Proceedings of the Optimization in Industry Conference, March 23-27, 1997, Palm Coast, Florida

Optimization as a Driver for Design Space Exploration

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ABSTRACT

This paper describes an approach toward the use of optimization which is a departure from the traditional role optimization plays in the design process. Traditionally, optimization is used to improve point solutions in the latter phases of design. In this work, optimization is used as an aid for design space exploration, through the integration of optimization and iterative design. Two applications of the concept of optimization-driven design are given: CAD tools for HVAC layout and an assembly design framework.

1 INTRODUCTION

The use of optimization in design is becoming increasingly prevalent in industry today. This is due to a variety of factors, including a marketplace that imposes greater competitive pressures to produce higher-quality products at lower costs while reducing product development times, as well as more powerful computer hardware and new optimization techniques, both of which allow the application of optimization to problems where it was not previously possible. While optimization is more widespread in practice, the way in which optimization is used for design has remained largely unchanged. The development of new approaches toward the use of optimization as an integral part of the design process has been, for the most part, an unexplored research area. This paper presents a shift in paradigm to a new view of the role of optimization in design. This discussion is descriptive, rather than prescriptive; determining how to achieve this goal is the subject of ongoing and future research.

Design is often viewed as search through a state space, or design space. Rather than searching through a space that contains all possible solutions to a given problem, it is convenient to make a problem more tractable by searching through a series of smaller design spaces. One of the ways in which this is accomplished is by breaking a design process into a series of stages, where a designer may make decisions[1] at one stage before moving on to subsequent stages. Making a decision may simplify the search problem by limiting search to a subset of the overall state space. For example, if a designer selects steel as the material for a component, designs where the material is aluminum are not reachable (unless the de-

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[1] The term *decision* is used in a very general sense here; decisions might include selecting a particular design concept or configuration, assigning values to variables, applying or refining constraints, selecting materials, and so on.

cision is changed), so the size of the remaining space to be explored has been reduced. Subsequent decisions may then be made to further limit the size of the space.

In general, design is not a uni-directional process in which a series of decisions is made, each further narrowing the design space until a path to a final design is reached. Rather, design is a complex activity, typically an iterative process where a designer may move back and forth between design stages. Alternative concepts may be explored and decisions made previously may be modified, which in some cases may render decisions made after that earlier decision invalid. This can lead to patching of solutions as well as partial or even complete redesign. Furthermore, design stages may not be revisited in the same order as in a previous design. For larger-scale problems, the concepts described in the above paragraphs still hold true, although the situation is more complicated when there is a design team a group of design teams instead of a single designer, and where multiple design stages (and related decision-making) are occurring concurrently.

Traditionally, optimization is used to improve a point solution in a design space, at a given design stage, in the latter phases of the design process. That is, for a given decision (e.g., material selection) or a set of related decisions (e.g., selecting topology and/or diameters for structural members in a truss), optimization techniques are generally used to find an optimal or near-optimal solution. The use of optimization as an aid for design space exploration, through the integration of optimization and iterative design, represents a departure from the usual role of optimization[2].

Two different applications that embody a methodology of optimization-driven design have been developed. The first is a set of CAD tools for HVAC (heating, ventilation and air conditioning) layout design and the second is a framework for assembly design. These are described in Sections 2 and 3, respectively. Section 4 discusses conclusions and areas for future research.

2 CAD TOOLS FOR HVAC LAYOUT DESIGN

A joint university-industry collaboration initiated between Untied Technologies Carrier and Carnegie Mellon University has led to the development of a set of CAD tools for HVAC layout (Cagan et al., 1996). Initially, design generation approaches were created for each of the two subproblems which comprise HVAC layout: component placement and tube routing.

For the routing problem, two alternative methods were devised: one which generates “traditional” tube routes and one which produces “non-traditional” tube routes. The traditional routes are similar to those created by Carrier’s designers and are subject to certain constraints on allowable bend angles and tube shapes. Non-traditional routes are less constrained and therefore more difficult to optimize, but can lead to solutions that have shorter route lengths and fewer bends. Although these advantages often lead to lower routing costs, traditional routes may at times be more desirable because they can be easier to manufacture and/or assemble. The component placement and non-traditional tube routing approaches are

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[2] Note that while it is not uncommon for an optimization technique to use an iterative algorithm, this is distinctly different from the concept of using optimization to drive the iterative design process.

driven by optimization algorithms, while the traditional routing is not. The two optimization algorithms have also been combined into a single integrated concurrent layout-and-routing algorithm (Szykman et al., 1996).

Many factors enter into the evaluation of a candidate solution in HVAC design. A few of the ones which are directly linked to component placement include packing density, assembly issues, accessibility/maintenance issues, weight distribution, etc.; those related to tube routing include manufacturability due to limitations of bending tooling, assembly issues, tube vibrations during shipping and due to the compressor during operation, refrigerant flow changes and pressure drops across bends, material costs due to tube route lengths, and so on.

Because of the complexity of HVAC layout, a fully-automated layout tool is impossible to realize. Not only is it infeasible to create a system that can quantify tradeoffs and optimize so many complex objectives, but it is not even possible to articulate all the objectives in a way that lends itself to evaluation by a computer. Thus, the human designer must remain an integral part of the design process. The optimization placement and routing tools include evaluation of only a subset of the design objectives, primarily those that are common across many HVAC design tasks, such as packing density, fitting components into a specified container, length of tube routes and number of tube bends.

Designers at Carrier are already using CAD tools to aid in the HVAC layout process, though the layout and routing are done for the most part manually (using a CAD system). The HVAC layout design process is highly iterative, and designers may generate new concepts or modify candidate solutions many times to reach final solutions. By integrating the new automation tools into existing CAD tools, the exploration of the design space can be aided by giving the designer the ability to partially automate search. Figure 1 shows an interactive design process that encompasses manual component placement and tube routing, as well as the new automation tools. In a typical layout design process, the design may undergo a number of iterations. As seen in the figure, the designer has several options about how to interact with the design at any given time.

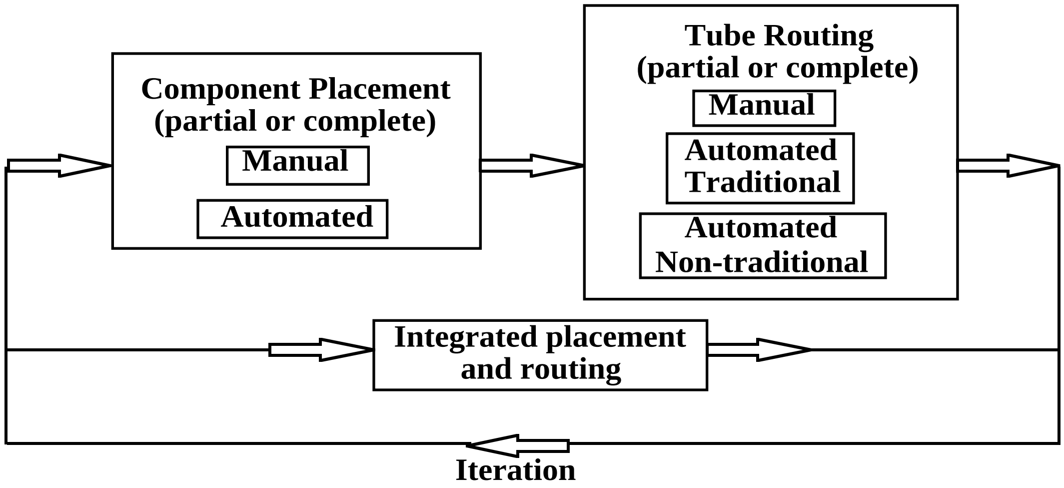

Figure 1. Driving design iterations using optimization-based CAD tools.

Initially, a designer may generate one or more candidate designs that optimize the simple objectives described above, either with the integrated placement and routing tool or by sequentially using the automated placement and tube routing approaches. The designer then has a number of alternatives for how to proceed in subsequent iterations using any of the alternative paths in Figure 1. The designer may feel that it would be better to move the compressor slightly because of weight distribution considerations and can do so manually. This might, in turn, cause a tube to penetrate another component, which would be remedied by generating a new optimized route for that tube using the non-traditional routing tool. A different group of tubes may be too intermingled and would cause assembly difficulties. This problem could be remedied by generating new routes for those tubes using the automated traditional routing tool, which produces longer but simpler routes than the non-traditional router, or alternatively, the designer could improve the routing manually.

This scenario illustrates a few of the possible modes of interaction with the HVAC design tools that have been developed. With this approach, the designer is in control of the iterative design process and makes decisions about problematic areas, how to improve the design, and uses knowledge which could not be readily captured to evaluate candidate solutions. However, the design iterations are driven by optimization, which allows the designer to use the CAD tools for performing tasks that a human is not as good at doing, such as rapidly generating multiple candidate solutions, optimization of routing paths for minimum length, optimization of packing density, or fitting all required components into a container when spatial constraints and limitations make it difficult for the designer to do manually.

3 A FRAMEWORK FOR ASSEMBLY DESIGN

The Conceptual Assembly Modeling Framework (CAMF) is an assembly design tool which began development at the University of Southern California and continued at the National Institute of Standards and Technology. One of the new components of CAMF is a design refinement tool for assembly design (Kim and Szykman, 1996). Because of the complexity of assembly designs, not all aspects of the design process lend themselves to automation. For reasons similar to those described in the previous section, the assembly refinement tool is not intended to be a complete automation tool; rather it is used interactively by the user as a design aid during the assembly design process. The tool is driven by an optimization algorithm so that design space exploration is driven toward optimal or near-optimal solutions.

An example scenario taken from (Kim and Szykman, 1996) illustrates the use of the refinement tool for assembly design. In this interactive session a designer is given the task of designing a television remote control assembly. The designer generates an initial candidate solution and calls the assembly refinement tool. The optimization-driven refinement results in wood being selected as the battery material. This is a result of an oversight on the part of the designer, who did not correctly map (i.e., constrain) the battery material in the design to the corresponding entry in the material library. The choice of wood was driven by the optimization performed by the tool; without the refinement, the deficiency which was identified early on may otherwise have been overlooked.

The designer makes changes to the battery material and also decides at this point to constrain the keypad material to rubber for human factors reasons. After this iteration another call to the assembly refinement tool is made. The material changes made by the designer rendered some of the previous assembly liaison choices invalid. The refinement tool is able to find valid liaisons for the new materials, which in turn results in some of the existing mating feature types and shapes becoming invalid. Again, the tool finds valid feature types and shapes. Not only do the design decisions described above (material, liaison type, feature type and shape selection) result in feasible solutions, but they are optimal or near-optimal ones due to the optimization.

In the case of the remote control assembly design, the number of design variables and allowable values leads to a combinatorial explosion in the set of possible solutions. Once design decisions are made by the designer, manually searching the large resulting design space for the best solutions would not be a practical undertaking. As with the HVAC layout example in the previous section, the designer is in control of the design iterations. Within a design iteration, however, optimization is used to drive search toward better solutions.

4 CONCLUSIONS

This paper motivates the integration of optimization into the design process and describes two applications of the concept of optimization-driven design: CAD tools for HVAC layout and an assembly design framework. Typically, the complexity of design problems such as these makes full automation impossible. The aim of this approach is therefore to create design tools that are able to aid a designer in generating alternatives and directing search towards good or optimal designs. The distinctions between this approach and traditional applications of optimization are:

- a focus on interactive tools where the designer remains an integral part of the design process,
- the possibility of multiple modes of operation that combine manual changes, design refinement, partial automation and optimization,
- the use of optimization to drive the iterative design process rather than to optimize a point solution,
- the use of optimization not just at latter design stages, but also to enable design space exploration at earlier design stages.

The development of a theory that describes not only how to approach the use of optimization in the design process, but how to more tightly couple the two, is an open research area and one that requires further attention. One of the primary issues is attempting to describe how to exploit the structure of a problem to improve the use of optimization for design. As an example, in design of complex systems a design is often broken up into a set of subsystems, which may further be divided into smaller systems, and so on. This leads to a design space which has a hierarchical structure. Schmidt and Cagan (1995) describe a recursive optimization approach that optimizes machine designs across multiple levels of abstraction in a hierarchical decomposition.

Exploiting a hierarchical structure is only one example of how knowledge can improve the use of optimization in design practice. Work such as this provides a basis for further exploring the relationship between optimization and the structure of a design problem. Additional research is necessary to provide insight into how knowledge about a problem's structure can be used to develop better optimization approaches. For reasons of practicality, it is desirable that such approaches be applicable to a spectrum of optimization techniques rather than being limited to a single optimization algorithm.

The work described in this paper demonstrates that optimization can be integrated into the design process in a way which traditionally has not been done. Long term objectives are to demonstrate (1) that this kind of integration can also be done by explicitly making use of knowledge about the structure of a design problem or design process, and (2) that incorporating this knowledge into an optimization produces designs that are superior to those produced by applying similar, if not identical, optimization techniques without integration. Other issues that must ultimately be addressed are how to deal with coupling between design stages (through constraints or information flow), concurrent design activities, and multiple designers or groups of designers.

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