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Team Design Processes and Decompositions in Facility Design

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Abstract

When faced with the problem of designing a complex system, a design team must make many decisions. Because many design problems are too difficult to solve all at once, the design problem is decomposed into more manageable subproblems. The way in which a problem is decomposed may affect the quality of the solution that can be constructed, especially when time and resources are limited. This paper describes the 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 preliminary study, we observed four teams of professional engineers who redesigned a manufacturing facility, and we analyzed their decision-making processes and the facility layouts that they generated. As we expected, teams used a variety of decomposition approaches. Some teams focused initially on designing manufacturing cells, while others began by laying out a high-level flow through the facility. These two strategies appeared to lead to different kinds of final facility designs (cellular and functional, respectively).

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

1. Introduction

When faced with the problem of designing a complex system, a design team must make many decisions. Because many design problems are too difficult to solve all at once, the design problem is decomposed into more manageable subproblems. The way in which a problem is decomposed may affect the quality of the solution that can be constructed, especially when time and resources are limited. The decomposition of design problems is governed by the design process, which may be a formal process imposed by an organization or an informal set of activities and responsibilities organically determined by a team of designers. Investigating the impact of decomposition on design solution quality will support the design of better design processes.

Most design is carried out by teams of bounded rational human designers. Although many aspects of engineering design teams have been studied, our understanding of how teams solve design problems and how their decomposition strategies affect solution quality 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 describes our initial steps toward 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 four teams of human designers as they decomposed and solved a facility layout design problem. Based on our analysis of the results, we have identified their decomposition strategies and assessed the impact of the problem decomposition on the design solution quality.

2. Related Work

Humans as Designers. 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].

Problem decomposition is even more important when a problem is solved by more than one designer 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. Instead, one recent study of design teams showed how our theoretical concepts of decomposition do not match the ways teams actually work [7].

Design Processes. Previous work on engineering design has shown that design occurs via a series of decisions [8]. Some decisions may be done sequentially while others occur concurrently, and different patterns of decision-making can occur [9]. A design process includes the tasks needed to make these decisions. The informal design processes employed by humans are largely dictated by the way they decompose problems. When human designers work within organizations, they usually carry out the organization's design process, but they may use informal decompositions when solving design problems within the phases of that process.

Design Solution Quality. The fact that design decisions and the design process affect the quality (measured using performance metrics) of the design solutions is generally recognized. 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 simple design processes to assess the quality of the design processes by evaluating the quality of the product designs that are generated, accounting for certain characteristics of bounded rational designers [9, 14-16].

The research described herein 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. While 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.

3. Methods

In this preliminary study, we observed four teams of engineers redesigning a factory as part of a two-day lean facility design course offered by the University of [blank]. Each team redesigned a fictional factory that makes multiple products and has a traditional functional layout. The exercise took approximately four hours. Each team was given a scenario that specified (a) information about the existing factory and products; (b) constraints, such as areas that cannot be changed; (c) goals for the redesigned factory, such as freeing up space; and (d) criteria for evaluating the redesigned factory, including productivity and material handling effort. Teams presented their final designs to each other for discussion and feedback. We observed and recorded the activities and discussions of the teams as they completed the exercise.

The 20 participants were professionals at manufacturing firms, with an average experience in industry of 14 years (min = 2 years, max = 38 years). The participants included eight engineers, three production and facility managers, six executives, two sales personnel, and one maintenance technician. The participants were segmented by their experience level, then those in each segment were divided randomly into four teams, to ensure that every team had some persons with more experience and some with less.

We adopted this type of field experiment because it represents a useful balance between a completely controlled but highly artificial laboratory experiment and a natural but time-consuming field study [17]. A data analysis of this type proved successful in documenting the activities of teams solving an operational planning problem [18], so we were confident that it could be applied successfully here.

Data Collection. The primary data collection method was field observation, or ethnography [19, 20]. During each exercise, the teams' design activities and presentations were video-recorded. Each team was observed by one researcher, who took notes during observation and then expanded them into field notes [19]. Observation is a useful supplement to recording because researchers may catch behavioral elements that might be missed on camera and interact with participants outside of the design activity. All documents produced during the exercise were either physically collected or photographed, to triangulate the other data and document the design solution created by each team.

Data Analysis. The goals of the data analysis were to identify how the teams decomposed their design problems and to evaluate the solutions (facility layouts) they created. To accomplish the first goal, we used qualitative data analysis methods to describe team activities. The rich but unstructured observational data captured each team's activities, and in the analysis process we built structured descriptions of what happened [21]. To accomplish the second goal, we relied primarily on expert evaluation of the facility layouts produced by each team.

We used qualitative data analysis methods including grounded theory [22, 23] and process mapping [24]. These methods complement one another in their emphasis on, respectively, organizing data into conceptual categories and linking actions or categories in a logical manner (e.g. chronologically). These are the same kinds of methods used to analyze verbal protocols [25, 26], which have been used extensively to study human designers [27].

To describe activities in a structured manner, we developed conceptual categories, or codes, to organize the data and link similar patterns to one another. We applied the codes to the data to create structured descriptions of each team's process; these descriptions identify the individual subproblems and variables that each team considered and how they were arranged into a decomposition of the design problem. (A subproblem consists of a set of design variables that must be determined and are considered collectively by a team, and a decomposition is a set of subproblems considered in some sequence.) Further details are given in steps (1) and (2) below.

The data analysis process consisted of three steps:

(1) *Coding variables:* Based on the elements of the facility design problem, we developed an initial set of codes to label the variables that the teams considered. For example, facilities are commonly designed using block layouts that abstract away the complexity of detailed operations, and the problem that was given to the teams included some pre-defined blocks like the machine shop, so one variable code was "location of machine shop." Two researchers 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. Next, 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. The inductive development of codes from the data ensures that the codes represent the variables actually considered by the teams, rather than a framework imposed by the researchers. In the end, our complete set of codes (i.e., the variables teams considered) included the location of each block in the facility, assignment of operations and products to groupings like cells, and seven aggregate variables: flow logic, location of blocks, shape of blocks, buffers and storage, layout of activities (within a block), and staffing. Each of these aggregate variables represented multiple detailed variables that the teams considered jointly.

(2) *Coding subproblems:* To understand the broader strategies teams followed, we identified the subproblems that the teams considered during the design process. (Recall that a subproblem consists of a set of design variables that are considered collectively by a team). Subproblems were identified by analyzing patterns in the timelines (created in step 1) showing which variables each team considered over time and re-examining the team's discussions to determine the relationships between these variables. The codes for the subproblems were developed in an iterative and inductive process similar to the one that we used for coding the variables. Five subproblems were found through this process; they are given in Table 1 and discussed in Section 4, below. This paper captures our preliminary analysis of the data, but further examination and additional teams will enrich the dataset and enable more robust conclusions.

(3) *Evaluating layouts:* We evaluated the layouts that the teams created in three ways. First, we examined a photograph of each layout and identified the overall structure of the layout (especially the existence of product-specific assembly cells). Second, we determined the location of each area and then estimated the total distance that material needed to move to manufacture each product. Third, we asked a subject matter expert to evaluate his overall impression of layout, the flow of material, whether areas are in the proper locations, and the design of assembly operations.

Two researchers independently performed the coding of the variables and subproblems. We determined the agreement between the researchers by counting the number of times that both researchers concurrently coded the same aggregate variable. To compensate for minor discrepancies in the timing of these codes (due to difficulties understanding the teams' discussions and differences in recording times), two codes for the same variable were considered concurrent if they were within 4 minutes of each other. Cohen's kappa coefficient for these codes is 0.76 (N = 3600). This is a measure of inter-coder agreement, where 0 indicates agreement only by chance and 1 indicates perfect agreement. The value of 0.76 indicates substantial agreement between researchers [28].

Table 1: The subproblems considered by the four teams.

Subproblem	**Description**	**Variables (codes) included**
High-level logic	Logic of flow through facility, including order of steps, grouping of operations into cells (independent of geography)	High-level flow logic, Assignment of products to cells, Assignment of operations to cells
Flow	Direction and shape of flow through facility (spatially)	Spatial flow pattern
Block locations	Location of blocks representing functional areas or groups of operations, such as machine shop or assembly cells	Location of [all blocks], Storage
Cell design	Design of assembly cells or lines that group a series of operations. Includes shape, layout of operations, determination of operations and products to include in cells.	Layout of cell, Shape of cell, Assignment of products to cells, Assignment of operations to cells
Staffing and operations	Sequencing and balancing of operations, including takt times, staffing numbers and tasks.	Staffing in cell, Staffing in functional area, Operation sequencing and balancing

4. Results and Discussion

Facility Layouts. Figure 1 shows the layouts that the teams created. The problem they were asked to solve involved redesigning an existing facility, which had a traditional functional layout. The manufacturing process consists of building a frame, painting the frame, building various modules (five modules, a drive train, and a control box), and mounting these various modules onto the main frame to assemble the final product. The facility makes three types of products, large, medium, and small, that require the same sequence of operations but use modules of different sizes. Additional functions included a machine shop, incoming and outgoing quality control, storage, and crating and shipping. In addition to areas for each of these functions, the redesigned facility required an R&D area for developing new products, a refurbishment area, and a fitness center. Many of these areas were treated as "black boxes," but the assembly operations (building and assembling modules) required determining the detailed layout of these operations. In most of the layouts in Figure 1, the "black box" areas (also referred to as "blocks" in this paper) are arranged around the outside of the factory and the assembly operations are roughly in the center of the facility.

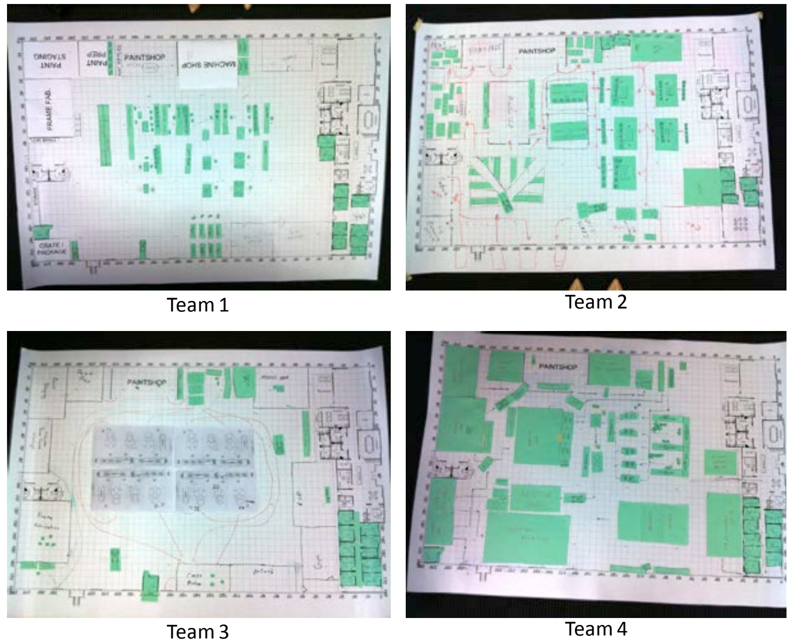

Figure 1: Facility layouts created by each team.

Optimizing facility layouts is a difficult problem with many good (and bad) solutions and multiple relevant performance measures. One important attribute is the type of layout, which can be functional or cellular. Functional layouts group similar operations together; for example, all of the products are painted in one area and then sent to another area for the next operation. Cellular layouts include areas that group diverse operations together to assemble a product; for example, in one cell, several modules are built and mounted onto a single product (and multiple cells exist in the same facility). Facility layouts may have both cellular and functional components, and cells may be arranged in various ways, including U shapes, L shapes, and lines. 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 (which the teams did to varying degrees). The total product travel distance for the major components was approximated from the layouts. This total includes the travel from the factory entrance, through processing operations, to machine assembly, and then to the factory exit. Each of the layouts is described below.

- Team 1's layout includes three assembly cells integrating module and final assembly, each one dedicated to one product. The assembly cells are arranged in the center of the layout and oriented so that material flows from the paint shop and machine shop (at the top center) to the area near the loading docks, which are along the bottom of the factory on the left-hand side. The remaining blocks are arranged around the outside of the layout; the frame fabrication shop is on the right-hand side. The total product travel distance was approximately 2,600 feet.
- Team 2's layout includes five final assembly areas (on the right-hand side near the offices) and two module assembly areas (between the machine shop and the assembly areas), but these are not dedicated to specific products. The remaining blocks are arranged around the top and left sides of the facility, but the control box assembly shop is on the right-hand side. The total product travel distance was approximately 3,000 feet.
- Team 3's layout includes four assembly cells that integrate all of the assembly and test operations. The cells are arranged close to each other in the central area of the facility. The remaining areas are arranged around the outside: the frame fabrication shop is the lower left corner, the machine shop is in the upper right corner, and the refurbishment area is in the lower right corner. The total product travel distance was approximately 3,100 feet.
- Team 4's layout includes one assembly area, which is laid out largely functionally, with module assembly in one area and final assembly in another. The remaining areas are arranged around the top and left sides of the facility, the frame fabrication shop and machine shop are in the left part of the middle area, and the control box assembly is directly above the final assembly area. The total product travel distance was approximately 3,300 feet.

Each layout was evaluated along three key dimensions of performance: assembly operations, flow of material, and location of major areas within the factory. The assembly operations are the most important because they largely determine the productivity of the factory that was redesigned in the exercise. The expert ratings and the reasoning that led to each of them are given in Table 2.

Table 2: The evaluations of the four teams' layouts.

	Assembly Operations (most important)	**Flow of Material**	**Area Locations**
Team 1	GOOD. Took advantage of machine sizes to create flow lines, accounted for demand in staffing. However, flow of module frames into lines and flow within lines is not clearly defined.	FAIR. Refurbishment and crating areas may be difficult to access due to placement.	GOOD. All basic location requirements have been met, but frame fabrication and machine shop could be closer together.
Team 2	FAIR. Module assembly is largely functional, and excessive module travel to some assembly areas.	EXCELLENT. Good overall flow from incoming to shipping.	EXCELLENT. All location requirements met.
Team 3	GOOD. Cellular design, but flow of modules into area not clearly defined.	FAIR. Excessive moving materials around the central set of cells, no indication of internal aisles, refurbishment could be closer to loading docks.	GOOD. All basic requirements met, but frame fabrication and machine shop could be closer together.
Team 4	FAIR. Separation of module assembly and machine assembly requires additional movement of modules.	EXCELLENT. Good overall flow from incoming to shipping.	EXCELLENT. All basic location requirements met.

The evaluations summarized in Table 2 suggest that the layouts from Teams 1 and 3 were similar to each other and that the layouts from Teams 2 and 4 were similar to each other. Teams 1 and 3 better integrated the assembly operations, including module building and final product assembly. These layouts minimize space and inventory, improve communication, and develop more of a "team" structure, leading to better facility performance. The assembly operations of Teams 2 and 4 remained somewhat functional, which requires additional movement and storage space. However, they connected their functional areas via kanban connections, so assembly processing was nevertheless a significant improvement over the original layout. The layouts from Teams 2 and 4 demonstrated better material flow and better locations than the layouts from Teams 1 and 3.

Decomposition patterns. Table 1 shows the complete set of subproblems considered by the four teams in the study, along with a description of each subproblem and the variables (captured as codes; see Section 3) that make up each subproblem. Figure 2 shows the timelines for the four teams; these indicate when each team was working on each subproblem. When teams worked on subproblems in parallel, they usually had two sub-teams working on each, but they were often considered together. For example, cell layout is determined in part by the sequence of operations, so the subproblems "Cell layout" and "Staffing and operations" were sometimes worked in parallel, with one sub-team calculating operation times and another using those numbers to determine the layout of operations within the cell.

The timelines summarize each team's decomposition, but they leave out much of the contextual detail. Based on the timelines in Figure 2, along with the more detailed timelines showing variables considered over time, and the activities captured in the video, we developed the following narrative descriptions of each team's decomposition and solving strategy.

- *Team 1* began by selecting locations for the blocks, placing them around the edges and leaving a big blank space in the layout for the assembly cells. In parallel, some team members worked on sequencing operations and allocating staff. They next spent time laying out the assembly operations in cells, independent of the main layout. They added the cell layouts to the main layout, and finally returned to locating blocks (this time including the grouped assembly operations).
- *Team 2* began by considering the high-level flow logic, including the number of cells and which products would be assigned to them, independent of the spatial characteristics of the facility layout. Next, they started selecting locations for the major blocks and the assembly operations without specifically and separately discussing assembly cells. At the end, they considered the sequencing of operations and allocation of staff.

- *Team 3* began by thinking about the assembly operations, specifically the sequencing and staffing of operations. The team decided quite early that these operations should be grouped in a cell and designed the layout of a single cell, considering operation timing and staffing at the same time. They copied the cell and set it in the layout, but realized they had to adjust the cell layout due to an earlier mistake. They redesigned the cell, then determined the number of cells, set them in the layout, and located the remaining functional blocks around it.
- *Team 4* began their work at a very high level, thinking about the direction of flow through the entire facility, and how each element should connect to the other elements. They then selected locations for the major functional areas of the factory and left a big space for the assembly operations (module assembly and machine assembly). Finally, they determined the layout of the assembly areas, again thinking in terms of overall flow and connections between elements.

Discussion. The aim of this research was to investigate how the decomposition of a design problem influences the solution character and quality. In this preliminary research, we considered the decompositions of each team (Figure 2) alongside the character and quality of the solutions they produced (Table 2). This research remains preliminary, and it is difficult to draw strong conclusions from four teams, but this exploration confirms the importance of understanding decomposition and identifies dynamics for further investigation in future research.

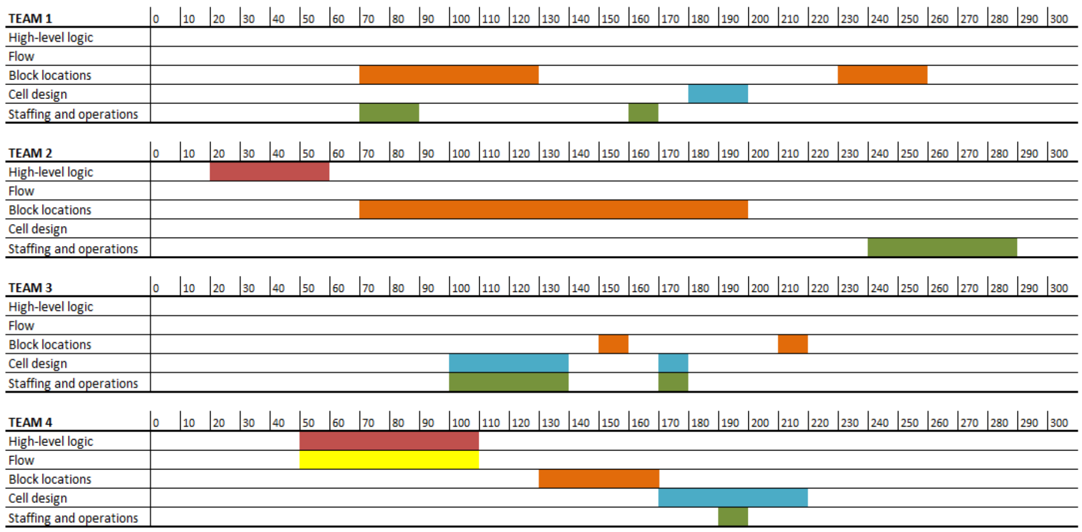

Figure 2: Subproblems solved over time for each of the four teams.

One of the key differences among the four facility layouts is in the quality of the assembly operations. Teams 1 and 3 produced cellular layouts, which are associated with better performance, while Teams 2 and 4 produced largely functional layouts. On the other hand, Teams 2 and 4 produced layouts that perform better on the two remaining performance dimensions, which are less important than the assembly operations but nevertheless relevant to overall performance. It is possible that the limited time frame (the four hour exercise) prevented the teams from optimizing both the overall layout and the assembly operations. The differences in the decompositions indicate another influence, however.

Examining the decompositions, one element that distinguishes Teams 1 and 3 from Teams 2 and 4 is *when* in the design process they considered cell design. It is clear that Team 1 considered the cell design (assembly operations) early in their process and before laying out the block locations. Team 3 laid out the block locations early but then considered cell design specifically and adjusted their block locations accordingly. Team 2 never explicitly considered cell design but rather included it in their discussions of the block locations. Team 4 did consider cell design (or, rather, the design of their assembly area), but it was late in their design process. While Teams 1 and 4 considered cell design at approximately the same time, Team 1 continued adjusting their design, but it was the last element considered by Team 4. The evidence suggests that considering cell design early in the design process, rather than last, leads to more cellular layouts and, thus, to better-performing solutions. This may reflect two different solution strategies: the teams who did this decided to create a cellular layout (and thus needed a cell design before moving forward), but the ones who didn't were just considering the operations in sequence from beginning to end.

A second element that distinguishes Teams 1 and 3 from Teams 2 and 4 is the time and effort devoted to high-level logic and flow. Teams 2 and 4 spent significant time at the beginning of the design process thinking through the high-level logic of flow through the facility. Teams 1 and 3 started their substantive work on the problem by laying out block locations or cells, and considering staffing and operations within them. It is surprising that a consideration of the high-level logic at the start of the problem would lead to poorer solutions; however, the evidence suggests that this is the case for this problem. Probably, focusing on high-level logic and flow caused Teams 2 and 4 to focus too heavily on designing the overall flow of material and the locations of areas within the factory, which are less important than designing assembly cells that improve the assembly process.

It appears that Teams 2 and 4 took a generally top-down approach in which they first established the overall flow of material through the factory (without reorganizing the operations into assembly cells) and then considered the individual blocks and assembly areas to determine each one's specific location, shape, and layout. Teams 1 and 3 took a generally bottom-up approach in which they first reorganized the operations into assembly cells and created a layout for those cells; then they determined the location of the blocks and the assembly cells. Of course, all of the teams backtracked often as they rearranged blocks and layouts that they had already created; the coupling between variables caused by the flow of material between areas and the limited space in the factory made backtracking likely.

Given the evidence from only four teams, and the messy and noisy character of human behavior, it is difficult to draw strong conclusions. However, the evidence suggests that problem decomposition influences the character and quality of design solutions. In particular, we have identified two dynamics for further study. (1) Considering high-level logic and flow early in the design process (in a generally top-down approach that does not modify the default organization of the areas) may cause teams to emphasize less important dimensions of performance, and (2) considering assembly cell design early in the design process, or at least not last in the process, may enable teams to design better-performing facilities because they reorganized the operations into a more efficient product-focused process. Once future research confirms or expands upon these findings, design guidelines can be developed to suggest which parts of the problem teams should investigate early in the design process.

5. Summary and Conclusions

This paper described the results of an empirical study of four 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 does indeed influence the character and quality of design solutions, and in particular, that top-down and bottom-up decompositions lead to different types of design solutions. These preliminary results motivate future work to examine the influence of decomposition on solution quality in more detail.

In future work, we plan to observe more teams, determine if the decomposition patterns described here will occur again, identify additional decomposition patterns, and generate more insights based on these observations. In addition, we will analyze the data from this study and future studies using alternative coding schemes derived from theories of design and decision-making, including levels of abstraction from details up to system [29]; macro-strategies such as top-down or backtracking [30]; and phases of decision-making from identification of the decision through alternative development and selection [31]. Coding the data on these dimensions will enable comparison of this study's results with previous work and provide a richer description of the strategies by which subproblems are formed, investigated, and integrated, thus providing additional insights into the decomposition that the team used.
In addition, we plan to formulate the teams' subproblems and decompositions as sets of linked optimization problems and use simulation techniques (developed in previous work by the author) to estimate the quality of the solutions that these decompositions can generate.

These results increase our understanding of how engineering teams decompose design problems and how the decomposition affects the quality of the solutions that are generated. As more evidence is gathered from more studies of this problem and in similar contexts, this line of research will eventually lead to a broad taxonomy of decompositions across various types of design problems and a more general understanding of their impact on the quality and characteristics of design solutions, from which we can expand our theories of design, support the design of better design processes, and improve our ability to organize and manage effective engineering design teams.

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