Problem Decomposition by Design Teams

A Study of Facility Design

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***Abstract*—Because of the complexity inherent in the design of a complex system, many design teams decompose large problems into more manageable subproblems. The strategies employed in decomposing a design problem may directly impact the quality of the solution that they produce, particularly when constraints are placed on time and resources. This paper describes the preliminary results of a study designed to (a) understand how design teams decompose complex design problems into sets of related subproblems and (b) assess the impact of these decompositions on the quality of the solutions that the design teams generate. In this study, we observed the strategies of ten teams of professional engineers as they re-designed a manufacturing facility, and we analyzed their decision-making processes. We then developed metrics and used expert advice to assess the quality of the facility layouts that they generated. Although the teams informally decomposed the problem, we were able to identify the subproblems that they considered as they solved the problem, and we looked for patterns among those decompositions. We also measured the quality of each team's design solution in order to link decomposition strategy to solution quality.**

Keywords—Design teams, design processes, decomposition, facility layout.

I. INTRODUCTION

The design of a complex system requires a design team to make many decisions. Because many design problems are too difficult to solve all at once, the design problem is decomposed into more manageable subproblems. It follows that the methods a design team employs in doing so may influence the quality of the solution they construct. By investigating the impact of decomposition on design solution quality, we hope to gain insight into which strategies will support the design of better design processes.

Most design is carried out by teams of bounded rational human designers. While previous studies have explored many aspects of engineering design teams, our understanding of how teams solve design problems and the impact their methods have on the final design is limited. Some decompositions that appear useful when each subproblem is solved optimally may perform poorly when humans solve them.

This research studies both *how* and *how well* teams of human designers solve complex system design problems like manufacturing facility layout problems. Specifically, this paper documents our ongoing progress towards the following research goals: (a) to understand how design teams decompose complex design problems into sets of related subproblems and integrate the solutions; and (b) to assess the impact of these decompositions on the quality of the solutions that the design teams generate.

The research study described herein observed ten teams of human designers as they decomposed and solved a facility layout design problem. Based on our analysis of the results, we have begun to identify a variety of decomposition strategies and to establish tentative links to their impact on the resulting solution quality.

Portions of the introductory material and literature review of this paper were included in Gralla and Herrmann [20]. The data collection and subproblem identification methodology described in this paper is an abridged version of that presented in Azhar et al. [29]. The evaluation of the layouts, the results, and accompanying discussion are original to this paper.

II. RELATED WORK

A. Humans as Designers

Previous studies of engineering design have shown that design occurs via a series of decisions [8]. Different patterns of decision-making can occur [9]: decisions may be made sequentially or in parallel. Empirical studies of human designers have shown that they exhibit characteristics of bounded rationality. Designers use various types of heuristics and search processes to find design solutions [1, 2]. Moreover, the design processes that human designers use are based on how they decompose the design problem [1, 3, 4].

When a team solves a design problem, problem decomposition is even more important because each subproblem may then be handed off to different individuals. Studies of teamwork, the process by which members seek, exchange, and synchronize information, show its importance for team decision-making [5, 6], but these studies did not address decomposition explicitly. Although teams do decompose system design problems, they may do this informally, without explicitly discussing and selecting the decomposition that they use [21].

This project is supported by National Science Foundation grants CMMI-1435074 and CMMI-1435449

B. Design Solution Quality

Design decisions and the design process affect the quality (measured using performance metrics) of the design solution. Some empirical studies have considered how specific design activities and team characteristics affect design solution quality [10-13]. A second stream of research has used models of bounded rational designers to predict the quality of the design solutions that a design process generates [9, 14-16].

The research study described in this paper is at the intersection of these three areas: human designers, design processes, and the quality of the resulting solutions. Studies of human designers have detailed their activities and described how they decompose problems but have not devoted much attention to how teams of designers decompose and solve design problems. Although several researchers have begun to investigate the impact of design processes on solution quality, there remains a need for empirical studies that shed light on the bounded rational strategies of human designers and can generate additional insights into how the decomposition of a design process affects design solution quality.

III. Methods

We observed teams of engineers redesigning a factory in a short exercise that was part of a facility design course. Based on their activities, we identified the decomposition they used in solving the problem. In addition, we evaluated the quality of their final layouts.

This type of field experiment was selected as a useful compromise between a more time-consuming, but natural, field study and an artificial, but controlled, experimental setting.

A. Research Setting and Data Collection

We observed ten teams of engineers redesigning a factory as part of a two-day lean facility design course. The ten teams were observed during three different courses over the span of three years. The 45 participants were professionals from a variety of industries (mostly manufacturing), with an average experience in industry of 17 years (min = less than 1 year, max = 45 years). The participants were segmented by their experience level, and then those in each segment were divided randomly to form to form teams of 3 to 5 people. This ensured that every team had some persons with more experience and some with less.

The teams were asked to redesign an existing facility which had a traditional functional layout over a four hour period. All teams were provided with information regarding areas which could not be altered, goals for the redesign, and the criteria on which their new layout would be evaluated. The manufacturing process required several related steps, including building frames, assembling modules and assembling the final product. The facility makes three sizes of the product, which require the same manufacturing operations. Additional functional areas included a machine shop, incoming and outgoing quality control, storage, crating and packaging, and shipping and receiving. Other areas included an R&D area, an area for refurbishing used machines, and a fitness center. Though the teams were not provided details on the inner workings of many of the areas in the facility, the assembly operations (building and assembling modules and machines) required determining the detailed layout of these operations.

Optimizing facility layouts is a difficult problem with many good (and bad) solutions which can be evaluated using a number of methods. One important attribute is the type of layout, which can anywhere on a spectrum from functional to cellular. Functional layouts group similar operations together, and cellular layouts include areas that group diverse operations together to assemble a product. In the problem that the teams solved in our study, the first several operations had to remain functional, but the module building and main assembly operations could be effectively grouped into cells.

The primary data collection method was observation. During each exercise, the teams' design activities and presentations were video-recorded for later viewing and analysis. All documents produced during the exercise were either physically collected or photographed, to triangulate the other data and to document the design solution created by each team.

B. Data Analysis

The data analysis included two distinct processes: the first aimed to identify how the teams decomposed their design problems and the second aimed to evaluate the solutions (facility layouts) they created. To accomplish the first goal, we used a combination of qualitative and quantitative data analysis methods to describe team activities. To accomplish the second goal, we relied primarily on expert evaluation of the facility layouts produced by each team. Quantitative measures were also developed to complement the expert analysis.

The data analysis process consisted of four steps:

1) Development of Variables and Coding

We first used qualitative data analysis methods to describe activities in a structured manner. Our method drew on grounded theory [23, 24] and process mapping [25]. These are the same kinds of methods used to analyze verbal protocols [26, 27], which have been used extensively to study human designers [28]. The method calls for the development of conceptual categories, or codes, to organize the data and link similar patterns. In this case, we aimed to develop codes to describe what teams were working on, precisely defined as the variables they were determining.

We coded the data by examining the teams' discussions and actions to determine which sets of variables were being considered by each team during every two-minute segment of video. We also noted when a team split into smaller groups to work on different variables concurrently, and whether a team mentioned a variable but chose to revisit it later without making a decision. The codes were refined by re-examining similarly coded data segments, editing or adding code definitions to better represent the observed behavior of the teams, and re-coding the data in an iterative and inductive process, which ensures that the codes represent the variables actually considered by the teams.

2) Identifying Subproblems

The next step was to identify the subproblems teams worked on. Subproblems, which are collections of variables that teams considered or decided upon together, were developed using association rules and further refined to more accurately represent the teams' activities.

a) Association rule learning:

In machine learning, association rules are utilized to discern relationships between sets of items which occur together. We utilize association rule learning to identify variables that are frequently coded together. For example, if the three variable codes "staffing in area," "operations sequencing and balancing," and "location of areas" were coded together regularly throughout the entire team's timeline, then these three variables would constitute one subproblem. The algorithms identify groups of variables (subproblems) by requiring the variables to be coded together in a certain percentage of the total dataset.

b) Subproblems from association rules

The algorithm generates different sets of subproblems depending on the parameters and on whether the data from all teams were included or from only one team. Since each team displayed slightly different decomposition patterns, using individual team codes (rather than all team codes together) yielded the most useful set of subproblems for each team. (The subproblems generated for all ten teams were very similar to those generated for individual teams, but did not include subproblems that were utilized only by one or two of the ten teams.) The initial set of subproblems generated based on each team is listed in Table I along with the variables which comprise them. Using this method, the decomposition timeline for Team 3 shown in Fig. 1 was produced.

3) Creating Decomposition Timelines from Subproblems

Once subproblems had been defined, further refinements were made in order to facilitate evaluation and pattern analysis.

a) Generating timelines for each team

For each team, the subproblems were then mapped on a timeline of ten minute segments that indicated when that team discussed each subproblem.

b) Collapsing timelines for analysis

In order to compare the ten timelines, we reduced the number of distinct subproblems by combining similar subproblems. High-level Logic and Flow was merged with Allocation of Regions to form a High Level Regions subproblem, and Office Layout Details was omitted because it was not discussed very often in the majority of the teams. Operations and Operations Sequencing were combined. Additionally, the variable Location of Areas was included in the final decomposition timelines because it was an important aspect of the teams' work, and it was not already included on the timelines because it consisted of only one variable. (Other single-variables subproblems were considered, but they all appeared to be accounted for within the existing set of subproblems.) The finalized decomposition timeline for Team 3 is shown in Fig. 2. Note that very little information has been lost in the collapsed timeline.

TABLE I. INITIAL SUBPROBLEMS

Subproblems	Variables
Allocation of Regions	Allocation of large regions, shape of area, location of area
High Level Logic and Flow	High level flow logic, spatial flow pattern, location of area
Internal Layout	Internal layout, division of area, spatial flow pattern, location of areas
Inventory	Inventory/batch sizes/storage/WIP/buffers, assignment of space for inventory, spatial flow pattern, high level flow logic, location of areas
Office Layout	Office layout details, high level flow logic, location of areas
Operations	Assignment of operations to areas, assignment of products to areas, high level flow logic, location of areas, spatial flow pattern
Operation Sequencing	Operation sequencing and balancing, assignment of operations to areas, staffing in area, internal layout of area, spatial flow pattern, high level flow logic, location of areas
Staffing	Staffing in area, facility staffing, shape of area, spatial flow pattern, location of area

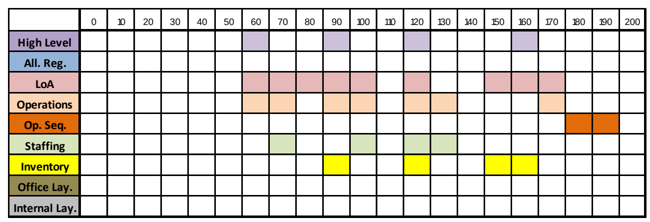

Fig. 1. Decomposition timeline using the original set of subproblem.

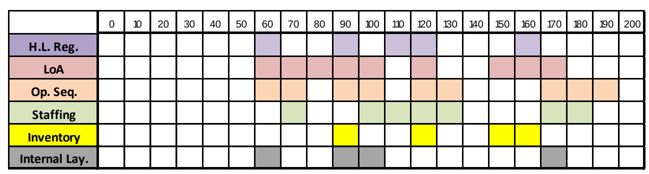

Fig. 2. Decomposition timeline using the final set of subproblem.

c) Categorizing subproblems

Based on the level of abstraction of the subproblems, we chose to categorize them into three groups: High-level, Mid-level Detailed, and Detailed. High-level subproblems focus on the high level logic governing the facility and location-related discussions, while Detailed subproblems are those which deal with very specific discussions about particular aspects of the layout. Mid-level Detailed subproblems were those which bridged the gap between the higher and lower level sets. This categorization allows us to examine the teams' decompositions to determine if a pattern exists in the way they worked through the level of details for their solution. The categories and their associated subproblems are listed in Table II.

TABLE II. SUBPROBLEM CATEGORIES

Category	Subproblems
High-level	High Level Regions, Location of Area
Mid-level Detailed	Operations, Operation Sequencing
Detailed	Staffing, Inventory, Internal Layout

4) Evaluating layouts

We evaluated the layouts that the teams created in three ways:

First, we estimated the total material travel distance. To do so, we examined each layout and determined the location of every area. We then estimated the total distance that raw materials, components, subassemblies, and completed machines would have to move through the facility in order to manufacture each product. The distance between two operations was calculated using the Manhattan distance metric because facilities are typically laid out with straight aisles around rectangular areas.

Second, we calculated an adjacency score to measure how well the layout co-locates areas that should be near each other and how well it separates areas that should not. We assigned a positive, negative, or neutral weight (+1, -1, or 0) to each pair of areas in the factory. The weights were determined from the steps of the manufacturing process and the facility redesign goals. The distance between two areas was multiplied by the appropriate weight, and the sum of these weighted distances provided the adjacency score.

Third, we asked a subject matter expert to assess each layout on the following items: overall impression (based on the improvements from the original layout), assembly operations (the use of product-focused manufacturing cells), and the overall flow of material through the facility.

IV. RESULTS AND DISCUSSIONS

A. Layouts and Expert Analysis

The subject matter expert's evaluations of the ten layouts are shown in Table III.

The material travel distance and adjacency score for each of the ten layouts are shown in Table IV. Note that a less negative adjacency score indicates a better facility layout.

A scatterplot of these measures (shown in Fig. 3) revealed a loosely positive correlation between these two measures. The original layout was also evaluated by these measures and is included in the plot. All ten teams' layouts had a better adjacency score and a better material travel distance than the original layout.

TABLE III. EXPERT RATINGS

Team	Overall Impression	Assembly Operations	Facility Material Flow
1	Significant Improvement	GOOD	FAIR
2	Minor Improvement	FAIR	EXCELLENT
3	Significant Improvement	GOOD	FAIR
4	Minor Improvement	FAIR	EXCELLENT
X	Minor Improvement	FAIR	FAIR
Y	No Noticeable Improvement	POOR	POOR
Z	Minor Improvement	FAIR	FAIR
J	Significant Improvement	GOOD	FAIR
K	Significant Improvement	GOOD	GOOD
L	Significant Improvement	EXCELLENT	GOOD

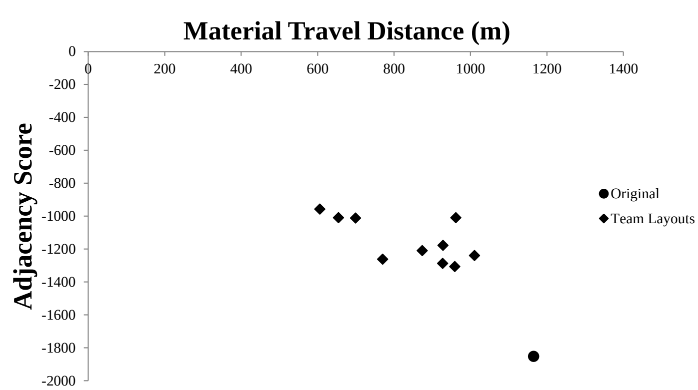

Fig. 3. Scatter plot of material travel distance and adjacency score.

TABLE IV. QUANTITATIVE METRICS

Team	Material Travel Distance (m)	Adjacency Score
1	874	-1209
2	959	-1306
3	770	-1263
4	962	-1010
X	927	-1288
Y	1010	-1240
Z	700	-1013
J	606	-958
K	928	-1178
L	655	-1010

B. Decomposition Patterns

From all ten timelines (not shown here due to space constraints), we can draw a few general observations about the way that the teams decomposed the facility redesign problem. While most teams did work on the same set of subproblems in the course of solving the problem, the sequence in which they did so varied tremendously. There did not appear to be a very evident set of patterns across all ten teams in the sequence in which they solve subproblems. Some teams iterated frequently between discussing high level subproblems and detailed problems, while others broke into sub-teams and discussed them both concurrently in separate groups. Those teams which did divide into sub-teams for a portion of time tended to have at least one of those sub-teams focused on discussing the detailed subproblems (staffing, inventory, internal layout).

From inspection of all ten timelines, it is quite clear that teams did not approach this design problem in a neat and organized fashion. More specifically, we showed in an earlier paper that teams do not explicitly decompose problems [21], and our current results suggest that they do not solve one subproblem and set it aside to work on the next. Many teams seem to iterate repeatedly and continuously through subproblems, discussing and revisiting a subproblem many times over the course of the design process. A number of teams discussed everything all at once, concurrently developing solutions to many subproblems, while a few tended to limit their topic to only a few subproblems at a time. Yet other teams exhibited both of these behaviors at different times in the course of their decomposition.

C. Linking Decomposition to Solution Quality

The aim of this research was to investigate how the decomposition of a design problem influences the solution character and quality. Expanding upon earlier research, we considered the decompositions of all ten teams alongside the quality of the solutions they produced (measured by material handling distance, adjacency score, and the expert's ratings). This research is ongoing, but so far it confirms the importance of understanding decomposition and identifies numerous avenues for further investigation in future research.

The messy and noisy character of human behavior contributes to the difficulty in drawing strong conclusions. However, the evidence suggests that problem decomposition influences the character and quality of design solutions, though the manner in which it does so is not readily apparent.

The quantitative measures (shown in Fig. 3) suggest that the layouts differed in quality. All layouts improved upon the original in both travel distance and adjacency score, but some did so more than others. Three, in particular, appear better than the remainder.

We examined the decomposition timelines for these three layouts in comparison with the others. There were no clear patterns that distinguished these from the others based on a visual examination of the timelines. It was hard to identify patterns because the timelines indicate that the teams iterated continuously through most of the subproblems. Nevertheless, there are preliminary indications that early or late consideration of certain subproblems lead to better and worse solutions. In our ongoing work, we are investigating these possibilities and working on ways to eliminate some of the "noise" in the timelines due to the continuous iteration among subproblems.

V. SUMMARY AND CONCLUSIONS

This paper described the results of an empirical study of ten teams of engineers who were presented with the problem of redesigning a factory layout. The goal of the study was to gain insights into how teams decompose design problems and how their decomposition affects the solution quality. The evidence from this study suggests that problem decomposition may influence the character and quality of design solutions, but the study also reveals the difficulty of determining that link given the messy quality of human behavior. These preliminary results motivate future work to examine the influence of decomposition on solution quality in more detail.

In our ongoing work, we are further investigating the link between decomposition and solution quality. We are examining ways to describe the decompositions that abstract away some of the messy character of human behavior, and in particular, investigating the apparent continuous iteration between subproblems. The goal is to identify clearer patterns that link decomposition to solution quality.

These results increase our understanding of how engineering teams decompose design problems and are a first step in understanding how the decomposition affects the quality of the solutions that are generated.

ACKNOWLEDGMENT

The authors acknowledge the assistance of David Rizzardo, who organized and led the facility design course and evaluated the teams' facility layouts.

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