Flower. This work led to the notion of the pinch concept which states that there is a temperature within most processes where heat exchange will occur with a minimum permissible driving force and that this temperature partitions the process into a hot part that needs heat and a cold part that gives up heat.

This work showed how to invent heat exchanger networks that can meet this target. There were too many exchanges in these networks in general. Breaking *heat loops* as in Su's work with Motard became the basis for reducing the number of exchangers in a network.

Next it was discovered that the minimum utility problem can be posed as a network flow problem and then an even more compact transshipment problem, both special forms of linear programming. These formulations allow one to compute the minimum utility requirements when certain streams are forbidden to exchange heat with certain others. It also means that the minimum utility computation can be embedded within larger superstructure models for complete flowsheets.

The "pinch design" method provided a means to invent good network solutions by hand, concentrating first on matching streams which are near the pinch. There have been methods proposed for the automatic generation of networks based on first predicting the minimum utility use using an LP formulation and then finding a solution with the fewest exchanges using an MILP (mixed integer linear program) approach.

Methods to estimate the area needed for a heat exchanger network which has yet to be invented allow one to develop an estimate of the capital costs for the network. One can then look at the capital cost versus the assumed minimum approach temperature allowed within any exchanger, effectively trading off capital costs with utility costs. The capital cost tend to increase and the utility costs decrease as one decreases the approach temperature. Recent papers allow individual film heat transfer coefficients and even different materials of construction to be used for each stream to estimate the total network area.

Still more work has recently locked at reducing the number of matches required by allowing one to consider the mixing of streams before using them for heat exchange, if the process permits it. There will generally be a loss of temperature driving force so the exchanger area will increase, but there can often be fewer exchanges in the final solution.

With all this effort it is worth noting that this problem appears to be the simplest of those posed for synthesis in chemical engineering. As a community we have been at work on it for about two decades now. It is not solved.

The automatic network generation routines still do not discover the better solutions. There are often numerous alternative networks using the minimum amount of utilities and having the fewest matches. It appears that all of these need to be generated and compared; this generation is not yet a part of these procedures.

Another problem is that heat exchangers are seldom simple 1-1 countercurrent exchangers, rather they are multipass exchangers, and one must use several shells for exchangers having a small temperature driving force and operating over a large temperature change for the streams involved. Thus all sorts of tricks can be played on the topology of the networks which have yet to be a part of the methods posed.

And another problem is that one needs to worry about measures other than costs, for example flexibility. While there is considerable work on designing flexible networks, inventing a network which is going to operate flexibly within a process that interacts with it is not yet a readily solved problem.

4.5.1. Designing Process that Heat Integrate

In the late 1970's, Umeda showed how one could redesign a process to improve its ability to be heat integrated. This work is again a classic in establishing the importance of understanding the pinch.

Linnhoff and Umeda and their coworkers individually reported the use of the so called "grand composite curve" in the early 1980's. This plot shows very compactly how a process either locally requires or produces heat as a function of temperature. It shows at what temperatures heat can be injected into or removed from a process without affecting the utility requirements. It offers one a way to summarize the heat flows in one part of a process while looking at the design of other equipment one may want to couple with this process, such at the power generation equipment.

We have looked into the design of processes so they can be heat integrated, including the choosing of operating levels for distillation columns so they will heat integrate with each other and with a given "background" process characterized by its grand composite curve. Other of our work has looked at the selecting of the temperature levels for each of the effects in a multieffect evaporator system while integrating the system with a background process and minimizing the use of utilities.

In the last four to five years Grossmann and his coworkers have shown that one can create a superstructure within which are embedded many flowsheets alternatives. This model assumes the process is heat integrated and requires the minimum use of utilities. Mixed integer nonlinear programming can then be used to find the least cost process. The design selected while always accounting for the maximum heat integration can be significantly better than one found by optimizing the process as if it were not integrated to find the structure, integrating and then reoptimizing the result. Integrating while carrying out the original optimization reduces the cost of utilities relative to the cost of the feeds to the process and causes one to invest in more equipment to convert the feeds more selectively and completely to desired final products.

4.6. Non-Heat Driven Synthesis Methodologies

All of these synthesis results come at least in part from looking at the flow of heat in processes. Heat flow tends to provide a common framework. When this framework is missing, we see the use of hierarchical levels of decision making being used extensively. For example, in the early 1970's Rudd, Siirola and Powers in the AIDES program looked into the design of complete chemical process flowsheets as did Mahalec with Motard in the later 1970's and more recently Douglas and his students. Douglas[1] approach has become the theme of his new design text (Qouglas, 1988). Each of these works has broken the synthesis activity into a hierarchy of levels of decision making.

• We might discuss briefly here the synthesis of separation processes. Most of the literature on this topic is for the synthesis of distillation based separation processes. Much of the later literature involves heat integration and thus falls into the domain of the previous section. However, if we were to create a methodology for designing separation processes quite generally, we see we have quite a different problem to solve. At the first level of decision making, we would have to classify the species and the phases involved to decide the type of likely separation methods which might be used. King (King, 1980) lists 54 different separation methods. Some are for gas/gas separation, others for gas/liquid, still others for gas/liquid/solid and so forth. An approach is to make high level decisions on whether gas/gas, gas/liquid etc type separation is needed for each of the separation steps required (Douglas, 1988). Then based on these decisions, tower level decisions are needed to select exactly which method to use. We see the form for the design problem is that which we described in the beginning of the paper.

5.-SYNTHESIS IN OTHER ENGINEERING DOMAINS

We shall now look at a few papers from other engineering disciplines to gain an appreciation of how they approach the synthesis activity. Only one paper uses target setting to aid the process. Many of the others break the design process into levels of decision making. Some reformulate the problem as an optimization problem, where the entire set of design alternatives is explicitly stated in setting up the problem.

5.1. Electrical Engineering

Thomas et al (Thomas et al, 1987) present the design of a *system architect's workbench.* It automatically converts an abstract behavioral description into a set of register-transfer components and a control sequence table. The behavioral description is in the form of a PASCAL-like description of the computation that the hardware is to perform. An analog would be to write a recipe for manufacturing a pharmaceutical chemical in an as-yet-to-be-designed batch process. This behavioral description is converted into a *value-trace* which shows how the variables (chemicals) fed into the hardware will be propagate through it in time. Storage registers (tanks, reactors) to hold results and operators (reacting, heating, cooling) are shown as nodes on the trace. Once created this trace is partitioned in several different ways. The activities may be partitioned into those that will be physically placed on separate chips and/or by time steps so that the results can be *pipelined.* Each partitioning will be further designed so comparisons can be made among them. Each can lead to a very different implementation. Pipelining is like starting a second batch in the upstream equipment just after the first batch has been transferred into downstream equipment.

Control steps scheduling follows in which the propagation of the signals is coordinated with the clock pulses that are used to step the circuit. In a batch process this would correspond to deciding within which functional piece of equipment the various steps are to be done. For example heating could be done in a preheating tank and then the mixture passed into a reactor to carry out the reaction step, or the reactor could have heating coils and be able to accomplish both steps without the intermediate transfer.

The actual equipment (which pump by which vendor) is selected next. Finally the location of the busses are picked (the piping network is designed).

A criterion for choosing which is best is to choose that design that has the fewest clock pulses to process a mix of all the instructions to be handled by the circuit (makespan).

Why is this problem difficult? They are developing this system so it is capable of designing the hardware to run something as large as the IBM System/370 instruction set. That would be like designing a batch process to handle on the order of a thousand different recipes. Model behavior is also characterized by discrete decisions so well behaved continuous models are not feasible.

Claesen et al (Ciaesen et al, 1988) have just presented a paper on their CATHEDRAL Silicon Compiler system. CATHEDRAL designs digital filters. With such a limited domain, they can apriori make many decisions as to the structure of the final filter based on the characteristics of the input specifications for it. As in heat exchanger network design, they can establish characteristics that the final design will have without performing the design. Thus in principle they could have a filter design problem embedded within the design of a larger circuit, search the problem space for the larger circuit without developing the details on the filter design, pick the better overall designs and then for these only actually design the filter.

5.2. Mechanical Engineering

The first paper we review looks at designing by parameter optimization. Bennett and Botkin (Bennett and Botkin, 1983) describe an analysis package that can adjust the shape of a solid object to give a *best* design. The approach is to input the solid model, generate a finite element mesh for it, solve, refine the mesh, solve, etc until the desired accuracy is achieved, adjust the solid model parameters to improve performance (optimize), iterate. We (Hrymak et al, 1985) have shown that one can design extended heat transfer surfaces (fins) in a similar manner. We were able to eliminate the loops within loops nature of the above approach by adjusting the mesh to satisfy the necessary conditions for a good fit simultaneously with altering the object shape to improve its performance. In both these cases the idea is to design by the adjustment of continuously varying parameters.

Kota et al (Kota et al, 1987) describe the Minn-Dwell aid for designing linkage mechanisms to convert continuous motion into motion with a periodic pause. They catalog about 350 four bar straight line linkages and for each can display the motions they produce. The designer searches manually through these for a four bar linkage on which to base her/his design, looking for segments in the path that have one or more nearly constant radius of curvature segments or one or more straight line segments. Each of these can be converted into a pause by adding a two bar linkage. Gear pairs and other two bar linkages can be added to allow, for example, for rotational input if the four bar linkage does not have it. Once created the user can adjust dimensions to get the final behavior desired, with the system prompting the user as to the dimensional corrections to make.

Ulrich and Seering (Ulrich and Seering, 1987) presented a paper last year suggesting that novel designs can be discovered by analyzing several old designs, abstracting their attributes, and combining these in new ways. It is rather like carrying out a morphological search to find new areas to do research. They illustrated their ideas by inventing novel designs for fasteners. We will see a similar idea appearing later in the work appearing in Civil Engineering.

Brown and Chandrasekaran (Brown and Chandrasekaran, 1986) present a computer language and supporting system which can be used to create aids for routine design. One can create a set of hierarchically organized specialists (knowledge sources) which work cooperatively to perform the design. Higher level specialists try to design a major portion of the design following a prescribed plan. Steps in the plan can be to invoke lower level specialists to carry out a smaller part of the design. Constraints generated along the way are kept and watched so any subsequent decisions will stay within them.

Four phases exist for the design activity: setting requirements, a rough design, the actual design and redesign. Specialists communicate by sending messages to request actions, report failures, ask for assistance and make suggestions. They illustrate their ideas with a system created to design air cylinders.

Ishii and Barkan (Ishii and Barkan, 1987) describe an analysis method to check if a design is compatible with its stated objectives and if the components within a design are compatible with each other. They use fuzzy evaluation techniques.

Libardi et al (Libardi et al, 1988) prepared a literature review for CAD systems for mechanical systems and for assemblies of components which individually are well understood. The sections in the paper cover (1) representing/supporting top down design and multiple viewpoints, (2) representing and using functional knowledge, (3) representing spatial relationships and the geometry of components in assemblies, (4) consistency maintenance and (5) analysis and other support issues.

5.3. Civil Engineering

Arciszewski (Arciszewski, 198x) describes a way to generate interesting new combinations of functions to discover new structures to perform required functions. It is similar in concept to the article by Ulrich and Seering above. Here the illustrative example is the design of new beam-column joints.

Maher and Zhao (Maher and Zhao, 1987) present a methodology to use design experience in developing new designs for the preliminary structural design of buildings. They discuss at some length design and approaches to it, discussing their earlier work on HiRise (Maher, 1984) and their current work on EDESYN. The former is an expert system to design high rise buildings interactively with a designer. The latter is a general system to aid in the design of expert systems which themselves aid in the design of artifacts whose design can be decomposed into several levels of abstraction.

' The main contribution of this paper is the description of STRUPLE, an expert system for structural planning from experience. In STRUPLE, they have created a relational database in which they store the description of past building designs. Both the functional requirements against which these design were created and the high level design decisions are kept. The functional requirements of a new building are used to search this database of old designs. Design decisions for these buildings are weighted by the degree the new building has matching functional requirements with the old. Those design decisions with a high score then become the ones to consider as most likely to be good decisions for the new building.

In the work of Oxman and Gero (Oxman and Gero, 1987), we see the creation of an expert system capable using the same *rules* to generate designs, to criticize designs, and to complete design partially described by the designer. They illustrate the ideas with PREDIKT, a preliminary design system for kitchens.

In another work Rosenman and Gero (Rosenman and Gero, 1985) describe SID, their System for Integrated Design. In this system there is a set of n variables for which values are to be established. Each variable can be assigned a value from among a discrete set; for example, variable 1 which might be the material of construction for the floor of a building might be allowed to have one of the two values: concrete or wood. Each variable i has a cost Cy for each value j it can take. So, for example, there is a cost associated with variable 1 taking the value concrete, another for taking the value wood. There is also a binary interaction cost Cy,k, associated with the selection of value j for variable i while also selecting value I for variable k. The goal for designing is to assign to each variable a discrete value such that the total cost for the assignments in minimized. Multiobjective function optimization was included by allowing the user to assign weights to each objective, converting the problem back to a single objective. The paper describes, but not in detail, an heuristic "dynamic programming" based solution algorithm. In fact it appears this problem could be properly formulated as a mixed integer linear program with binary variables yy having value 1 if value j is assigned to variable i, zero otherwise, and variables y'y,k, having value 1 if variable i is assigned value j while variable k is assigned value I, and zero otherwise. Linear constraints can be written to relate variables y' to y, namely:

$$0 \le y_{ij} + y_{kl} - 2\,y'_{ij,kl} \le 1$$

6. DISCUSSION

We conclude our look at papers in other areas. Two of these papers have suggested how one might generate new design concepts by extracting the functions supported by known designs and mixing these functions in new ways.

The remaining support routine design. Generally lacking targets which can be set apriori, several of these papers carry out the synthesis activity by partitioning the problem into many levels of abstraction. Using expert system concepts, decisions are made first at the more abstract levels and the consequences propagated to lower levels where the details are established. Using more algorithmic approaches others have proposed setting up a superstructure and optimizing it to determine the substructure which is the best solution. We noted that the use of integer variables permit discrete decisions to be included. Finally one of the papers simply concerned itself with a method to evaluate if the design comes close to meeting the stated requirements for it. We see considerable overlap in concepts with those being developed in chemical engineering, with the exception that there is very little that is a counterpart to the target setting available for designing heat exchanger networks.

In this paper we have looked at engineering design which we see as a complex human activity with many different facets. We looked into how one might create computer aids that can support it. We then looked at the synthesis activity both in chemical engineering and in three other engineering disciplines to provide insight into how they approach this very intriguing problem in design.

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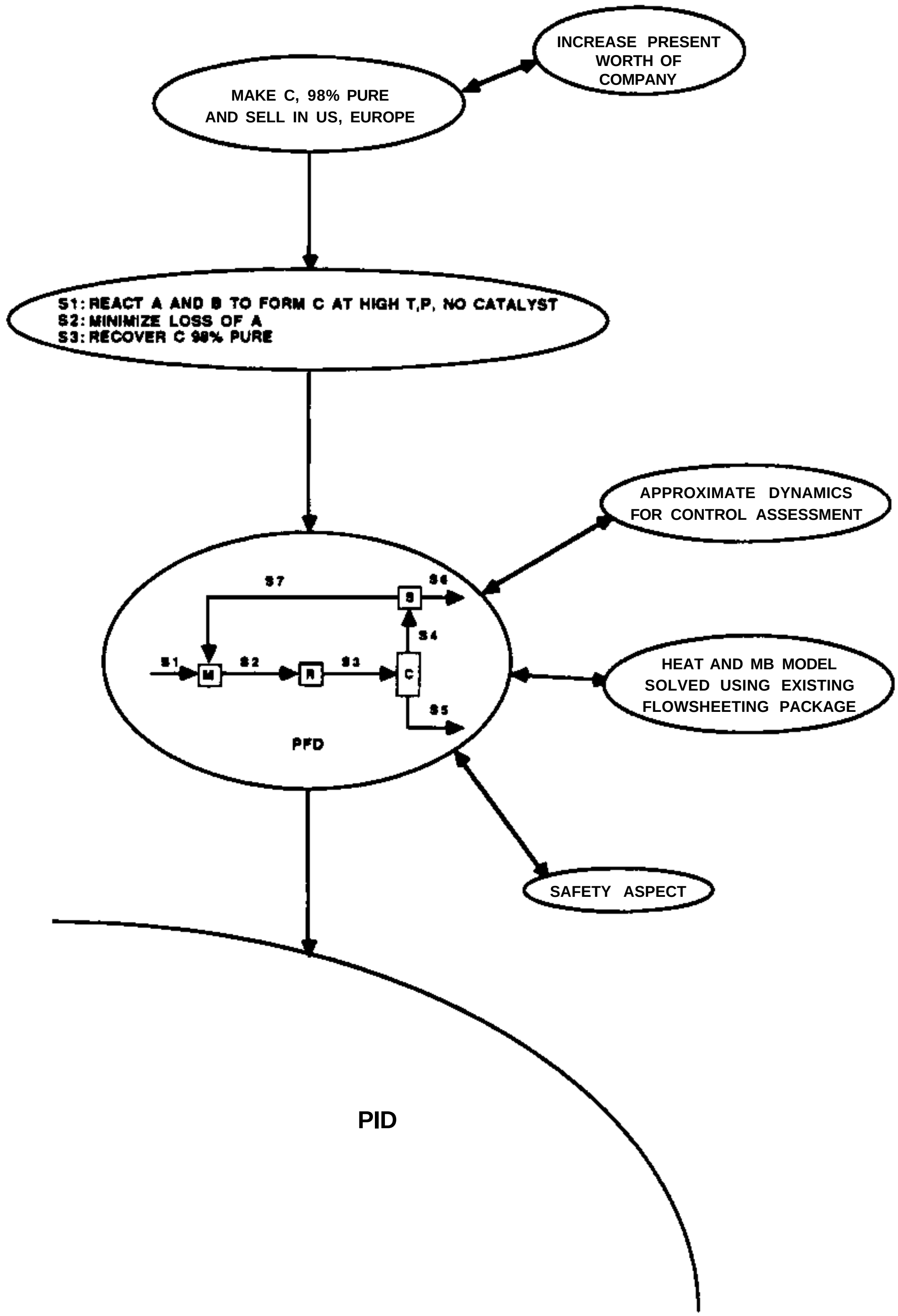

FIGURE 1 EXAMPLE TAO NETWORK FOR PROCESS DESIGN

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