ABSTRACT

Title of Thesis:	IDENTIFYING AND COMPARING SUBPROBLEMS IN FACTORY DESIGN PROCESSES
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When a design team faces a problem of designing a complex system, they are required to make several decisions. Because such design problems are difficult to solve all at once, teams often decompose the design problem into several smaller subproblems. This thesis discusses the results of a study designed to understand how design teams decompose a factory redesign problem into sets of related subproblems and compare the subproblems obtained for each design team. This exploratory study analyzed the design activities of six teams of professionals and used clustering to group the variables that the design teams considered. It was found that the design teams used different decomposition strategies and different subproblems, but they more often considered subproblems with design variables of the same type, and some teams followed a top-down design process.

IDENTIFYING AND COMPARING SUBPROBLEMS IN FACTORY DESIGN PROCESSES

by

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Chapter 1: Introduction

1.1.Background

Designing a system can often be a highly complex activity. Design teams who are solving design problems, thus, are required to make many decisions. Since many of these design problems cannot be solved all at once, the design team break the complex problem into smaller, less complex subproblems. This implies that the reasoning and techniques used to decompose the complex design problem into subproblems and the composition of the subproblems themselves are related to the quality of the design developed. Since the decomposition of design problems is a critical activity affecting the quality of the design, it is important to understand how design engineers decompose problems. Ultimately, identifying the decomposition strategies that lead to better quality designs will be helpful for design engineers and will also enable future research on designing better design processes.

1.2.Research Objectives

Currently, we have limited knowledge about how teams decompose complex design problems. Previous work in the field has been focused on describing the overall approach and experiments to identify the best clustering technique to identify the subproblems that were used by design teams [1,2,3,4,6,7], but they did not compare the subproblems across teams themselves. This research aims at identifying the subproblems used by each design team solving a factory design problem and comparing the subproblems across teams (six teams in total were studied).

The thesis presents the results of this research. It describes:

- The approach of the research
- The participants, design problem and data collection methods used.
- The data analysis performed, consisting of coding, clustering, and the results obtained.
- The team comparison results obtained on comparing the subproblems across teams
- The discussion of the results obtained
- Conclusions and future applications of the research.

The thesis discusses the similarities and differences in subproblems identified between all the six teams and discusses the relationships between identified subproblems and the quality of design developed for each team. Thus, the thesis provides objective evidence that the identified subproblems for each team are "meaningful".

1.3.Approach

The goal of this research is to understand how design teams decompose design problems. We approached this by observing teams engaged in solving a factory redesign problem and analyzing their design processes. A key feature of our approach is that we assume that the team decomposes the design problem into subproblems and that the variables that a team discusses concurrently are likely to belong to the same subproblem. Thus, we needed to identify the variables that a team discussed, determine when they discussed which variables, and examine groups of these variables as suggestions of the subproblems that the team considered. We then compared the results across multiple teams to determine if there are any similarities or common patterns.

Chapter 2 discusses the existing literature related to the research.

Chapter 3 describes in detail the data collection approach used.

Chapter 4 discusses in depth about the coding process and the clustering algorithms used to identify subproblems.

Chapter 5 presents a team wise comparison of the identified subproblems and variables in the design discussions.

Chapter 6 discusses the final layout designed by each team and the compares the progress in the layout with the subproblems identified across teams.

Chapter 7 discusses the results obtained in the thesis and what they mean.

Chapter 8 discusses future work and concludes the thesis.

Chapter 2: Literature Review

2.1.Design Teams

The design teams have been an interesting aspect of research and many researchers have examined the relationship between the experience level of a designer and the design strategy used by them. Studies by Ball et al. (1994) and Ahmed et al. (2003) tried to understand how novice and experienced designers approach design tasks. It was found that with experience, the more experienced designers and design teams tend to use their previous experiences to come up with design solutions [8,9].

Though most of the research has been focused on strategies used by the design teams, there has also been some research on exploring how design teams are selected. A research by Hong and Page (2004) identified that design teams value diversity. While selecting a design team from a diverse selection pool, picking a team of randomly selected individuals outperforms a team comprised of the best-performing ones. This was attributed to their diverse differences characteristics, cultural identities, training, and expertise that each member brings to the team [10].

2.2.Design Processes

Previous research on engineering design processes has shown that design processes are performed through a series of decisions [11]. These decisions may be made either concurrently or sequentially. Lewis and Mistree (1998) state that based on the strategy applied by the team performing the design process, there are different patterns of decision making that can occur [12]. When human designers work on a design problem, the final goal is to perform the design process as expected.

But, within that design process the team may use different (informal or formal) methods to solve the subproblems within the overall design process. Dinar et al. (2015) provided an overview of the previous research done to understand design studies. This lists common qualities and approaches adopted in many studies and identifies best practices and areas for improvement. Through this, a major weakness that was identified was the lack of a formal and repeatable methods to collect and analyze design data. The conclusion made was that engineers focus on data analysis and quality of final design rather than the process that leads to the final design [13].

2.3.Decomposition

Decomposition by design teams in complex design activities has been an area of interest to researchers. Decomposition of design problems is especially crucial when problems are solved by a design team as opposed to a single design engineer. Understanding how design teams decompose complex problems certainly gives insight into improvement of design quality. In this research, decomposition refers to breaking down the design goal into smaller sub-goals (referred to as subproblems) that are easier to solve for design teams [14,15].

Decomposition in design problems can be of two kinds, implicit and explicit decomposition [14]**.** Understanding the effectiveness of the two decomposition techniques helps gain insight into the best method to be followed while performing complex design activities. The case study performed by Sun et al. (2016) has shown that explicit decomposition and the breadth-first strategy had demonstrated to be more effective than the implicit decomposition strategy [15].

However, not all design activities follow a systematic decomposition strategy. A study by Ball et al. (1997) of an integrated-circuit design revealed that the designers, while implementing a systematic top-down approach, deviated to an extent from this process. This deviation was described as opportunistic, and the authors attributed the switches to the expert's strategic knowledge about how to conduct the design process effectively when faced with difficulties and uncertainties [16]. Analysis of three electronic design episodes using macro strategies showed decomposition happened at early stages of design process following of top-down and bottom-up approaches [17]. Guindon (1990) analyzed the protocols obtained from three computer science professionals solving the Lift Control Problem. The results showed an opportunistic design better described the ill-structured design problems while the top-down approach is more efficient when the designers know the correct decomposition [18].

2.4. Use of Clustering in Design

The problem in studying decomposition by design teams lies in the identification of what design variables go into the same subproblems. This has been studied in the past, and some research has been done on exploring the different clustering algorithms that can be used as a repeatable way of identifying subproblems in design processes

Morency et al. (2017) and Herrmann et al. (2018) studied design teams solving different design problems to identify subproblems in their discussions by application of clustering algorithms. The goal was to evaluate different clustering algorithms and their ability to identify relevant subproblems [1,4,5]. However, this study involved studying medical POD design teams.

The researchers examined multiple clustering algorithms and evaluated their ability to identify groups of variables that form subproblems.

Previous research done on identification of subproblems in design processes has focused on finding the best clustering algorithm to successfully identify subproblems rather than evaluating the subproblems themselves. In addition, research by Morency et al. (2017) and Herrmann et al. (2018) used POD design as a problem statement to evaluate clustering algorithms [1,4,5]. The research presented in this thesis builds on the previous work done in POD design, applying the methods and clustering algorithms identified earlier to factory design problems. Moreover, the goal of this thesis is to identify subproblems (using clustering algorithms identified by Morency et al. and Herrmann et al.) effectively and evaluate the subproblems themselves, rather than to examine the clustering algorithms.

Chapter 3: Data Collection

3.1.Overview

A 2-day lean facility design course was conducted by Mr. David Rizzardo to collect data for the design teams solving a factory redesign problem [Appendix - A]. This chapter includes the processes, methods, and information used to collect and the data pertaining to the research. Section 3.2 highlights some frequently used terms in this chapter (and the proceeding chapters). Section 3.3 discusses the design teams participating in the research. Section 3.4 describes the methods used to record their discussions. Section 3.5 describes the tools and techniques used to code these recorded discussions. For this research, Microsoft Excel was used for coding the discussions. Section 3.6 displays the results of coding the design team discussions for each design team. This data will form the basis for applying clustering algorithms to form subproblems. This thesis presents the data analysis of clustering of variables into subproblems, however the process of colleting the data was conducted in previous research [1].

3.2.Important Terms

Throughout this thesis, there are some terms that will be used to depict certain artifacts of the research. As such, these terms are defined in Table 1 below [4].

Table 1: Important Terms and Definitions

Term	**Description**
Variable	A phrase used to capture each single aspect of the teams' discussions.
Cluster	A selection of variables that were grouped together by the algorithm.
Subproblem	A selection of variables that were discussed together by the team.

3.3. <u>*Participants*</u>

This research considered discussions of six teams (labeled Team J, Team K, Team L, Team X, Team Y, and Team Z) of professionals with expertise in manufacturing. These teams were given the task of redesigning a factory layout as a part of a two-day lean facility design course. Each team had 4-5 persons. The participants had an average industry experience of 17 years and were grouped such that each team had a good mix of more experienced persons and less experienced ones.

3.4. <u>*Design Problem*</u>

The design teams were given a fictional design of a manufacturing facility called *"We Assemble Super Terrific Equipment (WASTE) Inc"* as seen in Figure 1. A problem statement aimed at redesigning of the WASTE Inc. facility based on a set of factory redesign goals and constraints. Mr. David Rizzardo created this factory redesign problem [Appendix 1]. The goal of the discussion was to improve upon the existing design which had trouble meeting delivery targets. For a detailed description of the design problem statement, see Appendix 1.

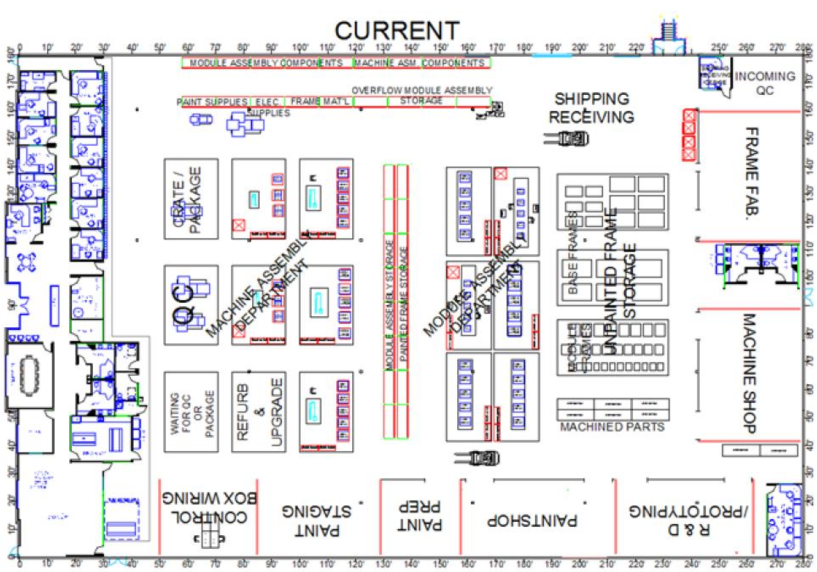

Figure 1: Current Factory Layout

3.5. *Data Collection Methods*

Other members of the research team collected the original video recordings and photographed the designs. A two-day lean facility design course was organized, where each team discussed the problem at length, and video cameras recorded the team's discussions (which took about four hours). The video cameras captured the layout that was being developed by the design teams. The camera was pointed towards the layout board, where the team drew the different areas, made changes to the layouts as the discussion progressed, and carried out other layout related activities [1].

The audio discussions from these recordings were used in combination with the visual information to understand the design strategy of each of the design teams. The final design layouts proposed by each of the teams were photographed and stored to serve as a basis of comparison across teams when comparing the quality of design solutions.

Chapter 4: Data Analysis

4.1.<u>Overview</u>

This chapter focuses on exploring the teams' discussions to understand how they decomposed the design problem. Analysis was done through a combination of qualitative and quantitative techniques that yielded clusters of variables and timelines describing when each team discussed each cluster.

This section includes the methods and algorithms used to code the design team discussions and analyze the codes obtained. This data was the basis for applying clustering algorithms to form subproblems. Once all the discussions were coded, different clustering algorithms were applied to explore an appropriate way to 'group' the variables discussed by the teams into clusters, thereby forming subproblems. For the clustering, two clustering techniques, namely: *Ward's Clustering and Spectral Clustering* were explored. Finally, a novel way to evaluate potential clusters was developed and used to identify and select strong clusters. This section describes how each of the clustering algorithms was applied and the results about each of the algorithms.

4.2.<u>Coding</u>

The teams' discussions were coded to extract the specific items that we could use to understand each team's decomposition strategy. The first step was to develop (identify) the variables that the teams discussed using techniques based on grounded theory [19,20], process mapping [21], and capturing them in a Microsoft Excel Spreadsheet. Each code sheet represents only the variables that the team discussed.

A codebook was created and maintained that listed all the variables that the teams discussed, precise definitions, and the rationale for developing these variables [Appendix - B]. Broadly, the variables used in this research can be classified based on the following properties: Many of the variables were related to the location, size, staffing, and internal layout of the functional areas in the factory (e.g. frame fabrication, paint, or machine assembly).

The code sheets were developed by observing the video of each design team's discussion and splitting the entire discussion into 2-minute time segments. Then, the variables that were discussed by the team in each time segment were recorded on the code sheet.

Let $a_{ij} = 1$, if variable *i* is discussed in time segment *j*

$a_{ij} = 0$, if variable *i* is not discussed in time segment *j*

Where every a_{ij} represents a cell in Microsoft Excel, pointing to the i^{th} variable and j^{th} time segment. Note that the code sheet did not include any variables that were never discussed by the design team.

4.2.1.Coding Results: Code Sheet

Based on the coding techniques described above, six code sheets were developed, one for each design team. The code sheet was developed such that the variables were listed in columns, and each row represented one 2-minute time segment. Table 2 shows a snippet of one of these code sheets.

Table 2: Code Sheet Sample (Team J)

2 Min Time Segments	Internal layout of assembly cell	Office layout details	Facility Staffing	Staffing in area - Frame Fab	Staffing in area - Paint	Staffing in area - Control Box Wiring
60						
62			1			
64			1			
66			1	1		
68				1	1	1
70				1	1	1
72				1	1	1
74						
76						
78						
80			1	1	1	
82			1			
84			1			
86						

Based on the sample presented in Table 2, the variable "Facility Staffing" is coded in time segment 62. This means "Facility Staffing" was discussed by the Design Team (Team J in this case) between minutes 62 and 64 of the discussion video.

4.2.2.Coding Results: Timelines

To better visualize the variables discussed throughout the discussion and to look for any patterns in the discussions, timelines were developed for each of the code sheets. The timelines followed the same two-minute time segments as in the code sheet. Each timeline shows, like the code sheet, only those variables that were discussed (at least once) in the discussion. The timelines show the variables as rows and time segments as columns. The number of segments coded can also be seen on the timeline. The first set of timelines were exploratory, to see if any early patterns emerged. A sample timeline for this can be seen in Table 3.

Table 3:Timeline Sample (Team J)

Variables	# Coded	170	172	174	176	178	180	182	184	186	188	190	192	194	196	198	200	202	204	206	208	210	212	214	216	218	220	222	224	226	228	230	232	234	236
Location of Inventory (Storage)	3																																		
location Incoming QC	3																																		
location machine shop	2																																		
location Frame Fab	3																																		
location paint staging	2																																		
location paint prep	2																																		
location control box assembly	4																																		
location of assembly cell	2																																		
location crate & packaging	3																																		
location R&D	2																																		
location of Gym	2																																		
location QC	1																																		
location production mgr Supervisor officer	3																																		
location of S&R office	1																																		
location refurbishment	2																																		
location of show room	3																																		
location of employee break and meeting room	1																																		
size of R&D	6																																		
size of refurn upgrade	1																																		
size machine shop	2																																		
Size of gym	2																																		
size of frame fabrication	2																																		
size of module assembly	1																																		
Size of Control Box Assembly	3																																		
Size of Crate and Packaging	1																																		
size of paint prep	1																																		
Size of QC	2																																		

In the timeline sample shown in Table 3, all the “Location” variables are grouped together (in orange) and the “Size” variables are grouped together (in blue). Even though there were some instances visible from these timelines where the variables of the same type were coded together, it was inconclusive because there were variables of other types that were coded during the same time segments (Time Segment 180 is an example). This issue of inconclusive subproblems has led to group variables by using other techniques to obtain more accurate results. In the next section, Ward and spectral clustering are introduced to cluster the variables and form subproblems.

4.3. <u>Clustering</u>

4.3.1. Ward’s Clustering

Ward’s clustering is a form of hierarchical clustering which uses a minimum distance metric to cluster variables [22]. For the context of this research, the Euclidian distance was used to calculate the pair-wise distance between each of the variables discussed by the teams. The ‘pdist’ function in MATLAB was used to calculate the Euclidian distance.

Based on these pair-wise distances between the identified variables, a dendrogram was plotted for each team to visualize the clusters identified by Ward's method. The rationale behind creating these clusters was that a lower value of the distance metric implied that the cluster was strong.

The results obtained by applying Ward's clustering to the data were not conclusive. The algorithm was unable to identify clear clusters effectively. The dendrograms obtained showed huge chunks of variables clustered together, with no clear demarcations. Figure 2 shows the results for Team X obtained on application of Ward's clustering algorithm. No strong clusters can be identified. Note that we define strong clusters as having a very small distance between the variables and a large distance between the cluster and any other cluster(s).

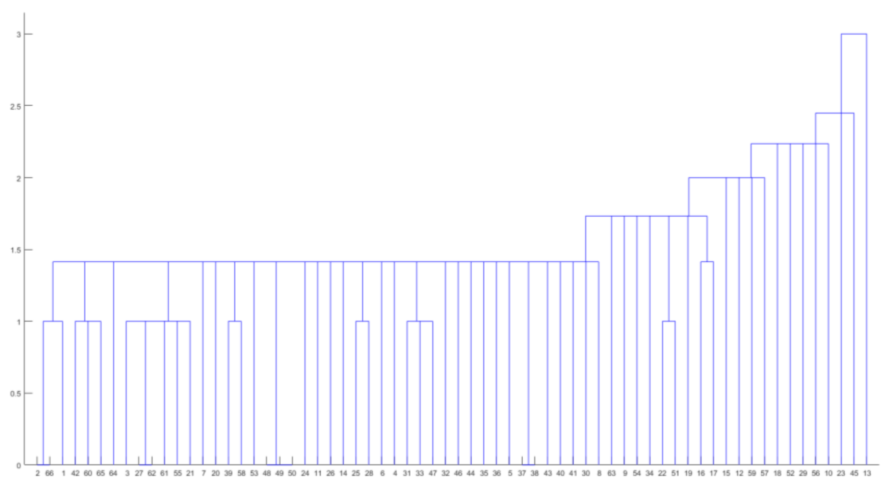

Figure 2: Wards Clustering Dendrogram (Team X)

4.3.2.Spectral Clustering

Since the Wards Clustering proved inconclusive, a different clustering algorithm was explored that would help better identify strong clusters in the data. Spectral Clustering was used, which makes use of eigenvalue spectrum of the data to perform dimensionality reduction before clustering in this reduced dimension space [23].

Application of this algorithm includes the following steps [4,5]:

a) Preparing the Input Matrix

b) Finding the Eigenvalues and Eigenvectors for the input matrix

c) Generation of reduced-dimension points

d) Clustering the reduced dimension points

e) Analysis of the obtained clusters

The first step in the process is to calculate the relative count for each pair of variables and create the relative count matrix A.

We will use the following notation:

n(i): number of time segments in which variable i was discussed

n(i,j): number of time segments in which both variable i and variable j were discussed

s(i,j): number of time segments in which either variable i, variable j, or both, were discussed.

Thus,

$$s(i,j) = n(i) + n(j) - n(i,j) \tag{1}$$

a(i,j): each element of this matrix A

Then,

$$a(i,j) = \frac{n(i,j)}{s(i,j)} \tag{2}$$

This is denoted as the relative count. (We set a(i,i)=0)

If a(i,j)=0 for all j, then variable i is removed from consideration (it was not concurrent with any other variables.) Let r be the number of variables remaining.

Next, the eigenvectors and eigenvalue spectrum are determined for A, which yields two additional matrices, D and V. D is the $r \times r$ diagonal matrix of the eigenvalues. V is the $r \times r$ matrix of eigenvectors.

Now to generate the reduced-dimension points, a plot of the eigenvalue spectrum is generated, and the k largest eigenvalues are identified. This was done by observation, and the k largest eigenvalues were selected such that there is a significant gap between the k^{th} largest eigenvalue and the $k+1^{st}$ largest eigenvalue.

Another matrix U is created, that contains the eigenvectors for the k largest eigenvalues a diagonal matrix S is also created, containing the corresponding eigenvalues. Then, the product U×S is a set of points in a k-dimensional space, and each point corresponds to one variable.

The points are clustered by calculating the Euclidean distances between every pair of points in this reduced-dimension space and (using the MATLAB function "linkage") to generate a hierarchical binary cluster tree, which can be visualized as a dendrogram. The dendrogram and the relative count matrix are then used together to make decisions about identification of strong clusters, which is discussed in the next section.

4.3.3.Cluster Selection

The dendrograms were used to explore identified clusters of variables and a novel way to evaluate potential clusters in terms of their strength was developed. The goal was to select meaningful clusters of concurrent variables that likely represent the subproblems considered by the teams.

In this selection process, the data was explored, potential clusters were quantitatively evaluated, and clusters were selected using engineering judgment. Thus, the procedure involved a human element and was not completely automated.

Because the concurrency of the variables is the key characteristic of variables in the same subproblem, and concurrency can be measured by relative count, a measure called "cluster strength" was defined, which is the average relative count of the pairs of variables in a cluster. (This can also be viewed as a measure of the similarity of the variables in a cluster.) This metric is different from the pair-wise distance that was used in spectral clustering.

The selection procedure began with the dendrogram created by the spectral clustering technique. Individual variables were combined into clusters one at a time (or combined two clusters) and the new cluster created at each step was evaluated to calculate the average cluster strength. This was repeated until one cluster remained.

	13	14	10	18	31	29	11
13	0	1	0.33	0.25	0.25	0.2	0.5
14	1	0	0.33	0.25	0.25	0.2	0.5
10	0.33	0.33	0	0.17	0.17	0.14	0.25
18	0.25	0.25	0.17	0	0.14	0.13	0.2
31	0.25	0.25	0.17	0.14	0	0.29	0.2
29	0.2	0.2	0.14	0.13	0.29	0	0.17
11	0.5	0.5	0.25	0.2	0.2	0.17	0

Figure 3: Snippet of Relative Count Matrix

Let C be the set of variables in a cluster. Let S_C be the average relative count (strength) of the cluster, which is equal to the following expression:

$$S_C = \frac{\sum_{i \in C} \sum_{j \in C} a(i,j)}{|C| \times (|C| - 1)} \tag{3}$$

For instance, if cluster C has variables 13 and 14 (shown in Figure 3), then its strength (using equation 3) $S_C = (1 + 1)/2 = 1$. If variable 10 is added to the cluster, then its strength becomes (using Equation 3):

$$\frac{(1 + 1 + 4 \times 0.33)}{(3 \times 2)} = 0.55$$

In general, the strength of a cluster is decreased (or slightly increased) when a new variable is added to the cluster (or two clusters are combined). The strength of the largest clusters was low. Using a single threshold to identify the clusters that were combined at a height below that threshold in the dendrogram yielded some clusters with a large strength and some with a low strength.

The clusters with low strength included variables that were concurrent with very few other variables, so most of the relative count values were zero; thus, they were similar enough to be grouped together by the spectral clustering algorithm.

These variables were not concurrent; however, and thus such clusters were not meaningful. Thus, the cluster strength was used as a way of selecting the most meaningful clusters from the dendrograms for the six design teams. The strength of every selected cluster was at least 0.3 (decided based on judgement).

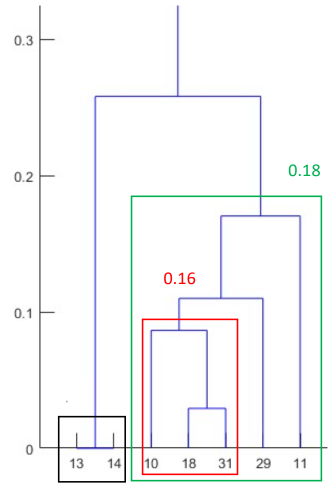

Figure 4: Snippet of Dendrogram

For example, Figures 3 and 4 display information about seven variables from one of the design teams. Figure 3 shows the relative counts for the variables. Figure 4 shows part of the dendrogram created by clustering the entire set of variables where three clusters that were combined at different heights and their corresponding strengths. The strength of the cluster with variables 13 and 14 equals 1.

Variables 10, 18, and 31 form another cluster; its strength equals 0.16. When variables 29 and 11 are added to this cluster, the strength increases slightly to 0.18. Finally, when the entire cluster is combined with variables 13 and 14, the strength of the resulting cluster equals 0.30.

4.4. Clustering Results

4.4.1. Spectral Clustering Results

Team J:

The eigenvalue spectrum for Team J can be seen in Figure 5. The first eigenvalue is significantly larger than all other eigenvalues, thus, k = 1 is a viable selection. However, it should be noted that k = 1 corresponds to just one cluster, and from the spectrum plot, the 2nd, 3rd, 4th, and 5th eigenvectors are also significantly larger than all eigenvectors from 5 onwards. Thus, k = 2,3,4,5 can also be viable choices for reducing dimensions.

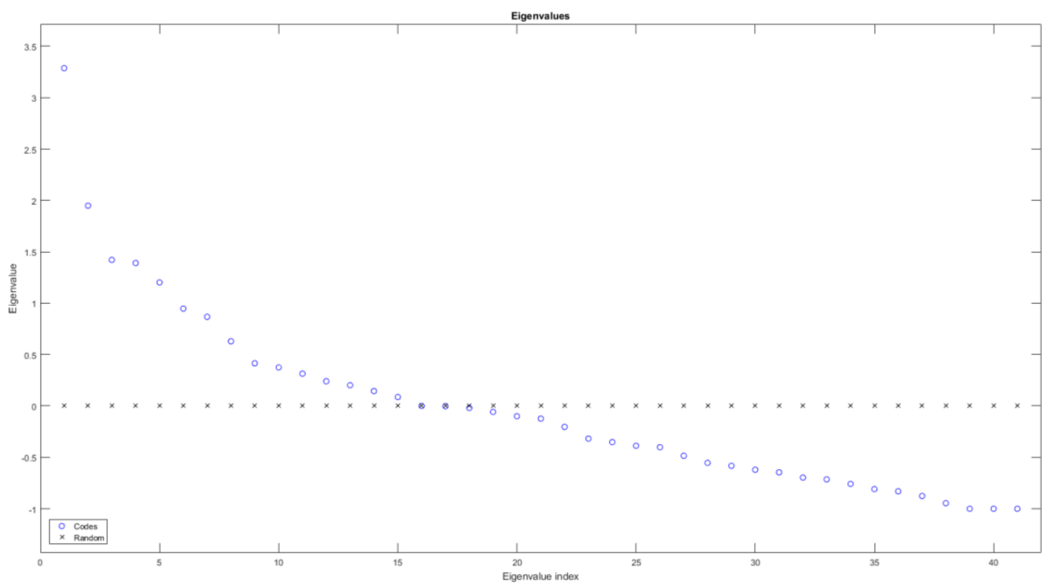

Figure 5: Eigenvalue Spectrum for Team J

The dendrograms for the reduced dimension points were also plotted. Each dendrogram provided an increasing level of detail into the clusters until k = 5 after which there is minimal change in the detail offered by the dendrograms. Thus, k = 5 was picked for dimension reduction. The dendrogram for this selection can be seen in Figure 6.

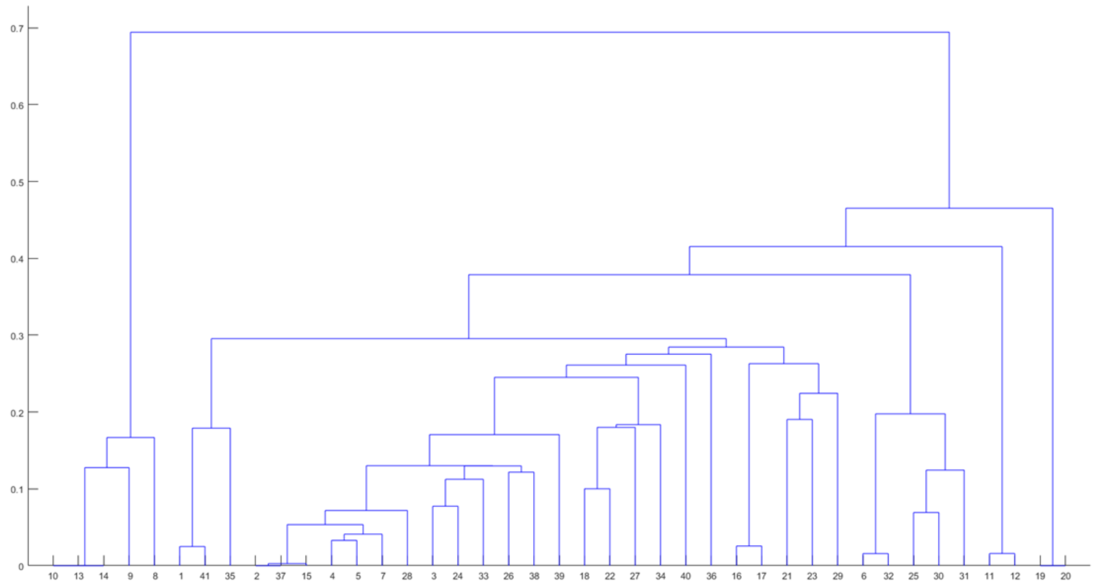

Figure 6: Dendrogram for Team J with k = 5

In addition to creating the dendrograms, the relative count matrix was also recorded which shows the strength of each pair of variables coded in Team J. This matrix for Team J can be seen in Figure 7.

	10	13	14	9	8	1	41	35	2	37	15	4	5	7	28	3	24	33	26	38	39	18	22	27	34	40	36	16	17	21	23	29	6	32	25	30	31	11	12	19	20
10	0	1	1	0.75	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0.18	0	0
13	1	0	1	0.75	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0.18	0	0
14	1	1	0	0.75	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0.18	0	0
9	0.75	0.75	0.75	0	0.8	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16	0.17	0	0
8	0.6	0.6	0.6	0.8	0	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0.16	0	0
1	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0.5	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0.25	0.5	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0.5	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.33	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0.18	0	0
5	0	0	0	0	0	0	0	0	0	0	0.08	0.08	0	0	0	0.29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.12	0.12	0	0
7	0	0	0	0.07	0.14	0	0	0	0.09	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0.04	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0.29	0	0	0	0	0	0	0	0	0.11	0.13	0	0	0	0	0.11	0.13	0	0	0	0	0	0	0	0	0.09	0.04	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0.25	0	0.25	0	0	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.33	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0.25	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0.33	0	0	0.2	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0.25	0	0	0	0	0	0.25	0	0.25	0	0.25	0.2	0.25	0	0	0	0	0	0	0	0	0	0	0.25	0.25
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0.25	0	0.25	0	0	0	0.25	0.33	0	0	0	0	0	0	0	0	0	0	0.33	0.33
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0.25	0	0	0.2	0	0	0.25	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0.25	0.25
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0.33	0	0	0.2	0.25	0	0	0	0	0	0	0	0	0.33	0.33
40	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0.33	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0.25	0	0	0.2	0	0.2	0.25	0.2	0	0	0	0	0.67	0.17	0.2	0.25	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0.25	0.33	0	0	0	0	0.67	0	0.2	0.25	0.33	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0.25	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0	0.2	0	0	0.17	0.2	0	0.75	0.2	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0.25	0	0	0.2	0.25	0.75	0	0.25	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0.25	0.33	0.2	0.25	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.86	0.29	0.43	0.14	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.86	0	0.33	0.29	0.17	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.29	0.33	0	0.25	0.5	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.43	0.29	0.25	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0.17	0.5	0	0	0	0	0	0
11	0.17	0.17	0.17	0.16	0.15	0	0	0	0	0	0	0.17	0.12	0.04	0	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.94	0	0
12	0.18	0.18	0.18	0.17	0.16	0	0	0	0	0	0	0.18	0.12	0.04	0	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.94	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.33	0.25	0.33	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	1
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.33	0.25	0.33	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Figure 7: Relative Count with Clusters for Team J with k = 5

The relative count matrix helped us to identify strong clusters. The matrix when created in combination with the dendrogram, was rearranged such that the variables were listed in the same order as they appear in the dendrogram (grouped in clusters) so that it is easier to visualize clusters along the diagonal of the matrix. Then, the clusters selected based on the cluster selection matrix (described in Chapter 6). For completeness, the Figure 7 identifies these clusters with black borders.

As can be seen from the relative count matrix, there are a few very strong clusters. Variables 10, 13, and 14 form a very strong cluster since they are only coded together and are never coded separately (Relative count = 1). This is confirmed by the dendrogram too, since in Figure 4 these variables have 0 distance from each other. Variables 19 and 20 also have a relative count = 1. In addition, there are a few other clusters too, though they are not as strong as the ones mentioned above. All these clusters are marked with a dark border in Figure 7.

Looking at the corresponding clusters in the dendrogram, it is interesting to note that a few clusters that seemed to be apparent from the dendrogram (like 18-22-34-36, or 4-5-7) were not identified in the Relative Count Matrix, meaning they are not strong clusters. Thus, such clusters were not selected as acceptable subproblems for this research.

Once these clusters were identified, a new set of timelines were created with all these clustered variables to better visualize how closely the variables had been coded to group them as 'subproblems'.

Table 4: Timeline Snippet 1 for Team J

Variable	2 Min Time Segments	176	178	180	182	184
19	location paint staging					
20	location paint prep					

As can be seen from Table 4, the variables 19 and 20 (Location of Paint Staging and Location of Paint Prep) are coded together in time segments 178 – 182. Also, they are never coded separately, so this accounts for a very strong cluster.

Table 5: Timeline Snippet 2 for Team J

Variable	2 Min Time Segments	60	62	64	66	68	70	72	74	76	78	80
8	Staffing in area - Frame Fab											
9	Staffing in area - Paint											
10	Staffing in area - Control Box Wiring											
13	Staffing in area - Crate and Package											
14	Staffing in area - QC											

As can be seen from Table 5, Variables 10, 13, and 14 are coded together exclusively. In addition, variables 8 and 9 also can be clustered together and are close enough to the cluster 10-13-14 as can be seen in the timeline as well as the relative count matrix. Thus, these group of variables form a strong cluster.

Table 6: Timeline Snippet 3 for Team J

Variable	2 Min Time Segments	184	186	188	190	192	200	230	232	234	236
1	Aisle Space										
41	Size of QC										
35	Size of Gym										

In Table 6, Variables 1, 35, and 41 form a cluster since even though they are coded very few times, they are all coded together in time segment 190.

Table 7: Timeline Snippet 4 for Team J

Variable	2 Min Time Segments	174	176	178	180	182	184	186	188	190	192	194	196	198	220
16	location Incoming QC														
17	location machine shop														
21	location control box assembly														
23	location crate & packaging														
29	location refurbishment														

In Table 7, the variables 16, 17, 21, 23, and 29 corresponding to location of various areas are clustered together. Based on visual inspection from the timeline all these variables are coded together in time segment 182.

Time segments 184 and 186 also see variables 21 and 23 being coded together. Based on this observation and the relative count numbers from Figure 4, this is an acceptable cluster.

Table 8: Timeline Snippet 5 for Team J

Variable	2 Min Time Segments	190	192	194	196	198	200	202	204	206	208	210
6	Office layout details											
32	size of R&D											
25	location of Gym											
30	location of show room											
31	location of employee break and meeting room											

As can be seen from Table 8, the variables 6, 25, 30, 31, and 32 are coded together in different combinations through the time segments 194 – 208. Only during time segments 196 – 200 is the variable 32 coded alone. This accounts for a strong cluster and is in accordance with the relative count matrix.

Table 9: Timeline Snippet 6 for Team J

Variable	2 Min Time Segments	66	68	70	72	74	114	116	118	120	122	124	126	128	130	132	134	136	138	140	142	144	146	148	150
11	Staffing in area - Module Assembly																								
12	Staffing in area - Machine Assembly																								

Table 9 shows another strong cluster identified in the relative count matrix. Variables 11 and 12 (Staffing in areas – Module Assembly and Machine Assembly) are coded together almost exclusively, just missing one time-segment where only one of them was discussed. This is clearly, a strong cluster.

<u>Team K:</u>

The eigenvalue spectrum for Team K can be seen in Figure 8. As can be seen from the figure, the third eigenvalue is significantly larger than all other eigenvalues, thus, k = 3 is a viable selection. However, it should be noted that from the spectrum plot, the 4th, 5th, and 6th eigenvalues are also significantly larger than all eigenvectors from 6 onwards. Thus, k = 6 can also be viable choices for reducing dimensions.

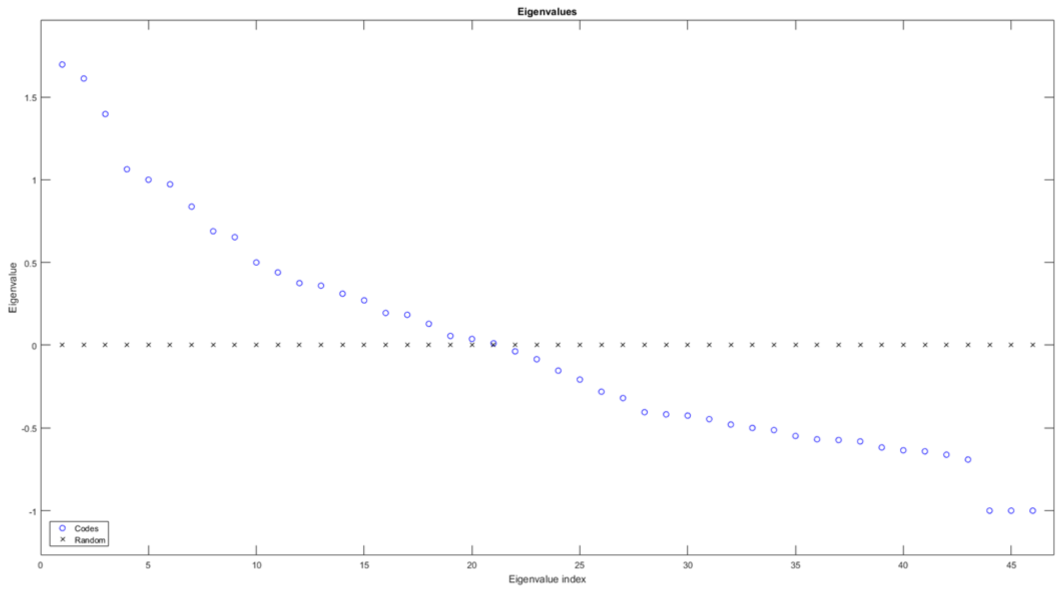

Figure 8: Eigenvalue Spectrum for Team K

The dendrograms for the reduced dimension points were also plotted. Each dendrogram provided an increasing level of detail into the clusters until k = 6 after which there is minimal change in the detail offered by the dendrograms. Thus, k = 6 is picked for dimension reduction. The dendrogram for this can be seen in Figure 9.

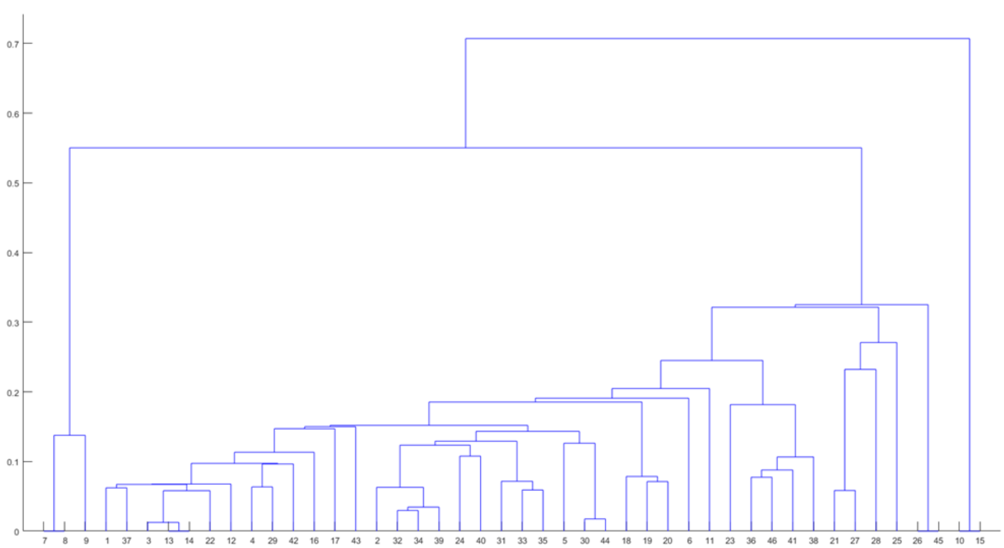

Figure 9: Dendrogram for Team K with k = 6

In addition to creating clusters, the relative count matrix was also recorded which shows strength of each pair of variables coded in Team K. This matrix for Team K has been split into two parts to ensure readability and can be seen in Figures 10 & 11.

	7	8	9	1	37	3	13	14	22	12	4	29	42	16	17	43	2	32	34	39	24
7	0.00	1.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.00	0.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.67	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.22	0.05	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.22	0.00	0.20	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.20	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.33	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.25
32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.25	0.00	0.00
34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.33	0.00
39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00
40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00
31	0.00	0.00	0.00	0.20	0.25	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.17	0.17	0.00	0.00	0.00
33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.40	0.17	0.00
35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00
5	0.00	0.00	0.00	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.17	0.13	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00
11	0.14	0.14	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00
46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
38	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.25	0.00	0.00	0.00	0.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.13	0.17	0.00	0.17	0.13	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.50
26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 10: Relative Count with Clusters for Team K with k = 6 (1)

	40	31	33	35	5	30	44	18	19	20	6	11	23	36	46	41	38	21	27	28	25	26	45	10	15
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.20	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
37	0.00	0.25	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.05	0.05	0.00	0.06	0.10	0.05	0.05	0.05	0.00	0.11	0.05	0.00	0.05	0.00	0.00	0.04	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00
42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.17	0.00	0.00	0.00	0.00	0.00
43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.17	0.00	0.20	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00
2	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00
32	0.00	0.17	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39	0.33	0.00	0.17	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00
40	0.00	0.00	0.00	0.25	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.17	0.00	0.00	0.00	0.00	0.00
31	0.00	0.00	0.13	0.17	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00
33	0.00	0.13	0.00	0.14	0.04	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.17	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00
35	0.25	0.17	0.14	0.00	0.05	0.14	0.14	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00
5	0.05	0.05	0.04	0.05	0.00	0.20	0.26	0.04	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.05	0.09	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.14	0.20	0.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
44	0.00	0.00	0.00	0.14	0.26	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.60	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.60	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.40	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.20	0.17	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.50	0.25	0.14	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00
36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.33	0.00	0.50	0.25	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.00	0.33	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.25	0.33	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
38	0.00	0.11	0.10	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.14	0.14	0.17	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.14	0.17	0.33	0.33	0.00	0.00
27	0.25	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.33	0.17	0.33	0.33	0.00	0.00
28	0.17	0.00	0.00	0.00	0.09	0.00	0.00	0.11	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.33	0.00	0.13	0.20	0.20	0.00	0.00
25	0.00	0.14	0.13	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.17	0.17	0.13	0.00	0.25	0.25	0.00	0.00
26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.33	0.20	0.25	0.00	1.00	0.00	0.00
45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.33	0.20	0.25	1.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00

Figure 11: Relative Count with Clusters for Team K with k = 5 (2)

The relative count matrix when created in combination with the dendrogram, was rearranged such that the variables were listed in the same order as they appear in the dendrogram (grouped in clusters) so that it is easier to visualize clusters along the diagonal of the matrix. Then, the clusters selected based on the cluster selection matrix (described in Chapter 6). For completeness, the Figure 10 and 11 identify these clusters with black borders.

As can be seen from the relative count matrix, there are a few very strong clusters. Variables 10 and 15 form a very strong cluster since they are only coded together and are never coded separately (Relative count = 1), as do variables 26 and 45; and 7 and

8. This is confirmed by the dendrogram too, since in Figure 8 these variables are at 0 distance from each other. In addition, there are a few other clusters too, though they are not as strong as the ones mentioned above. These can be identified as highlighted in Figure 10.

Once these clusters were identified, a new set of timelines were created with all these clustered variables and any other 'frequently coded variables' that were not included as a part of any of these clusters, to better visualize how closely the variables had been coded to group them as 'subproblems'.

Table 10: Timeline Snippet 1 for Team K

V. No	Variable	76	78	80	230	232	234	236	238
7	Staffing in area - Frame Fab								
8	Staffing in area - Paint								
9	Staffing in area - Control Box Wiring								

Table 11: Timeline Snippet 2 for Team K

D.No	Variable	234	236	238	240
10	Staffing in area - Machine Shop				
15	Staffing in area - Material Handling				

Table 12: Timeline Snippet 3 for Team K

V. No	Variable	162	164	166	168	170
26	location paint staging					
45	size of paint prep					

As can be seen from Table 10, the variables 7, 8, and 9 (Staffing in areas – Frame Fab, Paint, and Control Box Wiring) are coded together in time segments 78 – 80 and 232 – 234. Also, two of them are coded together in 234 – 236. Variables 7 and 8 are never coded separately, hence the relative count value of 1. Also, variables 10 and 15 (Table 11) and variables 26 and 45 (Table 12) form a Strong cluster since they are coded only once (and together) in the time segment shown.

Table 13:Timeline Snippet 4 for Team K

V. No	Variable	80	82	224	226	228
13	Staffing in area - Crate and Package					
14	Staffing in area - QC					

Table 13 shows another cluster that was identified in the relative count matrix and the corresponding dendrogram. Variables 13 and 14 are coded together once in the time segment 82. In addition, variable 13 is coded in time segment 226 too, without variable 14.

Table 14:Timeline Snippet 5 for Team K

V. No	Variable	104	106	108	110	112	122	124	126	128	130	132	134	140	142	144	146	148	150	152	154	156	178	180	182	184	186
30	location machine assembly																										
44	size of machine assembly																										
5	Internal layout of Machine assembly Cell																										

In Table 14, an interesting cluster is depicted containing variables 5, 30, and 44. The variables are coded together in multiple time segments (124, 126, 178, 180). In addition, the variables are coded many more times, however not always together. However, the segments when they are coded together contribute significantly to the cluster strength and thus this cluster can be classified as a strong cluster.

Table 15: Timeline Snippet 6 for Team K

V. No	Variable	98	100	102	128	130	156	158	186	188	190	192
18	Location of Inventory (Drive Storage)											
19	Location of Staging Modules											
20	Location of Electrical Supplies											

Table 15 identifies another cluster which has location variables. Variables 18, 19, and 20 are all coded together in the time segment 128. Combinations of two of these variables are also coded together in other time segments (segments 156, 188, and 190). Thus, this cluster is acceptable.

Table 16: Timeline Snippet 7 for Team K

V. No	Variable	70	72	128	130	132	134	136	138	160	162	164	198	200	210	212
23	location Incoming QC															
36	location production mgr Supervisor officer															
46	Size of QC															
38	location refurbishment															
41	size of refurbish															

Table 16 presents a similar cluster as Table 15. Variables 23, 36, 38, 41, and 46 are all coded together in the time segment 200. Combinations of two of these variables are also coded together in other time segments (segments 136, 138). Thus, this cluster is acceptable.

Team L:

The eigenvalue spectrum for Team L can be seen in Figure 12. As can be seen from the figure, the fourth eigenvalue is significantly larger than all other eigenvalues, thus, k = 4 is a viable selection. However, it should be noted that from the spectrum plot, the 5th eigenvalue is also significantly larger than all eigenvalues from 6 onwards. Thus, k = 5 can also be a viable choice for reducing dimensions.

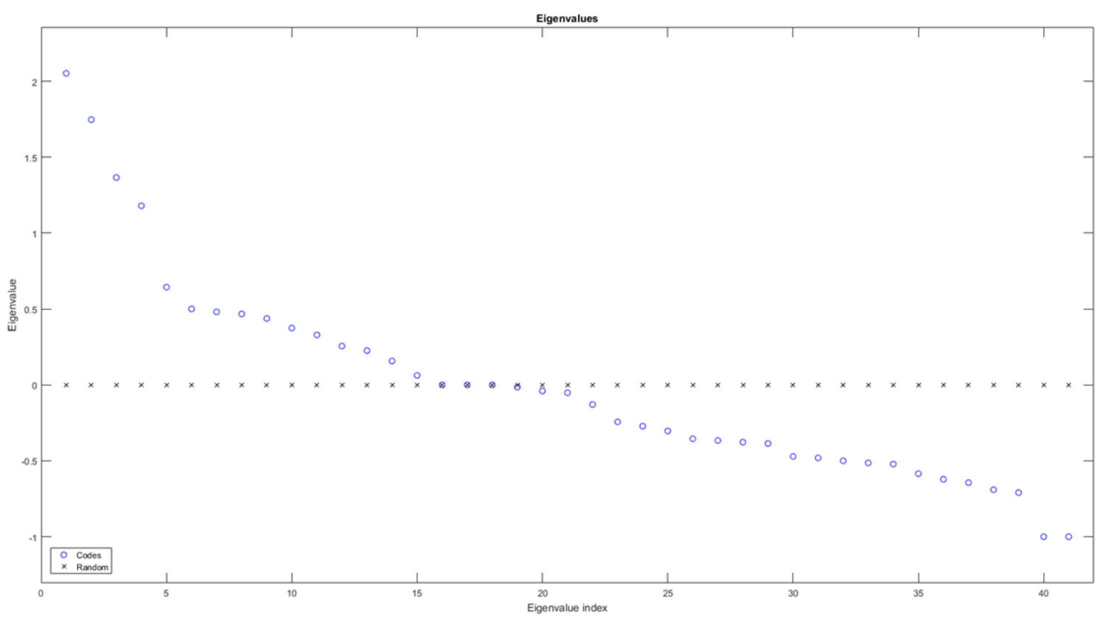

Figure 12: Eigenvalue Spectrum for Team L

The dendrograms for the reduced dimension points were also plotted. Each dendrogram provided an increasing level of detail into the clusters until k = 5 after which there is minimal change in the detail offered by the dendrograms. Thus, k = 5 is picked for dimension reduction. The dendrogram for this selection can be seen in Figure 13.

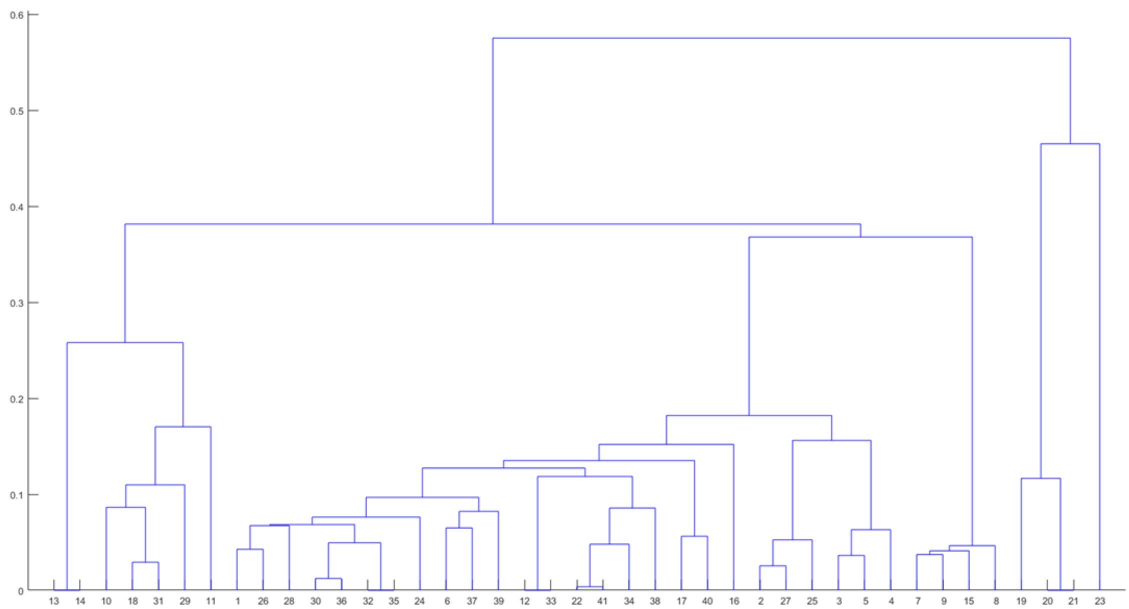

Figure 13: Dendrogram for Team L with k = 5

In addition to creating dendrograms, the relative count matrix was also recorded which shows the strength of each pair of variables coded in Team L. This matrix for Team L can be seen in Figure 14.

	13	14	10	18	31	29	11	1	26	28	30	36	32	35	24	6	37	39	12	33	22	41	34	38	17	40	16	2	27	25	3	5	4	7	9	15	8	19	20	21	23
13	0	1	0.33	0.25	0.25	0.2	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
14	1	0	0.33	0.25	0.25	0.2	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
10	0.33	0.33	0	0.17	0.17	0.14	0.25	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14
18	0.25	0.25	0.17	0	0.14	0.13	0.2	0	0	0	0.2	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13
31	0.25	0.25	0.17	0.14	0	0.29	0.2	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13
29	0.2	0.2	0.14	0.13	0.29	0	0.17	0.14	0	0.33	0	0	0	0	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.07	0.08	0	0	0	0	0	0	0	0.11
11	0.5	0.5	0.25	0.2	0.2	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17
1	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08	0.1	0	0	0	0	0	0	0	0
30	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0.1	0.09	0	0.11	0	0	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0	0.11	0	0	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.09	0.09	0.09	0.1	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0
39	0	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0.18	0.1	0	0	0.25	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.33	0.14	0.1	0.13	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0.17	0.22	0.08	0.2	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.17	0	0.11	0.08	0.1	0	0	0	0	0	0	0	0.14
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0.14	0.22	0.11	0	0.31	0.5	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0.07	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.18	0.1	0.08	0.08	0.31	0	0.5	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0.08	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.13	0.2	0.1	0.5	0.5	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.09	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33	0.5	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0.09	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0.33	0.5	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.09	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0	0	0.33	0.33	0	0.5	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0.67	0.67	0.33
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.67	0	1	0.4
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.67	1	0	0.4
23	0.2	0.2	0.14	0.13	0.13	0.11	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0.33	0.4	0.4	0

Figure 14: Relative Count with Clusters for Team L with k = 5

The relative count matrix when created in combination with the dendrogram, was rearranged such that the variables were listed in the same order as they appear in the dendrogram (grouped in clusters) so that it is easier to visualize clusters along the diagonal of the matrix. Then, the clusters selected based on the cluster selection matrix (described in Chapter 6). For completeness, the Figure 14 identifies these clusters with black borders.

As can be seen from the relative count matrix in Figure 14, there are a few very strong clusters. Variables 13 and 14 form a very strong cluster since they are only coded together and are never coded separately (Relative count = 1), as do variables 20 and 21. This is confirmed by the dendrogram too, since these variables are at 0 distance from each other. In addition, there are a few other clusters too, though they are not as strong as the ones mentioned above. These can be identified as highlighted in Figure 14.

Once these clusters were identified, a new set of timelines were created with all these clustered variables and any other 'frequently coded variables' that were not included as a part of any of these clusters, to better visualize how closely the variables had been coded to group them as 'subproblems'.

Table 17:Timeline Snippet 1 for Team L

V.No	Variable	118	120	122	124
13	Staffing in area - Crate and Package				
14	Staffing in area - QC				

Table 18:Timeline Snippet 2 for Team L

V.No	Variable	118	120	122	124
32	Location R&D Prototyping				
35	size machine shop				

As can be seen from Table 17 and 18, the variables 13 and 14 (Staffing in areas) and variables 32 and 35 are coded together in time segments 120 and 122 respectively. They are never coded separately, hence the relative count value of 1 and a strong cluster strength.

Table 19: Timeline Snippet 5 for Team L

V.No	Variable	144	146	148	150	152	168	170	186	194	196	198	200	202	204	206	208	214	216	228	230	232	234
3	Internal layout of module assembly																						
5	Internal layout of assembly cell																						
4	Internal layout of Machine assembly																						

Table 19 presents a cluster with many variables coded very often. The main reason these variables can be considered a cluster is because they are all coded together in time segments 200 – 204. In other instances, they are coded in some combinations of pairs almost every time except time segment 146 and segments 230-234. Hence, this can be considered as a cluster for our analysis.

Table 20: Timeline Snippet 6 for Team L

V.No	Variable	58	60	62	112	114	116	118	120	190	192	194
7	Staffing in area - Frame Fab											
9	Staffing in area - Control Box											
15	Location of Inventory (Storage)											
8	Staffing in area - Paint											

Table 21: Timeline Snippet 7 for Team L

V.No	Variable	108	110	112	114	116	118	120	122	124	126	150	152	154
19	location Frame Fab													
20	location paint staging													
21	location paint prep													
23	location machine shop													

Table 20 presents variables that were coded together in one segment (predominantly staffing variables) while Table 21 shows variables coded together in two segments (location variables) and never else. The instances when the variables were not coded together reduce the overall cluster strength of these clusters.

Team X:

The eigenvalue spectrum for Team X can be seen in Figure 15. As can be seen from the figure, the first four eigenvalues are significantly larger than all other eigenvalues, thus, k = 4 is a viable selection. However, it should be noted that from the spectrum plot, k = 6 or 7 can also be viable choices for reducing dimensions.

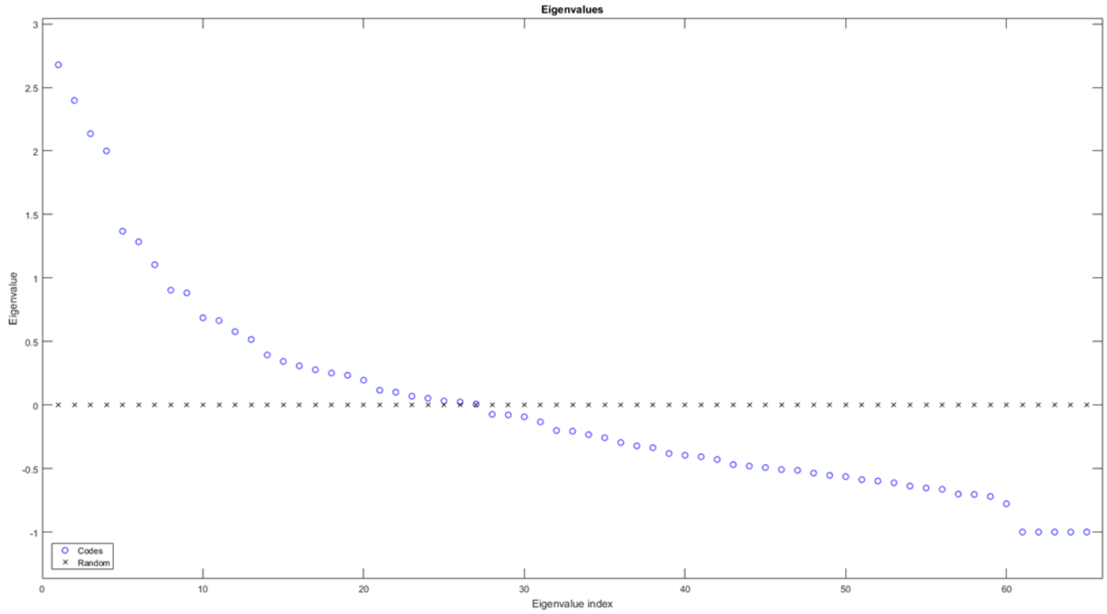

Figure 15: Eigenvalue Spectrum for Team X

The dendrograms for the reduced dimension points were also plotted. Each dendrogram provided an increasing level of detail into the clusters until k = 6 after which there is minimal change in the detail offered by the dendrograms. Thus, we picked k = 6 for dimension reduction. The dendrogram for this selection can be seen in Figure 16.

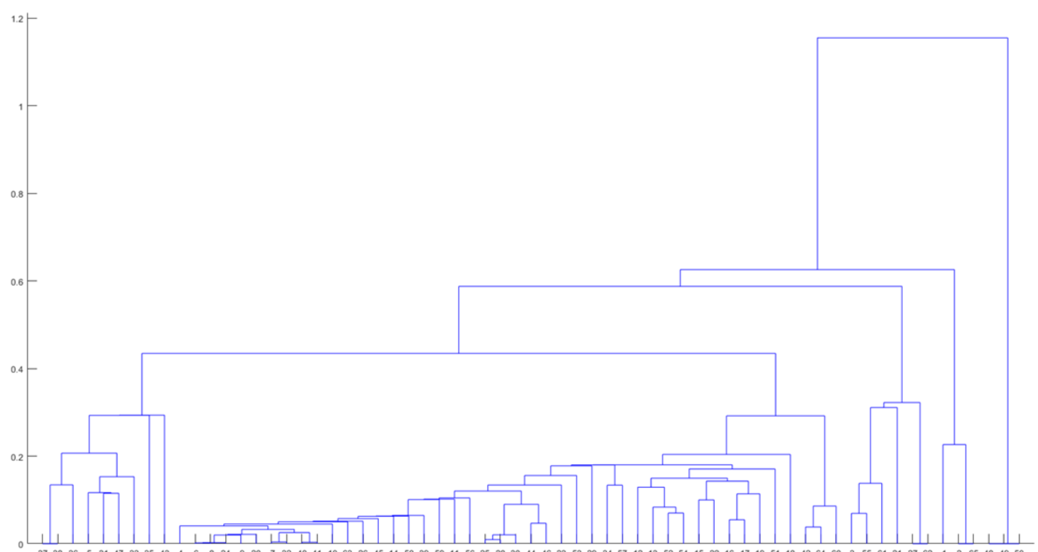

Figure 16: Dendrogram for Team X with k = 6

In addition to creating clusters, the relative count matrix was also recorded which shows the strength of each pair of variables coded in Team X. This matrix for Team X has been split into two separate figures to ensure readability and can be seen in Figure 17 and Figure 18.

	37	38	36	5	31	47	33	35	43	4	6	8	24	9	20	7	32	40	41	10	63	26	45	14	58	39	59	11	56	25	28	30	44	46
37	0	1	0.5	0.2	0.3	0.3	0.3	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	1	0	0.5	0.2	0.3	0.3	0.3	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0.5	0.5	0	0.2	0.3	0.3	0.3	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.2	0	0	0	0	0	0
5	0.2	0.2	0.2	0	0.3	0.3	0.3	0.2	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0	0	0
31	0.3	0.3	0.3	0.3	0	0.3	0.5	0.3	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.3
47	0.3	0.3	0.3	0.3	0.3	0	0.5	0.3	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0.3	0.3	0.3	0.3	0.5	0.5	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0.2	0.2	0.2	0.4	0.2	0.2	0.3	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0.3	0	0	0	0.4	0	0	0	0	0	0	0.1	0	0.1	0	0	0	0.2	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.4	0	0	0	0	0	0	0.1	0	0	0	0	0	0.1	0	0.2	0	0	0	0	0
63	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0.1	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0.3	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0
59	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0.1	0.3	0	0	0	0	0
11	0	0	0.2	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.1	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0.2	0.2	0	0.2	0	0	0	0.3	0	0	0	0	0	0	0
25	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0
28	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0.3	0	0
30	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0.2
44	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0.2	0	0.3	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0
23	0	0	0	0.3	0.1	0	0	0	0.2	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3
29	0.1	0.1	0.1	0.1	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0.2	0.1	0	0
34	0.2	0.2	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.1	0.3	0	0	0	0	0	0
57	0.2	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.2	0.2	0.1	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0.1	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0.1
52	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.3	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0.2	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0.1	0	0	0	0	0	0.1	0	0	0	0	0
51	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0.1	0.1	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0.1	0	0.3	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3
64	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.2	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 17: Relative Count with Clusters for Team X with k = 6 (1)

	23	53	29	34	57	12	13	52	54	15	22	16	17	19	51	18	42	64	60	3	55	61	21	27	62	1	2	65	48	49	50
37	0	0	0.1	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0.1	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0.1	0.4	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0.3	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0.1	0	0.3	0.1	0	0.2	0.2	0.1	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0.2	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.3	0.5	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0.1	0	0.1	0.1	0	0	0	0	0	0	0	0.1	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0.2	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0.1	0.2	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0.3	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0.1	0	0.3	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0
25	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0.1	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0.1	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0
46	0.1	0.3	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0.2	0.1	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0.2	0	0	0.2	0	0.2	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0.2	0	0	0.1	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0.1	0	0.1	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0.1	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.1	0	0.3	0	0	0	0.1	0.1	0	0	0.2	0.1	0.1	0.1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0.2	0	0	0	0.1	0	0.1	0.2	0.3	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0.1	0.1	0	0	0	0.1	0.2	0.4	0.2	0.1	0.1	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0
54	0	0	0	0	0	0	0.2	0	0	0.2	0	0.2	0.2	0.1	0.3	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0.2	0	0	0	0	0.3	0	0.2	0	0.2	0.3	0.1	0.2	0.3	0.2	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0.2	0.1	0.1	0	0.2	0	0.2	0.2	0.3	0.7	0.1	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0
16	0	0.2	0	0	0	0.1	0.1	0.2	0.2	0.3	0.2	0	0.6	0.3	0.4	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0.1	0.1	0.4	0.2	0.1	0.2	0.6	0	0.3	0.4	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0.1	0.1	0.2	0.2	0.1	0.2	0.3	0.3	0.3	0	0.5	0.4	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0.2	0.2	0.1	0.3	0.3	0.7	0.4	0.4	0.5	0	0.3	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0
18	0	0	0	0	0.3	0	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.4	0.3	0	0	0	0	0.1	0	0	0.1	0	0	0	0	0	0	0	0
42	0	0.3	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0.5	0.3	0	0	0	0	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0
60	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0.5	0.3	0.3	0.3	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0.3	0.5	0.5	0	0	0	0	0	0
21	0	0	0	0	0	0	0.1	0	0	0.1	0.3	0	0	0.1	0.2	0.1	0	0	0	0.3	0.3	0.3	0	0.7	0.7	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0	1	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	1	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	1	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0

Figure 18: Relative Count with Clusters for Team X with k = 6 (2)

The relative count matrix when created in combination with the dendrogram, was rearranged such that the variables were listed in the same order as they appear in the dendrogram (grouped in clusters) so that it is easier to visualize clusters along the diagonal of the matrix.

Then, the clusters selected based on the cluster selection matrix (described in Chapter 6). For completeness, the Figures 17 and 18 identify these clusters with black borders.

As can be seen from the relative count matrix in Figure 17 and Figure 18, there are a few very strong clusters. Variables 48, 49 and 50 form a very strong cluster since they are only coded together and are never coded separately (Relative count = 1), as do variables 37 and 38; 27 and 62; and 2 and 65. This is confirmed by the dendrogram too, since in Fig 3 these variables are at 0 distance from each other. In addition, there are a few other clusters too, though they are not as strong as the ones mentioned above. All these clusters are marked with a dark border in Figure 17 and Figure 18.

Once these clusters were identified, a new set of timelines were created with all these clustered variables and any other 'frequently coded variables' that were not included as a part of any of these clusters, to better visualize how closely the variables had been coded to group them as 'subproblems'.

Table 22: Timeline Snippet 1 for Team X

V.No	Variable	188	190	192	194
48	location of lockers				
49	location of employee break and meeting room				
50	Location R&D Prototyping				

As can be seen from Table 22, the variables 48, 49 and 50 are coded together in time segments 180 and are only coded once, hence the relative count value of 1 for this cluster is justified by visual inspection and is considered as a strong cluster.

Table 23: Timeline Snippet 2 for Team X

V.No	Variable	142	144	146	148	150
1	Aisle Space					
2	Allocation of large areas of factory					
65	Size of Storage					

Table 24: Timeline Snippet 3 for Team X

V.No	Variable	66	68	70	72	74
25	Location of Raw Materials (Supplies)					
28	location R&D					

Table 23 and 24 show similar clusters. The variables are coded together in one time-segment (146 in Table 23 and 68 in Table 24). Also, one of the variables (variable 1 in Table 23 and variable 28 in Table 24) is coded one more time separately, thus reducing the relative count of the cluster. However, these are still strong clusters.

Table 25: Timeline Snippet 4 for Team X

V.No	Variable	64	66	68	70	72	74	100	102	104	106	108	120	126	128	130	132	134	136	138	140	162	164
36	location control box assembly																						
37	location module assembly																						
38	location machine assembly																						
5	Spatial flow pattern																						
31	location Frame Fab																						
33	location paint prep																						
35	location machine shop																						
43	location crate & packaging																						
47	location refurbishment																						

Table 25 shows an interesting cluster that was identified in the relative count matrix and the dendrogram. All the variables are coded together in one time-segment (segment 72). In all other time segments, the variables are either coded in pairs or individually, thus reducing the strength of the cluster.

Table 26: Timeline Snippet 5 for Team X

V.No	Variable	98	100	114	116	118	120	130	132
27	location of material handling								
62	size of paint staging								
3	Assign ops to areas								
21	Staffing in area - material handling								
55	size of frame fabrication								
61	size of paint prep								

In Table 26, another strong cluster is shown that was identified in the relative count matrix and the corresponding dendrogram. The variables are coded together within the two time-segments between 116 – 118.

Apart from that, they are coded sporadically in other time segments, twice to be exact. This can be classified as a cluster.

Table 27: Timeline Snippet 6 for Team X

V.No	Variable	90	92	94	96	98	100	102	104	106	108
16	Staffing in area - Control Box										
17	Staffing in area - Machine Shop										

Table 27 shows a cluster that has two variables. Both these variables were coded together three times. In addition, they were coded separately in two segments. This is an acceptable cluster.

Table 28: Timeline Snippet 7 for Team X

V.No	Variable	80	82	84	134	136	138	140	142
42	location QC								
60	Size of Crate and Packaging								
64	Size of QC								

Finally, Table 28 shows the last identified cluster for Team X. The variables 42, 60, and 64 were all discussed together in the time segment 136. In addition, they were discussed separately in two segments, 82 and 138.

<u>Team Y:</u>

The eigenvalue spectrum for Team Y can be seen in Figure 19. As can be seen from the figure, the third eigenvalue is significantly larger than all other eigenvalues, thus, k = 3 is a viable selection. However, it should be noted that from the spectrum plot, the 6th eigenvalue is also significantly larger than all eigenvalues from 7 onwards. Thus, k = 6 can also be viable choice for reducing dimensions.

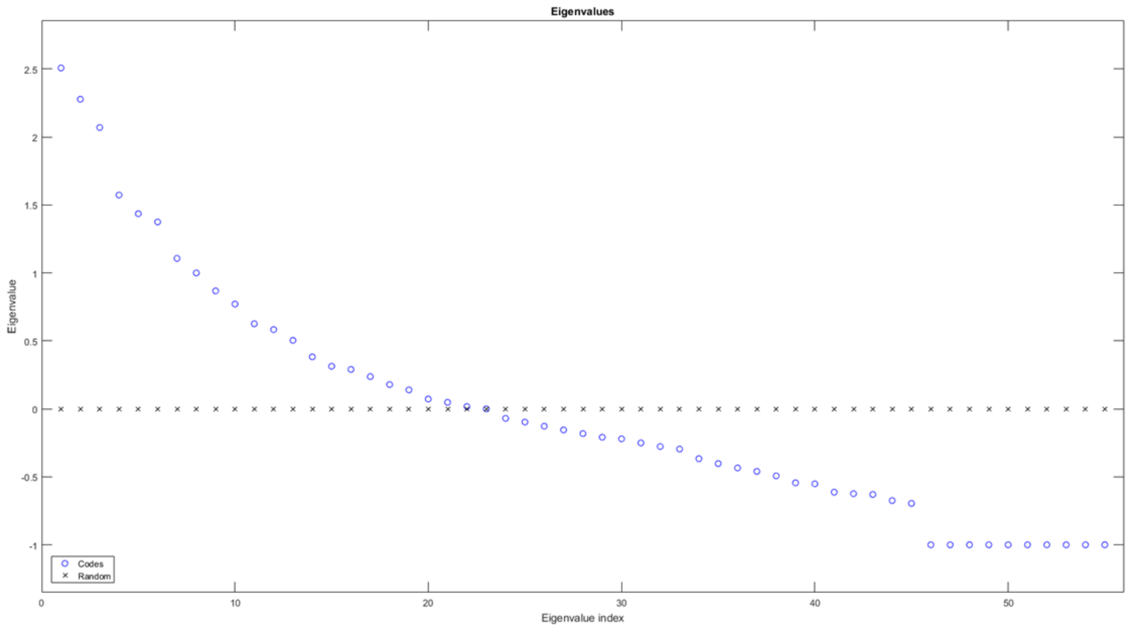

Figure 19: Eigenvalue Spectrum for Team Y

The dendrograms for the reduced dimension points were also plotted. Each dendrogram provided an increasing level of detail into the clusters until k = 6 after which there is minimal change in the detail offered by the dendrograms. Thus, k = 6 for was picked dimension reduction. The dendrogram for this can be seen in Figure 20.

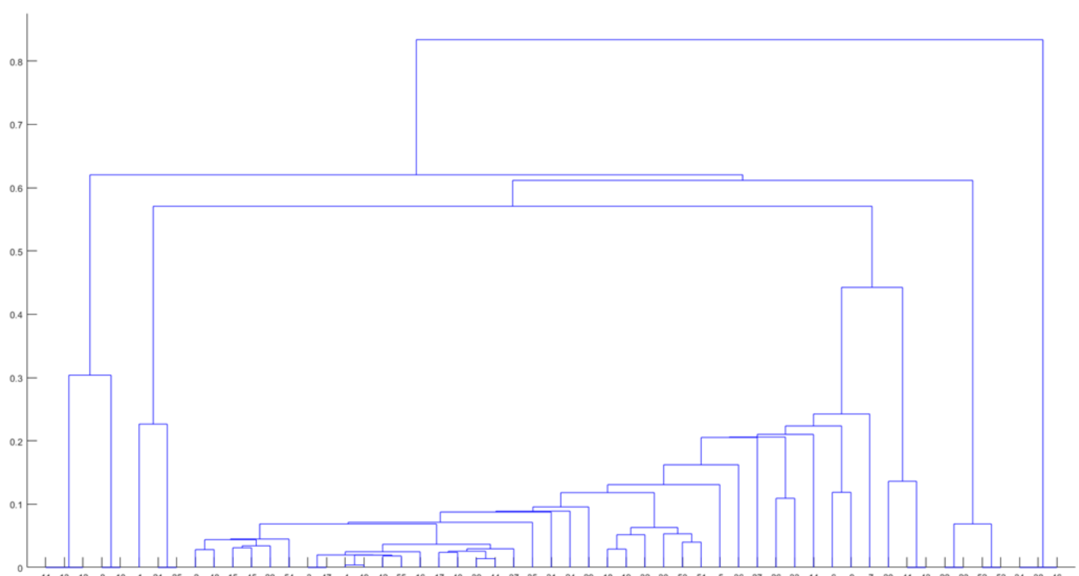

Figure 20: Dendrogram for Team Y with k = 6

In addition to creating clusters, the relative count matrix was also recorded which shows the strength of each pair of variables coded in Team Y. This matrix for Team Y has been split into two images to ensure readability and can be seen in Figure 21 and Figure 22.

	11	13	12	8	10	1	21	25	2	48	15	45	28	54	3	47	4	49	42	55	16	17	40	39	44	37	35	31	24	29
11	0	1	1	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1	0	1	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1	1	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0.3	0.3	0.3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.3	0.3	0.3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0.5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0.5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0.2	0	0.3
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3
15	0	0	0	0	0	0	0	0	0	0	0	0.1	0.2	0	0	0	0	0	0	0.2	0.1	0	0	0	0	0.1	0.1	0.2	0	0
45	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0
28	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.1	0.1	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0.1	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0.1	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0.2	0.1	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0.2	0	0	0	0	0.1	0.2	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.2	0	0	0	0	0	0.2	0	0.1	0.1	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0.2	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3
37	0	0	0	0	0	0	0	0	0	0	0.1	0	0.1	0	0	0	0	0	0	0	0.2	0.1	0.1	0	0	0	0.2	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0.1	0	0.1	0	0	0	0.1	0.1	0	0	0.1	0.2	0.1	0	0	0.2	0	0	0	0
31	0	0	0	0	0	0	0	0	0.2	0	0.2	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0.2	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0.1	0.2	0.3	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0.2	0	0	0.2	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0.1
32	0	0	0	0	0	0	0	0	0.1	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0.1
30	0	0	0	0	0	0	0	0	0.1	0.2	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.5
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0.2	0.1	0.1	0	0	0	0	0	0	0.1	0	0	0	0	0	0.1	0.1	0.1	0	0
26	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0
33	0	0	0	0	0	0.2	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0.1	0.1	0.1	0.1	0	0.1	0	0.3	0	0	0	0	0	0	0	0.1	0.1	0.1	0	0	0.1	0.1	0.1	0	0.1
6	0	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 21: Relative Count with Clusters for Team Y with k = 6 (1)

	18	19	32	30	50	51	5	36	27	26	33	14	6	9	7	20	41	43	22	23	52	53	34	38	46
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0.1	0	0	0	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0.1	0	0	0	0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0.1	0.1	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0.2	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0.2	0.1	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0.1	0	0	0	0	0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0.1	0.2	0.1	0	0	0	0	0	0.1	0	0.1	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0.3	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0.1	0.1	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0.2	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0.1	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0.1	0.1	0	0	0.1	0	0	0	0.1	0	0	0	0	0	0	0	0	0
31	0	0	0.1	0.2	0	0	0	0	0.1	0.2	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0
29	0	0.1	0.1	0.5	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0.3	0.1	0.1	0.3	0.3	0	0	0.1	0.1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0.3	0	0.1	0.2	0.2	0.1	0	0	0.1	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0.1	0.1	0	0.2	0.2	0.1	0	0	0.1	0.1	0.3	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0.1	0.2	0.2	0	0.2	0.2	0	0	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0.3	0.2	0.2	0.2	0	0.5	0	0	0.1	0.2	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0.3	0.1	0.1	0.2	0.5	0	0	0	0.1	0.2	0.2	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0	0	0	0.1	0.1	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.5	0	0	0	0	0	0	0	0	0
27	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0.5	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1
26	0.1	0.2	0.1	0.1	0.2	0.2	0	0	0.5	0	0.3	0.1	0	0	0	0	0	0	0	0	0	0	0.2	0.2	0.2
33	0.2	0.1	0.3	0.1	0.3	0.2	0	0	0.2	0.3	0	0.1	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.3
14	0	0	0.1	0.1	0	0	0	0.1	0.1	0.1	0.1	0	0	0	0	0.1	0.1	0.1	0	0	0	0	0.1	0.1	0.1
6	0	0	0	0	0	0.3	0.1	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0.1	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0	0	0	0	0
20	0	0	0	0	0	0	0	0.5	0	0	0	0.1	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.5	0	1	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0.5	1	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0.3	0	0	0	0	1	0.5	0.5	0	0	0
23	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0.3	0	0	0	1	0	0.5	0.5	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	1	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	1	0	0	0	0
34	0	0	0	0	0	0	0	0	0.1	0.2	0.3	0.1	0	0	0	0	0	0	0	0	0	0	0	1	1
38	0	0	0	0	0	0	0	0	0.1	0.2	0.3	0.1	0	0	0	0	0	0	0	0	0	0	1	0	1
46	0	0	0	0	0	0	0	0	0.1	0.2	0.3	0.1	0	0	0	0	0	0	0	0	0	0	1	1	0

Figure 22: Relative Count with Clusters for Team Y with k = 6 (2)

The relative count matrix when created in combination with the dendrogram, was rearranged such that the variables were listed in the same order as they appear in the dendrogram (grouped in clusters) so that it is easier to visualize clusters along the diagonal of the matrix.

Then, the clusters selected based on the cluster selection matrix (described in Chapter 6). For completeness, the Figures 21 and 22 identify these clusters with black borders.

As can be seen from the relative count matrix in Figure 21 and Figure 22, there are a few very strong clusters. Variables 11, 12, and 13 form a very strong cluster since they are only coded together and are never coded separately (Relative count = 1), as do variables 8 and 10. This is confirmed by the dendrogram too, since in Fig 3 these variables are at 0 distance from each other. We identify strong clusters in variables 34, 38, and 46; 22 and 23; 53 and 34; and 43 and 22. In addition, there are a few other clusters too, though they are not as strong as the ones mentioned above. All these clusters are marked with a dark border in Figures 21 and 22.

Once these clusters were identified, a new set of timelines were created with all these clustered variables and any other 'frequently coded variables' that were not included as a part of any of these clusters, to better visualize how closely the variables had been coded to group them as 'subproblems'.

Table 29: Timeline Snippet 1 for Team Y

V.No	Variable	190	192	194	196	198	200
11	Staffing in area - Machine Assembly						
13	Staffing in area - Crate and Package						
12	Staffing in area - QC						
8	Staffing in area - Paint						
10	Staffing in area - Module Assembly						

As can be seen from Table 29, the variables 11, 12, 13, 8 and 10 (Staffing in areas) are all coded together in time segment 194. Also, two of them (8 and 10) are coded together in segments 192 and 196. Variables 11, 12, and 13 are never coded separately, hence the relative count value of 1.

Table 30: Timeline Snippet 2 for Team Y

V.No	Variable	108	110	112	114
3	Internal layout of Machine assembly				
47	Size of attach main drive				

Table 31: Timeline Snippet 3 for Team Y

V.No	Variable	46	48	50	52	54
34	location shipping and receiving					
38	Location R&D Prototyping					
46	size of machine assembly					

In Table 30, the variables 3 and 47 are only coded once, and they are coded together. Thus, the relative count matrix gives this cluster a value of 1. Variables 34, 38, and 46 exhibit a similar behavior (Table 31).

Table 32: Timeline Snippet 4 for Team Y

V.No	Variable	66	68	70	72	74	76	78	80
50	Size of Control Box Assembly								
51	Size of Crate and Packaging								

In Table 32, the cluster containing variables 50 and 51 is discussed very few times. They are discussed together in the time segment 68. However, variable 51 is discussed once more, individually in time segment 76.

Table 33: Timeline Snippet 5 for Team Y

V.No	Variable	40	42	44	46	48	50
1	Spatial flow pattern						
21	location Frame Fab						
25	location machine shop						

Table 34: Timeline Snippet 6 for Team Y

V.No	Variable	74	76	78	190	192	194	196
6	Staffing in area - Frame Fab							
9	Staffing in area - Control Box							

Table 35: Timeline Snippet 7 for Team Y

V.No	Variable	50	52	54	56	58	60
20	location Incoming QC						
41	size machine shop						
43	size of frame fabrication						

Tables 33 – 35 shows three different timelines with the same type of cluster. The variables 1, 21, and 25 (Table 33) are all coded together in time segment 46 hence giving rise to a strong cluster. Variable 1 is coded separately in one occasion (segment 44). Same goes for Variables 6 and 9 (Table 34); and variables 20, 41, and 43 (Table 35).

Table 36: Timeline Snippet 7 for Team Y

V.No	Variable	70	72	74	76	78	80	82
22	location paint staging							
23	location paint prep							
52	size of paint prep							
53	size of paint staging							

Table 36 shows variables 22, 23, 52, and 53 which are all paint variables (location and size). That is interesting, because it shows evidence that this team has discussed variables related to paint together. These variables were all coded together in segment 78. In addition, variables 22 and 23 were coded together in segment 74.

<u>Team Z:</u>

The eigenvalue spectrum for Team Z can be seen in Figure 23. As can be seen from the figure, the first eigenvalue is significantly larger than all other eigenvalues, thus, k = 1 is a viable selection. However, it should be noted that k = 1 corresponds to just one cluster, and from the spectrum plot, the values k = 3 and k = 5 can also be viable choices for reducing dimensions.

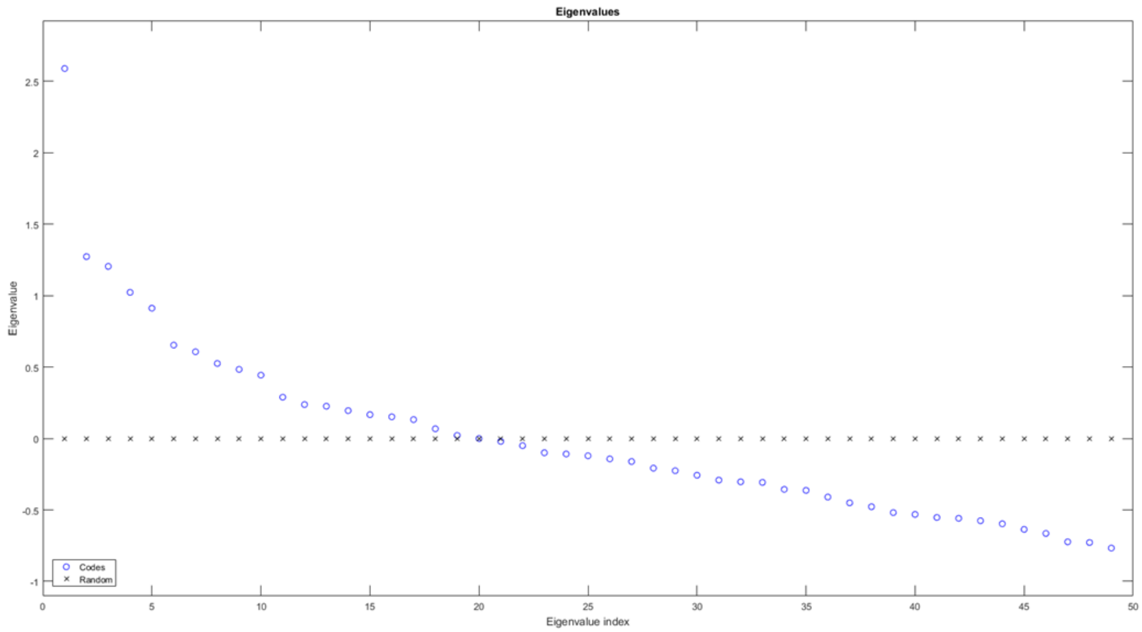

Figure 23: Eigenvalue Spectrum for Team Z

The dendrograms for the reduced dimension points were also plotted. Each dendrogram provided an increasing level of detail into the clusters until k = 5 after which there is minimal change in the detail offered by the dendrograms. Thus, k = 5 was picked for dimension reduction. The dendrogram for this can be seen in Figure 24.

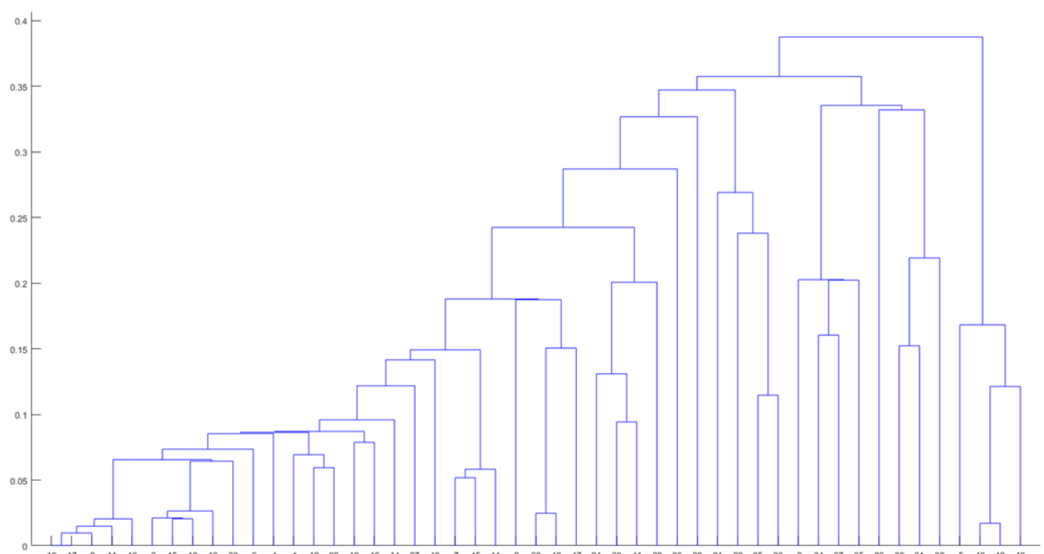

Figure 24: Dendrogram for Team Z with k = 5

In addition to creating clusters, the relative count matrix was also recorded which shows the strength of each pair of variables coded in Team Z. This matrix for Team Z has been split into two images to ensure readability and can be seen in Figure 25 and Figure 26.

	10	17	9	11	16	3	15	18	13	33	6	4	1	12	28	19	46	14	27	40	7	45	44
10	0	0	0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0.13	0.11	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0	0
3	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0.2	0	0	0	0	0	0	0
15	0	0	0.08	0.2	0	0	0	0	0	0	0	0	0	0	0.14	0.13	0	0	0	0	0.09	0	0
18	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0.25	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0.29	0	0.2	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0.14	0.13	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0.29	0	0	0	0.14	0	0	0	0.17	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0.14	0	0	0.2	0	0.25	0	0	0	0	0.2	0
12	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0.2	0.33	0	0	0	0	0	0
28	0	0	0	0	0	0	0.14	0	0	0	0.14	0	0.2	0	0	0.17	0	0	0	0	0.11	0	0
19	0	0	0	0	0	0.2	0.13	0.25	0	0.14	0.13	0	0	0.2	0.17	0	0.2	0	0	0	0.1	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0.17	0.25	0.33	0	0.2	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0.14	0	0.09	0	0	0	0	0	0	0	0.11	0.1	0	0	0	0	0	0.25	0.14
45	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0.25	0	0.33
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0.33	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0	0.11	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0
20	0	0	0	0	0	0.08	0.07	0	0	0	0.14	0.07	0.08	0	0.17	0.07	0.08	0	0	0.07	0.13	0.08	0.09
21	0	0	0	0	0	0	0	0	0	0	0	0.13	0.17	0	0	0	0.2	0	0	0.14	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.13	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0	0.11	0.14	0	0	0	0.18	0.13	0.17
31	0	0	0	0	0	0	0	0	0	0	0.18	0	0	0	0	0	0	0	0	0	0.15	0.1	0.13
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11	0.18	0.13	0.17
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25: Relative Count with Clusters for Team Z with k = 5 (1)

	8	38	42	47	24	39	41	29	26	20	21	22	25	36	2	34	37	35	23	30	31	32	5	43	48	49
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0	0	0.18	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0.07	0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0.08	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0.11	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0.08	0.2	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0.2	0	0.17	0	0.11	0	0.07	0.14	0	0	0	0	0.13	0	0.2	0	0	0	0.11	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0	0	0	0	0.18	0.15	0.18	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0.13	0.1	0.13	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0.09	0	0	0	0	0	0	0	0	0	0.17	0.13	0.17	0	0	0	0
8	0	0	0	0	0.13	0.13	0.17	0.09	0	0	0	0	0	0	0	0	0	0	0.11	0.09	0.08	0.09	0	0	0	0
38	0	0	0.5	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0.5	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0.25	0.25	0	0	0	0	0	0	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0
24	.13	0.25	0.33	0.25	0	0.2	0.33	0.13	0	0	0	0	0	0.2	0	0	0	0	0.17	0.13	0.1	0.13	0	0	0	0
39	.13	0	0	0.25	0.2	0	0.33	0.29	0	0	0.17	0	0	0	0	0	0	0	0.17	0.13	0.1	0.13	0	0	0	0
41	.17	0	0	0	0.33	0.33	0	0.17	0	0	0	0	0	0	0	0	0	0	0.25	0.17	0.13	0.17	0	0	0	0
29	.09	0	0	0	0.13	0.29	0.17	0	0	0	0.11	0	0.14	0.13	0	0.1	0.14	0	0.25	0.2	0.08	0.09	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.17	0	0	0.2	0	0.11	0.14	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0.15	0	0	0	0.08	0.14	0.08	0.18	0.07	0.13	0.19	0.21	0.07	0.17	0.18	0.09
21	0	0	0	0	0	0.17	0	0.11	0	0.15	0	0.25	0.2	0.17	0	0.29	0	0.2	0	0	0	0.11	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0.25	0	0.5	0.33	0	0.2	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0.14	0	0	0.2	0.5	0	0.67	0	0.17	0.33	0	0.2	0	0	0	0	0	0	0
36	0	0	0	0.25	0.2	0	0	0.13	0	0	0.17	0.33	0.67	0	0	0.14	0.25	0	0.17	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0.33	0.08	0	0	0	0	0	0.4	0.33	0.33	0.5	0.14	0.25	0.33	0	0	0	0
34	0	0	0	0	0	0	0	0.1	0.17	0.14	0.29	0.2	0.17	0.14	0.4	0	0.17	0.4	0.29	0.1	0.18	0.38	0	0	0	0
37	0	0	0	0	0	0	0	0.14	0	0.08	0	0	0.33	0.25	0.33	0.17	0	0.33	0.5	0.14	0.11	0.14	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0.18	0.2	0	0	0	0.33	0.4	0.33	0	0.2	0.14	0.11	0.33	0	0	0	0
23	.11	0	0	0	0.17	0.17	0.25	0.25	0.2	0.07	0	0	0.2	0.17	0.5	0.29	0.5	0.2	0	0.25	0.33	0.43	0	0	0	0
30	.09	0	0	0	0.13	0.13	0.17	0.2	0	0.13	0	0	0	0	0.14	0.1	0.14	0.14	0.25	0	0.4	0.5	0	0	0	0
31	.08	0	0	0	0.1	0.1	0.13	0.08	0.11	0.19	0	0	0	0	0.25	0.18	0.11	0.11	0.33	0.4	0	0.56	0	0	0	0
32	.09	0	0	0	0.13	0.13	0.17	0.09	0.14	0.21	0.11	0	0	0	0.33	0.38	0.14	0.33	0.43	0.5	0.56	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.17	0.2
43	0	0	0	0	0	0	0	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0.67	0.33
48	0	0	0	0	0	0	0	0	0	0.18	0	0	0	0	0	0	0	0	0	0	0	0	0.17	0.67	0	0.5
49	0	0	0	0	0	0	0	0	0	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.33	0.5	0

Figure 26: Relative Count with Clusters for Team Z with k = 5 (2)

The relative count matrix when created in combination with the dendrogram, was rearranged such that the variables were listed in the same order as they appear in the dendrogram (grouped in clusters) so that it is easier to visualize clusters along the diagonal of the matrix. Then, the clusters selected based on the cluster selection matrix (described in Chapter 6). For completeness, the Figures 25 and 26 identify these clusters with black borders.

As can be seen from the relative count matrix in Figures 25 and 26, there are a few very strong clusters. We identify strong clusters in variables 5, 43, 48, and 49; 38 and 42.

In addition, there are a few other clusters too, though they are not as strong as the ones mentioned above. All these clusters are marked with a dark border in Figure 25 and Figure 26.

Once these clusters were identified, a new set of timelines were created with all these clustered variables and any other 'frequently coded variables' that were not included as a part of any of these clusters, to better visualize how closely the variables had been coded to group them as 'subproblems'.

Table 37: Timeline Snippet 1 for Team Z

V.No	Variable	144	146	148	150	152
38	location of employee break and meeting room					
42	Size of gym					

In Table 37, the two variables are coded together in the time segment 146, and variable 38 is coded just one more time, in segment 148. This gives rise to a cluster strength of 0.5 which is reasonably strong.

Table 38: Timeline Snippet 2 for Team Z

V.No	Variable	90	92	94	96	98	136	138	140	142	144	170	172	174
21	Location of Raw Materials (Supplies)													
22	location paint supplies													
25	location Incoming QC													
36	location of S&R office													

Table 39: Timeline Snippet 3 for Team Z

V.No	Variable	90	92	94	96	98	100	102	104	106	132	134	136	138	140	142	144	146	148	150	152	168	170	178	180	182	184
2	Spatial flow pattern																										
34	location crate & packaging																										
37	location refurbishment																										
35	location shipping and receiving																										
23	location R&D																										
30	location control box assembly																										
31	location module assembly																										
32	location machine assembly																										

Table 40: Timeline Snippet 4 for Team Z

V.No	Variable	114	116	118	120	122	124	126	128	130	132
5	Internal layout of Frame Fab										
43	size of frame fabrication										
48	size of paint prep										
49	Size of Storage										

The clusters shown in Tables 38 – 40 above are some identified clusters. The variables in all these clusters are grouped together since they are all discussed together in exactly one of the time segments.

There are a bunch of other segments where they are discussed too, though not always together. Hence, none of these clusters are particularly strong clusters.

4.4.2.Cluster Selection Results

This section lists the selected clusters for each design team out of all the possible clusters identified by the spectral clustering analysis and describes some observations about these clusters. (Each cluster is given an identifying code.)

Table 41: List of Clusters (Team J)

Cluster	Code	Variables	Strength
Staffing 1	S1	Staffing in area - Frame Fab, QC, Control Box, Crate and Package, Paint	**0.79**
Staffing 2	S2	Staffing in area - Module Assembly, Machine Assembly	**0.94**
Size	Sz1	Size of area - QC, Gym. Aisle Space	**0.44**
Location	Loc1	Location of area - Control Box, Crate and Package, Refurbishment, Incoming QC, Machine Shop	**0.33**
Location & Size	LSz1	Location of area - Employee break room, showroom, Gym. Size of R&D. Office Layout	**0.33**
Paint Location	PL	Location of area - Paint Staging, Paint Prep	**1**

<u>Team J:</u> Six clusters were selected for Team J from the dendrogram created by clustering with k = 5 (Table 41). Two of the clusters (S1 and S2) contain variables about staffing different manufacturing areas. One cluster (Sz) contains variables about the size of two manufacturing areas and the aisle space, which affects size decisions. The fourth cluster (Loc1) contains variables about the locations of five manufacturing areas. The fifth cluster (LSz1) contains variables about the locations of three areas and the size of two other areas; none of these areas contain manufacturing operations. The sixth cluster (PL) contains variables about the locations of two paint areas.

Table 42: List of Clusters (Team K)

Cluster	Code	Variables	Strength
Staffing 1	S3	Staffing in area - Frame Fab, Control Box, Paint	**0.78**
Staffing 2	S4	Staffing in area - QC, Crate and Package	**0.5**
Staffing 3	S5	Staffing in area - Machine Shop, Material Handling	**1**
Location	Loc2	Location of area - Inventory, Staging Modules, Electrical Supplies	**0.42**
Location & Size	LSz2	Location of area - Incoming QC, Refurbishment, Supervisor Officer. Size of area - QC, Refurbish	**0.31**
Paint	P1	Location of Paint Staging, Size of Paint Prep	**1**
Machine Assembly	MA1	Location of Machine Assembly, Size of Machine Assembly, Layout of Machine Assembly Cell	**0.4**

Team K: Seven clusters were selected for Team K from the dendrogram created by clustering with k = 6 (Table 42). Three of the clusters (S3, S4, and S5) contain variables about staffing different manufacturing areas. One cluster (Loc2) contains variables about the location of three storage areas for inventory, modules, and electrical supplies. The fifth cluster (LSz2) contains variables about the locations of three areas (two of which are manufacturing areas) and the size of two manufacturing areas. Both Location and Size of Refurbishment and QC is included in this cluster. The sixth cluster (P1) contains variables about the location and size of two paint areas. The seventh cluster (MA1) contains location and size of machine assembly (and the cell).

Table 43: List of Clusters (Team L)

Cluster	Code	Variables	Strength
Staffing	S6	Staffing in area - Crate and Package, QC	**1**
Staffing and Location	SL1	Staffing in area - Paint, Frame Fab, Control Box. Location of Inventory	**0.42**
Assembly Layout	AL1	Internal Layout of area - Module Assembly, Machine Assembly, Assembly Cell.	**0.44**
Location	Loc3	Location of area - Paint Staging, Paint Prep, Frame Fab, Machine Shop	**0.58**
Location and Size	LSz3	Location of R&D, Size of Machine Shop	**0.5**

Team L: Five clusters were selected for Team L from the dendrogram created by clustering with k = 5 (Table 43).

The first cluster (S6) contains variables about staffing of two manufacturing areas. The second cluster (SL1) contains variables about the staffing of three manufacturing areas and the location of inventory. The third cluster (AL1) contains variables about the internal layout of the assembly cell (including module and machine assembly areas). The fourth cluster (Loc3) contains variables about the locations of four areas. The last cluster (LSz3) consists of variables about the location of R&D and the size of Machine Shop.

Table 44: List of Clusters (Team X)

Cluster	Code	Variables	Strength
Staffing 1	S7	Staffing in area - Control Box, Machine Shop	**0.6**
Location and Flow	LF1	Location of area – Module & Machine Assembly, Control Box, Frame Fab, Refurbishment, Machine Shop, Paint, Crate & package. Spatial Flow pattern.	**0.3**
Location 1	Loc4	Location of area - Raw Material, R&D.	**0.5**
Location 2	Loc5	Location of area - Lockers, Employee Break Room.	**1**
Location, Size, Staff	LSS	Size of area - Paint Staging, Paint Prep, Frame Fab. Location and staffing of material handling. Assign ops to areas	**0.43**
QC	QC1	Size and Location of QC	**0.5**
Miscellaneous	M1	Size of Storage, Allocation of large areas, Aisle Space	**0.67**

Team X: Seven clusters were selected for Team X from the dendrogram created by clustering with k = 7 (Table 44). The first cluster (S7) contain variables about staffing two manufacturing areas. One cluster (LF1) contains variables about the location of eight manufacturing areas and the spatial flow pattern, which affects location decisions. The third cluster (Loc4) contains variables about the locations of two areas. The fourth cluster (Loc5) contains variables about the locations of two more areas; none of the areas in these two clusters contain manufacturing operations.

The fifth cluster (LSS) contains variables about the location and staffing of material handling, and size of two paint areas and frame fabrication.

The sixth cluster (QC1) contains size and location of QC. The last cluster (M1) is a mixed cluster, containing size of storage, allocation of areas, and aisle space.

Table 45: List of Clusters (Team Y)

Cluster	Code	Variables	Strength
Staffing 1	S8	Staffing in area - Crate and Package, QC, Machine Assembly, Paint, Module Assembly.	**0.6**
Staffing 2	S9	Staffing in area - Frame Fab, Control Box.	**0.5**
Location and Flow	LF2	Location of area - Frame Fab, Machine Shop. Spatial Flow Pattern	**0.67**
Location and Size 1	LSz4	Location of Incoming QC. Size of area - Machine Shop, Frame Fab	**0.67**
Location and Size 2	LSz5	Location of area - Shipping & Receiving, R&D. Size of Machine Assembly	**1**
Size	Sz2	Size of area - Control box, Crate and Package	**0.5**
Layout and Size	LAS1	Layout of Machine Assembly. Size of Attach main drive.	**1**
Paint	P2	Location and Size of area - Paint Prep, Paint Staging.	**0.67**

Team Y: Eight clusters were selected for Team Y from the dendrogram created by clustering with $k = 6$ (Table 45). Two of the clusters (S8 and S9) contain variables about staffing different manufacturing areas. One cluster (LF2) contains variables about the location of two manufacturing areas and the spatial flow pattern, which affects location decisions. The fourth and fifth clusters (LSz4 and LSz5) contain variables about the locations and size of manufacturing areas. The sixth cluster (Sz2) contains variables about the size of two areas. The seventh cluster (LAS1) contains variables about the layout of machine assembly and size of attach main drive area. Finally, the eighth cluster (P2) consists of location and size of two paint areas.

Table 46: List of Clusters (Team Z)

Cluster	Code	Variables	Strength
Location	Loc6	Location of area - Incoming QC, S&R Office, Paint Supplies, Raw Materials	**0.35**
Location and Flow	LF3	Location of area - Crate & Package, Refurbishment, S&R, Control Box, Module Assembly, Machine Assembly, R&D. Spatial flow pattern	**0.3**
Layout and Size	LAS2	Layout of Frame Fab. Size of area - Frame Fab, Paint Prep, Storage.	**0.4**
Location and Size	LSz6	Location of employee break room. Size of Gym.	**0.5**

Team Z: Four clusters were selected for Team Z from the dendrogram created by clustering with $k = 5$ (Table 46). The first cluster (Loc6) contains variables about location of four different areas; one of them being a manufacturing area. The second cluster (LF3) contains variables about the location of seven manufacturing areas and the spatial flow pattern, which affects location decisions. The third cluster (LAS2) contains variables about the layout of frame fabrication and size of three areas; one of which is storage. The fourth cluster (LSz6) contains variables about the location of employee break room and size of gym.

4.5. Discussion on Rejected Clusters

Based on the analysis performed Section 4.4, there can be some comments that can be made on some clusters that were apparent from the dendrogram were not selected as a part of the final clusters. This was done owing to the value of the cluster strength of these clusters. For example, Figure 27 shows the dendrogram with clusters depicted for Team J.

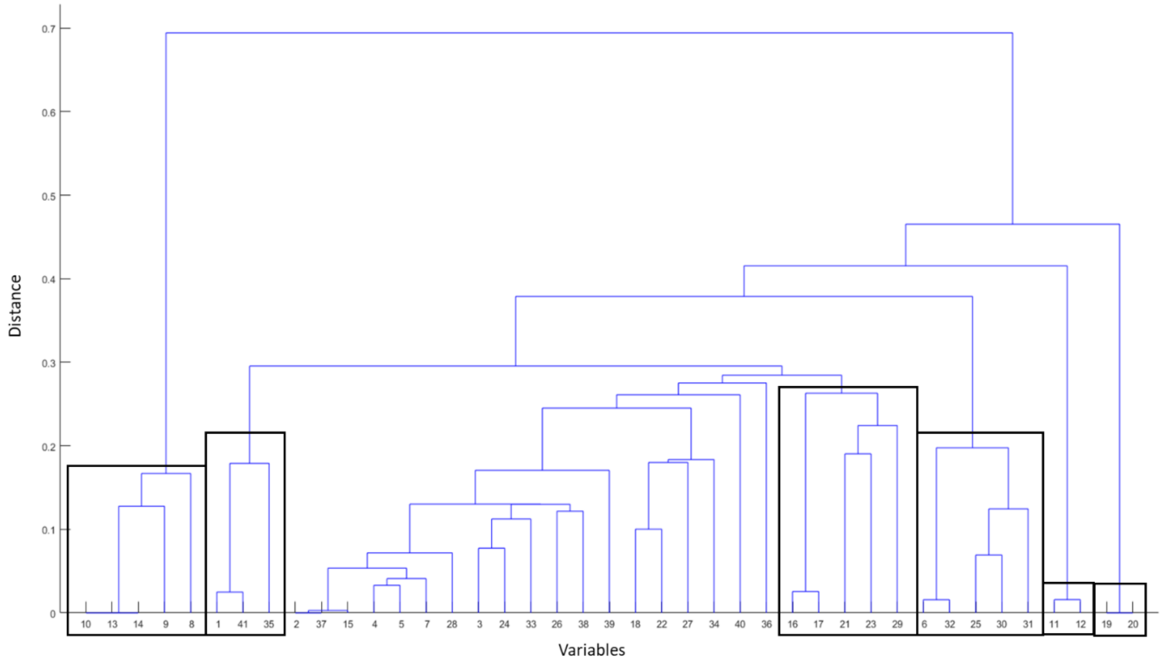

Figure 27: Dendrogram with Clusters - Team J

It seems intuitive to select the variables from 2 to 40 as a part of a seventh cluster, since all other pairs are selected as clusters. However, if these variables are revisited in the relative count matrix, their relative counts are extremely low, seen in Figure 28. Thus, this cluster was not selected as a final cluster for this team. This approach was followed to select clusters for all teams.

	2	37	15	4	5	7	28	3	24	33	26	38	39	18	22	27	34	40
2	0	0	0	0	0	0.09	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0.09	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0.08	0.08	0	0	0	0.29	0	0	0	0	0	0	0	0	0	0
7	0.09	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0
3	0	0	0	0	0.29	0	0	0	0	0	0	0	0	0.11	0.13	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0.25	0	0.25	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0.25	0	0	0	0.33	0	0	0.2	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0.11	0.25	0	0	0	0	0	0.25	0	0.25	0
22	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0.25	0	0.25	0	0
27	0	0	0	0	0	0	0.33	0	0.25	0	0	0.2	0	0	0.25	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 28: Relative Count Values for Rejected Cluster

Chapter 5: Team Comparison Results

After selecting the meaningful clusters for each of the teams, the results were compared across teams to see if there were any similarities (or patterns) that could be identified in the clusters of different teams. This comparison assumes that each selected cluster is a subproblem considered by that design team.

5.1. Variables

Throughout the coding activity, a total of 82 distinct variables were obtained that were discussed by at least one design team [Appendix – C]. The average number of variables discussed by a team was 50.2 variables. A total of 23 variables were discussed by all six teams. (referred to as "common" variables) The list can be seen in Table 47.

Table 47: List of "Common" Variables Coded by all Six Design Teams

Variables	
Spatial flow pattern	location control box assembly
Facility Staffing	location crate & packaging
Staffing in area - Frame Fab	location R&D
Staffing in area - Paint	location of Gym
Staffing in area - Control Box	location QC
Staffing in area - Module Assembly	location refurbishment
Staffing in area - Machine Assembly	size of R&D
Staffing in area - QC	size of refurbish
Location of Inventory (Storage)	Size of gym
location machine shop	size of module assembly
location Frame Fab	size of paint prep
location paint prep	

Ten of the 23 common variables were location variables, seven were staffing variables, five were size variables, and the last one was spatial flow pattern, a high-level variable.

The 23 common variables were often not included in any selected cluster, however. Across the six teams, the average number of common variables included in a selected cluster was only 7.5. It is interesting to note here that many of these variables coded by all six teams were unclustered in any of the clusters identified above.

There was a total of 93 times that the variables coded by all six design teams were unclustered, as compared to 45 times when the variables were clustered

Table 48: List of Frequently Coded Variables

Variable	Number of Teams	Total Times Coded
Facility Staffing	6	55
Internal layout of Machine assembly	5	42
Location of Inventory (Storage)	6	42
Staffing in area - Module Assembly	6	41
Internal layout of module assembly	4	34
location control box assembly	6	30
Staffing in area - Machine Assembly	6	29
location module assembly	5	29
location machine assembly	5	27
Internal layout of assembly cell	3	25
location crate & packaging	6	25

Table 48 identifies the variables that were coded most number of times across the six teams. The observation here is that many of the variables that were most often discussed across the six design teams (like Internal layout of machine assembly, Internal layout of module assembly) were not coded by all the six design teams. This points towards an intensive use of some variables by some teams while other teams did not even discuss these variables. Ultimately, this refers to a difference in design strategies used by the teams.

5.2. *Clusters*

To compare the teams' clusters, the metric defined by Rand was used to calculate the overall similarity of two teams based on whether they clustered each pair of common variables together or in different clusters [24,25].

Any common variable not in a selected cluster was considered as a cluster of one variable by itself. That is, the variables not in any of the selected clusters were in different clusters, and not one big cluster. The following notation is used to compare the clusters for two teams (Let the teams be Team A and Team B). Let,

a: number of pairs in the same cluster for both teams;

b: number of pairs in the same cluster for team A but in different clusters for team B;

c: number of pairs in the same cluster for team B but in different clusters for team A;

d: the number of pairs in different clusters for both teams.

n: the total number of common variables

M: the total number of pairs = n(n-1)/2 = a + b + c + d

R: the 'Rand' similarity statistic [25] =

$$R = \frac{a + d}{M}$$

As an example, consider the following: Let there be two teams, Team A and Team B. For this example, let's consider 8 variables that are to be compared across these two teams. The clusters formed by Team A and Team B for these 8 variables can be seen below:

Table 49:Example- List of Clusters for Team A

Cluster	Variable Numbers in the Cluster
Cluster 1	1, 2, 3, 4, 5
Cluster 2	6, 7
Cluster 3	8

Table 50: Example-List of Clusters for Team B

Cluster	Variable Numbers in the Cluster
Cluster 1	1, 2, 3
Cluster 2	4, 5, 8
Cluster 3	6
Cluster 4	7

The tables above show clusters for both Team A and Team B. In total, there would be 28 pairs of variables. To calculate the similarity of these two teams, the four counts are as follows:

a: pairs in the same cluster for both teams = 4

b: pairs in the same cluster for team A but in different clusters for team B = 7

c: pairs in the same cluster for team B but in different clusters for team A = 2

d: pairs in different clusters for both teams = 15

Then,

$$R = \frac{4 + 15}{28} = 0.68$$

Table 51: Cluster Similarity Pair Wise Matrix for All 6 Teams

Results	J	K	L	X	Y	Z
J	-	0.96	0.75	0.68	0.73	0.57
K	0.96	-	0.77	0.65	0.74	0.55
L	0.75	0.77	-	0.61	0.73	0.50
X	0.68	0.65	0.61	-	0.66	0.69
Y	0.73	0.74	0.73	0.66	-	0.54
Z	0.57	0.55	0.50	0.69	0.54	-

All the pairs of teams have a similarity metric as shown in Table 51. For these six teams' clusters, the similarity metric ranges from 0.50 to 0.96. However, for all combinations except Team J and Team K, the similarity values are not higher than 0.77.

The unusually high value of similarity between Team J and Team K was investigated to see which count contributed the most to the similarity. On investigation, it was found that even though the two teams did not cluster many of the variable pairs together, the similarity metric was still very high, because the two teams had a very high number of pairs of variables that were not clustered together. The following were the values for this calculation:

a: pairs in the same cluster for both teams = 3

b: pairs in the same cluster for team J but in different clusters for team K = 8

c: pairs in the same cluster for team K but in different clusters for team J = 1

d: pairs in different clusters for both teams = 241

Then,

$$R = \frac{3 + 241}{253} = 0.96$$

It is important here to note that the similarity metric R considered a large number of pairs that were not in any of the selected clusters for both the teams. This led to high values of the d count, which in turn led to large values of the metric. This was observed in all teams, however the comparison between Team J and Team K highlighted this fact the most.

To get more insight into the similarity between the teams, the following modified metric was calculated:

$$R'(A,B) = \frac{a}{a+b} \qquad\qquad R'(B,A) = \frac{a}{a+c}$$

This metric only considers the pairs of common variables that were clustered together by one team thereby eliminating the d count. This is done since a pair of variables not being in the same cluster for both teams did not necessarily mean that the variables were handled in the same way by both teams. They could have been in a different cluster which was not one of the selected clusters or could have simply been unclustered throughout the process.

This metric is designed to show the asymmetry. If team A is compared with Team B, the metric considers those variable pairs that were paired together by Team A and not together by Team B (b count). However, when Team B is compared with Team A, the metric considers variable pairs that were in the same cluster for Team B but not for Team A (c count).

Table 52 lists the values for every pair of teams. The values in the one row are the values of $R'(A,B)$ for one team A. For example, $R'(J,K) = 0.27$, and $R'(K,J) = 0.75$. Although three values of $R'(A,B)$ are greater than 0.7, the converse values $R'(B,A)$ are not greater than 0.27.

Table 52: Modified Cluster Similarity Pair Wise Matrix for All 6 Teams

Results	**J**	**K**	**L**	**X**	**Y**	**Z**
J	-	0.27	0.36	0.27	0.27	0.10
K	0.75	-	0.75	0.00	0.25	0.00
L	0.17	0.13	-	0.17	0.21	0.42
X	0.14	0.00	0.19	-	0.14	0.29
Y	0.25	0.83	0.42	0.25	-	0.83
Z	0.10	0.00	0.10	0.55	0.10	-

For the same example of two teams Team A and Team B shown above, the modified similarity metric R' is calculated. The values are as follows:

a: pairs in the same cluster for both teams = 4

b: pairs in the same cluster for team A but in different clusters for team B = 7

c: pairs in the same cluster for team B but in different clusters for team A = 2

$$R'(A,B) = \frac{4}{4+7} = 0.36$$

$$R'(B,A) = \frac{4}{4+2} = 0.67$$

Here, a relatively large value of R'(B, A) means that the clusters in team B were a subset of the clusters in Team A. This is because the high value of R' can be attributed to a low value in the b count. Since a count is the same, this means that the number of pairs clustered in Team B's discussion were lesser than those clustered in Team A's discussion and hence, the two teams are not similar. Thus, Table 52 indicates that there is no pair of teams where both $R'(A,B)$ and $R'(B,A)$ are large, which indicates that no two teams have similar clusters (with respect to the common variables).

To summarize, no two teams had similar subproblems. It is important here to note that the similarity metric R considered many pairs that were unclustered, or not in any of the selected clusters for both the teams. This led to high values of the d count, which in turn led to large values of the metric.

In the calculation of R’, the d count was discarded, since the finding was that the d count does not necessarily add to the similarity of the teams. Here, a high relative count of one team with the other team indicates that the team had a lower value of the “b” count, which meant that the number of pairs in the same cluster for the team were low. This meant that the teams with a higher R’ value potentially contained a subset of the other team’s clusters.

5.3.Timelines

Timelines were created to chronologically visualize and compare how each team discussed their subproblems. To facilitate comparison and discussion, each timeline contianing codes of the clusters mentioned in Tables 41 to 46 was divided into four parts and juxtaposed them in Tables 53 to 56. In these tables, each row is one time-segment, and each column shows the cluster(s) discussed by each team. In addition to the clusters, the timelines also depict the high-level variables (color coded) that were discussed by the teams.

High-level variables are defined as those variables that discuss aspects of the design problem without discussing specific aspects of the layout.

The following color coding is used for the different high-level variables being discussed:

Spatial Flow Pattern
High level flow logic
Allocation of large areas
Assigning operations to area
Assigning products to area

Even though this analysis identified some similarities, the differences far outweighed them. Teams started their discussion gradually (Team Z being the slowest) and took their time to understand the problem and the current design. Teams J, K, and L started their discussions with staffing subproblems while team X and team Y focused on location based subproblems. It is interesting to note that Team Y briefly discussed staffing at the beginning too. Team Z did not discuss any subproblems until the 82nd minute. (Table 53).

Table 53: Team Wise Timeline Comparison of Clusters (1)

Time	J	K	L	X	Y	Z
40						
42						
44					LF2	
46					LF2	
48						
50					LSz5	
52						
54					LSz4	
56					LSz4	
58						
60			SL1			
62						
64						
66	S1			LF1		
68	S1, S2			LF1, Loc4	Sz2	
70	S1, S2			Loc4		
72	S1, S2			LF1		
74					P2	
76					Sz2 ,S10	
78		S3			P2	
80	S1					
82		S4		QC1		

Table 54 shows the next part of the timeline (beyond the 82nd time segment). Team J exclusively discussed size subproblems, which was not observed in any other teams' discussions. The only other team to discuss some form of size subproblems was Team Z, which discussed a Location and Size subproblem. Apart from Team J, all other teams discussed some form of Location subproblems during the time segments 92 – 156. In addition, Team K discussed a Machine Assembly subproblem; Team X discussed a QC subproblem, and Team L discussed am Assembly Location subproblem.

These subproblems are interesting because they focus on variables of a given area and are not grouped by a function.

It is also important to note that there were some teams which discussed two subproblems in the same time segment, indicating switching their discussion between subproblems erratically (Team L – 120th segment, Team X – 102, 106, 136 – 138th time segments, Team Z – 138th time segment).

Team X was the only team to depict a subproblem with all three kinds of variables, pointing to a highly fluid and overlapping nature of discussion by Team X.

Table 54: Team Wise Timeline Comparison of Clusters (2)

Time	J	K	L	X	Y	Z
92				S7		Loc6, LF3
94				S7		LF3
96						LF3
98						
100		Loc2		LSS		
102				S7, LF1		
104				S7		LF3
106				S7, LF1		
108						
110			Loc3		LAS	
112			Loc3			
114			SL1			
116	S2			LSS		
118	S2		SL1	LSS		
120			S6,Loc3	LF1		
122			LSz3			
124	S2	MA1	Loc3			
126	S2	MA1				LAS2
128	S2	Loc2		LF1		LAS2
130	S2			LSS		LAS2
132	S2			LF1		LF3
134	S2	MA1		LF1		
136	S2			OC1, LF1		LF3
138	S2			QC1, LF1		Loc6, LF3
140	S2					Loc6
142	S2					
144	S2			M1		LF3
146	S2		AL1	M1		LSz6
148	S2					LSz6
150			AL1			LF3
152			Loc3			LF3
154		MA1				
156		Loc2				
158						
160						

Table 55 continues the comparison from the 162nd time segment. Major takeaways from this section of the timeline are as follows: All teams except Team Y discussed some combination of location subproblems (they discussed staffing). Team J discussed location related subproblems almost exclusively, except for the 188th time segment, where they discussed the size subproblem. Team K, Team L, and Team X continued to discuss area based subproblems, as they did in the previous time segments. The other teams still did not exhibit signs of decomposing subproblems based on area yet.

Table 55: Team Wise Timeline Comparison of Clusters (3)

Time	J	K	L	X	Y	Z
162				LF1		
164		P1				
166						
168			AL1			
170						LF3
172						
174						
176	Loc1					
178	PL	MA1				
180	PL	MA1				LF3
182	Loc1					LF3
184	Loc1					LF3
186	Loc1		AL1			
188	Sz	Loc2				
190	Sz,Loc1	Loc2		Loc5		
192	Loc1		SL1		S10,S9	
194	LSz1				S8,S9	
196	LSz1		AL1		S9	
198	LSz1					
200	LSz1	LSz2	AL1			
202			AL1			
204	LSz1		AL1			
206	LSz1					
208	LSz1		AL1			
210						
212		LSz2				
214						
216			AL1			

Finally, Table 56 concludes the timelines. Teams X, Y, and Z were done with their discussions and did not discuss any subproblems during this time. Team J was pretty much done as well, and they only discussed subproblems in two time-segments.

Team K now revisited their staffing subproblems, two of which they initially discussed during time segments 78 – 82. Team L continued discussing the Assembly Layout subproblem and once they finished, they briefly discussed the Location and Size subproblem to conclude their discussion.

Table 56: Team Wise Timeline Comparison of Clusters (4)

Time	J	K	L	X	Y	Z
218						
220	Loc1					
222						
224						
226		S4				
228						
230			AL1			
232		S3	AL1			
234	Sz	S3	AL1			
236		S5				
238						
240						
242			LSz3			
244						

In addition to the clusters, Tables 53 to 56 also identify the high-level variables discussed by the teams. The variables discussed were: Spatial Flow Pattern, High Level Flow Logic, Allocation of Large Areas, assigning operations to areas, and assigning products to areas. The time segments when the high-level variables were discussed are highlighted according to the color scheme defined above.

Chapter 6: Team Wise Final Design Discussion

The following sections discuss the progression of each team's layout through a series of figures that show how the layout evolved and comparison of the changes in layout with the subproblems discussed during the same period. Refer to Tables 41 to 46 for the subproblems identified for each team and the corresponding codes (used in the discussions in the proceeding sections).

6.1.<u>Team J Layout Discussion</u>

From the timeline, from the start of the discussion until the 82nd minute, the team discussed staffing subproblems (S1 and S2). These discussions saw no changes in the layout, as expected. The discussion was focused on calculating how many people per area would be needed, before the locations or sizes of any of these areas were decided.

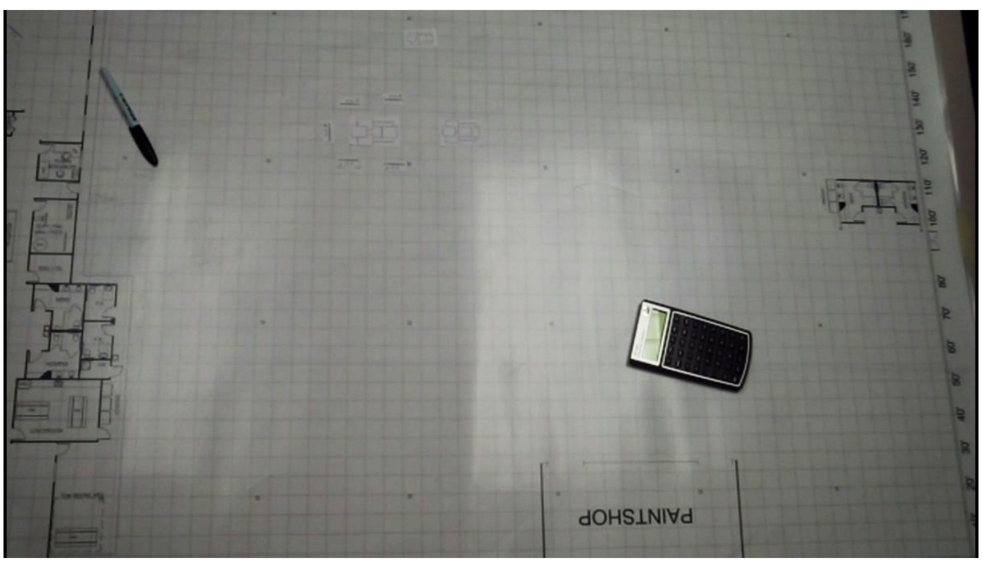

Figure 29: Team J Layout at 160 minutes

Time segment 82-160 follows a similar pattern, with the addition of a couple of high-level variables being discussed too. Figure 29 shows the layout at the end of 160 minutes.

During this time, the team discussed staffing (S2) along with “high level flow logic” and “spatial flow pattern”. The only difference here in the layout is the appearance of certain elements of the machine assembly cell.

This can be attributed to the discussion of flow pattern and logic of the facility, perhaps the assembly cell. However, the timelines show no evidence of discussion of layout of the assembly cell.

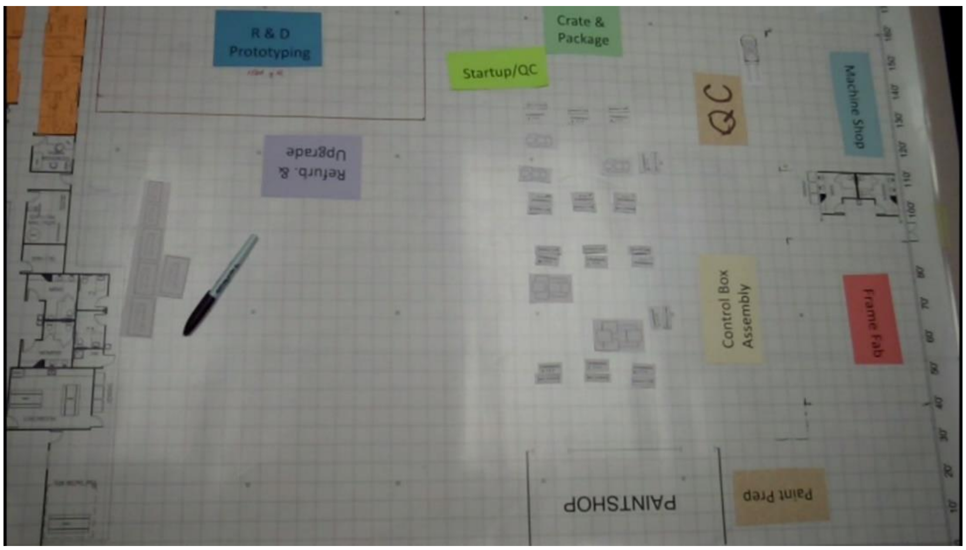

Figure 30: Team J Layout at 200 minutes

Figure 30 shows the facility layout at the end of 200 minutes. During the time segment160-200, the team discussed location (Loc1), Paint location (PL), Size (Sz), and Location & Size (LSz1) subproblems. Since all these subproblems deal with either the location or size (or both) of areas, the layout is expected to have a lot more detail than before. This is evident in figure, where we can see that the location of Pint prep (PL), Control Box Assembly, Crate & Package, Refurbishment & Upgrade, QC, and Machine Shop (Loc1) have been decided. In addition, the location and layout of the module and machine assembly cells seems to have been discussed too, which is not evident from the timeline.

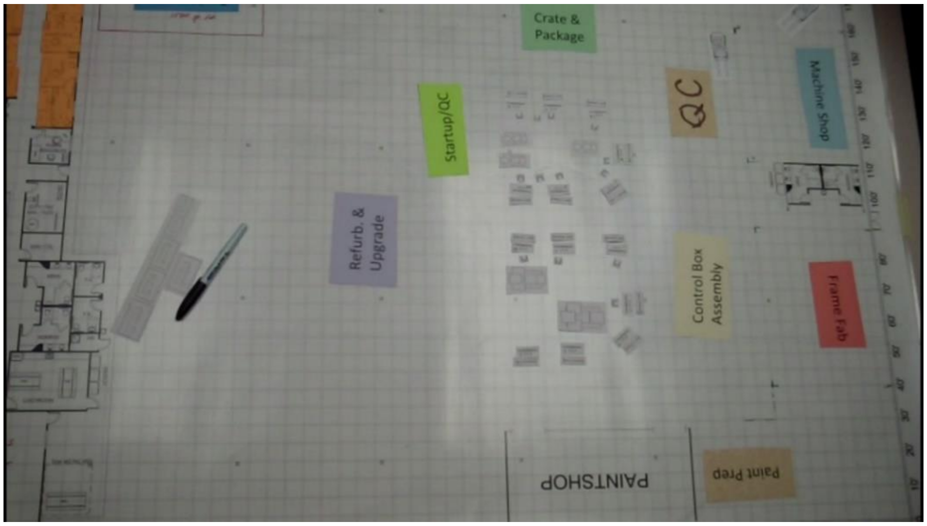

Figure 31: Team J Layout at 210 minutes

Figure 31 shows the layout after 210 minutes. Only the locations of Incoming QC and Refurbishment & Upgrade have been changed. From the timeline, the team discussed only the location and size subproblem (LSz1). Location of both areas are not identified to be a part of this subproblem.

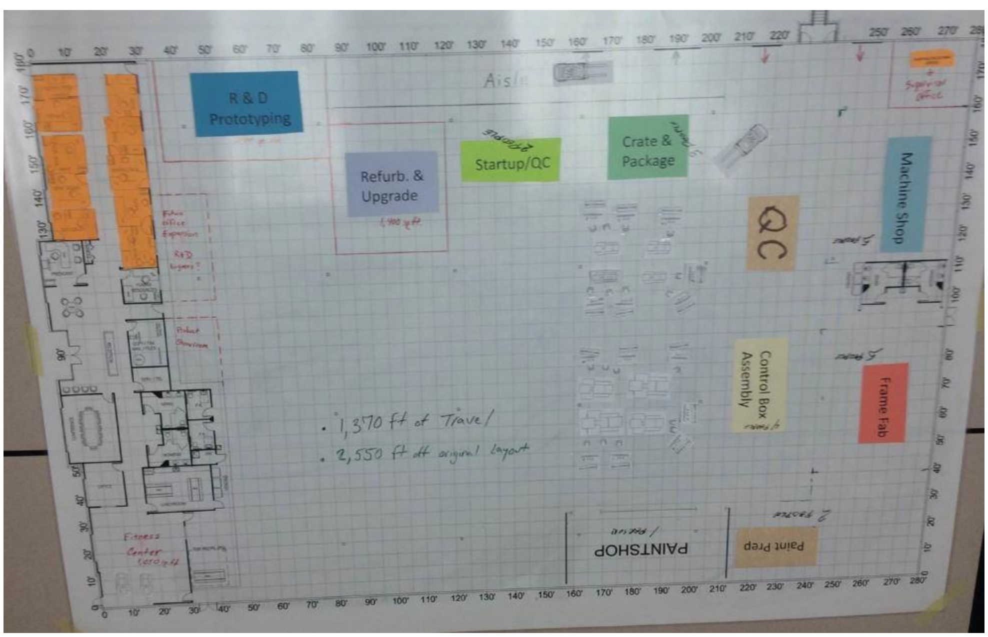

Figure 32: Final Layout of Team J

Finally, Figure 32 shows the layout of Team J at the end of the discussion. During this time, the team discussed Location (Loc1) and Size (Sz) subproblems.

The location of refurbishment & upgrade and incoming QC has been decided on the layout, and this can be attributed to the discussion of Loc1 subproblem. Also, the fitness center (gym) has been identified, presumably because of the LSz1 discussion in the previous time segment. The layout also shows the number of people staffed per area, likely obtained using the results of the staffing discussions at the beginning of the discussion. This is the final layout of Team J.

6.2.<u>Team K Layout Discussion</u>

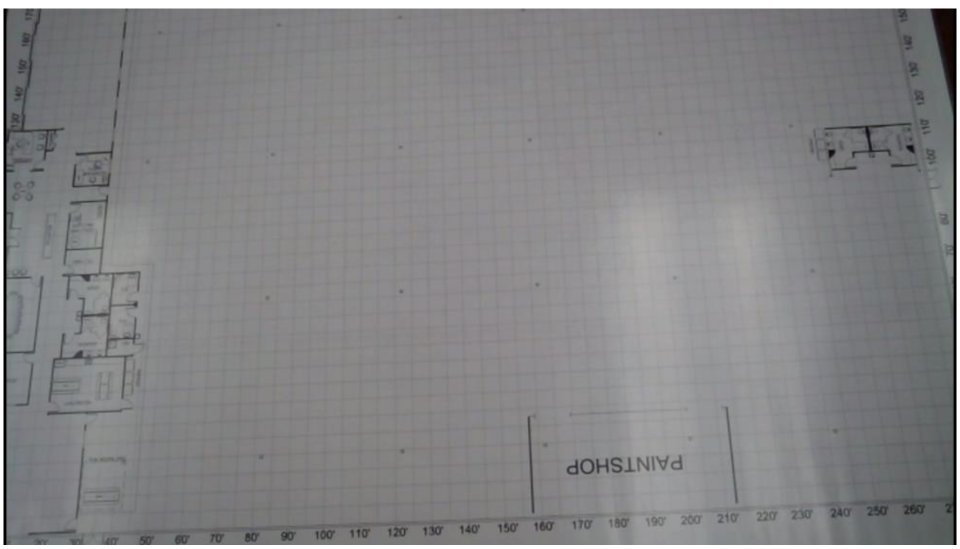

Figure 33: Team K Layout at 84 minutes

From the timeline, from the start of the discussion until the 84th minute, the team discussed only staffing subproblems (S3 and S4) along with one high-level variable (spatial flow pattern). These discussions saw no changes in the layout, as seen in Figure 33. The discussion was focused on calculating how many people per area would be needed and the general layout of the entire facility, before the locations or sizes of any of the areas were decided.

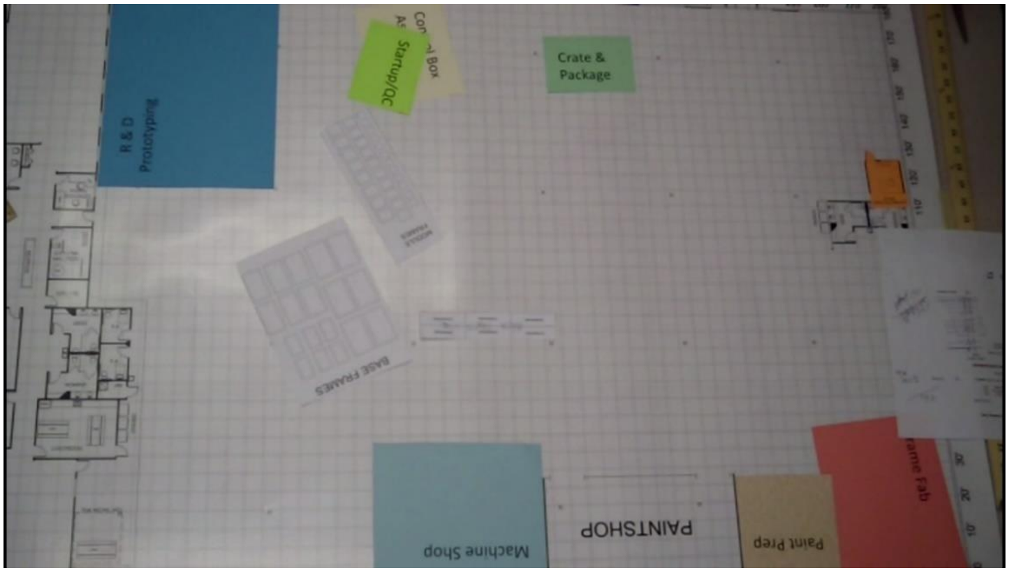

Figure 34: Team K Layout at 124 minutes

Figure 34 shows the layout after 124 minutes. During this time, the team discussed one subproblem (location – Loc2) and two high-level variables (spatial flow pattern and assigning operations to areas). It is interesting here that even though the location subproblem (Loc2) does not include location variables for any of the major areas of the facility, most of the areas have been assigned a location in the layout. Frame Fabrication, Paint Prep, Machine Shop, R&D, and Crate & Package have been assigned locations in Figure 32.

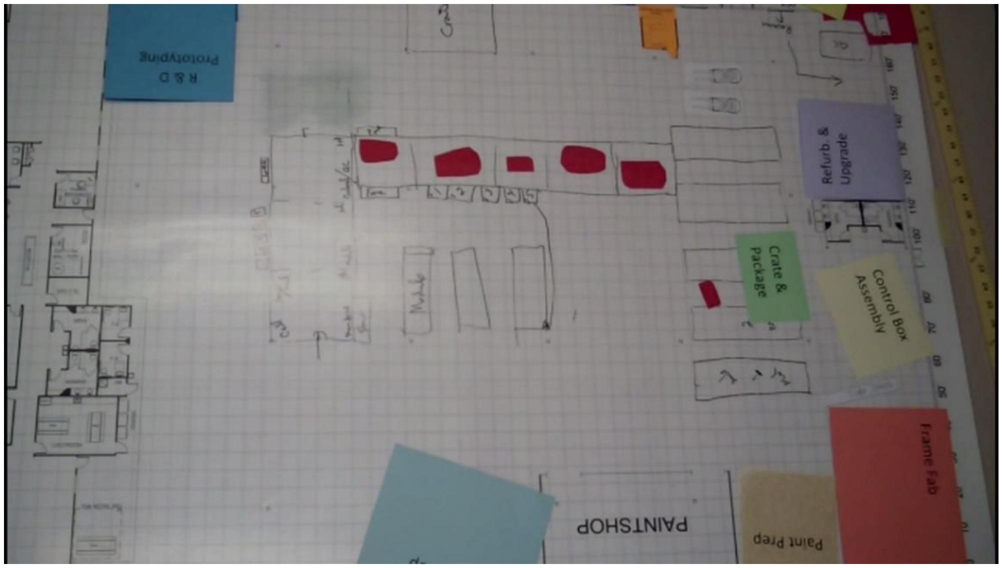

Figure 35: Team K Layout at 162 minutes

Figure 35 shows the layout at the end of 162 minutes. Between minutes 124 and 162, the team discussed Machine Assembly (MA1) and Location (Loc2) subproblems. In addition, they also discussed the assigning operations to areas high-level variable. From the figure, the machine assembly area has been designed, and the layout has been decided. This can be attributed to the discussion of the MA1 subproblem. Locations for a host of inventory areas and staging areas have also been identified, which is in accordance with the Loc2 subproblem. However, the location of Control Box Assembly, Refurbishment & Upgrade, and Crate & Package also seem to be modified, which cannot be attributed to discussion of any of the identified subproblems.

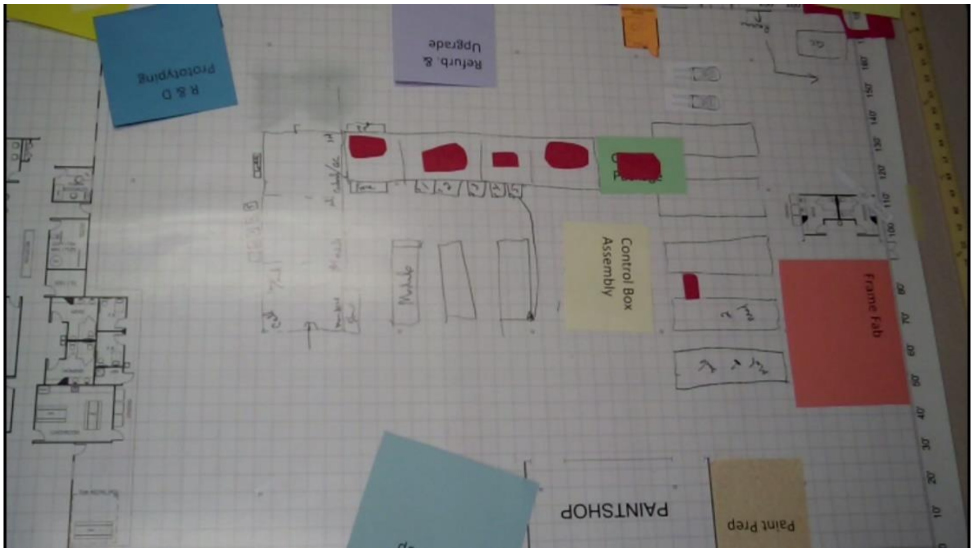

Figure 36: Team K Layout at 166 minutes

Figure 36 shows the layout after 166 minutes. During minutes 162 – 166, the team discussed the paint subproblem (P1). The layout shows that the location of Frame Fabrication has been modified, presumably to make way for the paint staging location (discussed as a part of P1). Location of control box assembly, refurbishment & upgrade, and crate & package continues to change without any identified discussions.

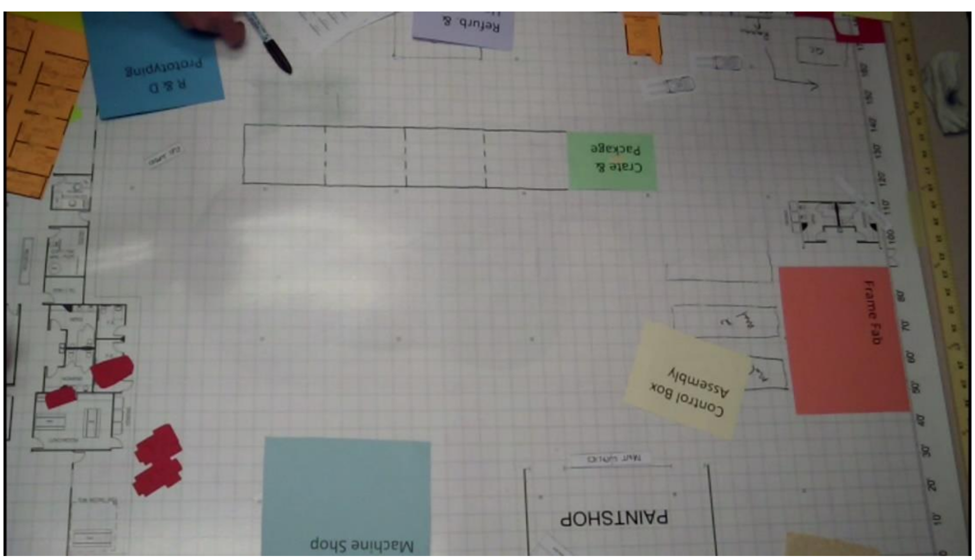

Figure 37: Team K Layout at 182 minutes

Figure 37 shows the layout at 182 minutes. From the timeline, the team discussed only the Machine Assembly subproblem (MA1) during this time. The result is coherent, the machine assembly area in the layout is undergoing modification as can be seen in the figure. No other significant changes can be seen.

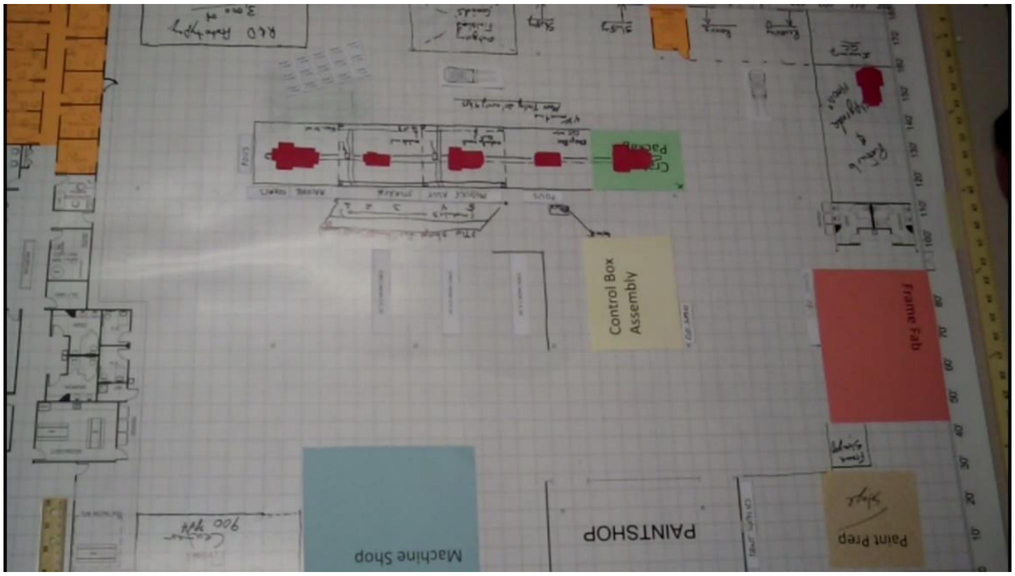

Figure 38: Team K Layout at 214 minutes

Figure 38 shows the layout at the end of 214 minutes. The machine assembly area is now fully developed. The team discussed two subproblems during this time: location (Loc2) and Location & Size (LSz2). The layout shows that the location and size of refurbishment & upgrade and QC have been decided, owing to the discussion of LSz2 subproblem which contains these variables. Also, the size of R&D, location of gym, and location of control box assembly is decided, but no corresponding discussions are identified from the timelines. Also, the paint storage area has been located, presumably decided during the previous time segments when P1 was discussed.

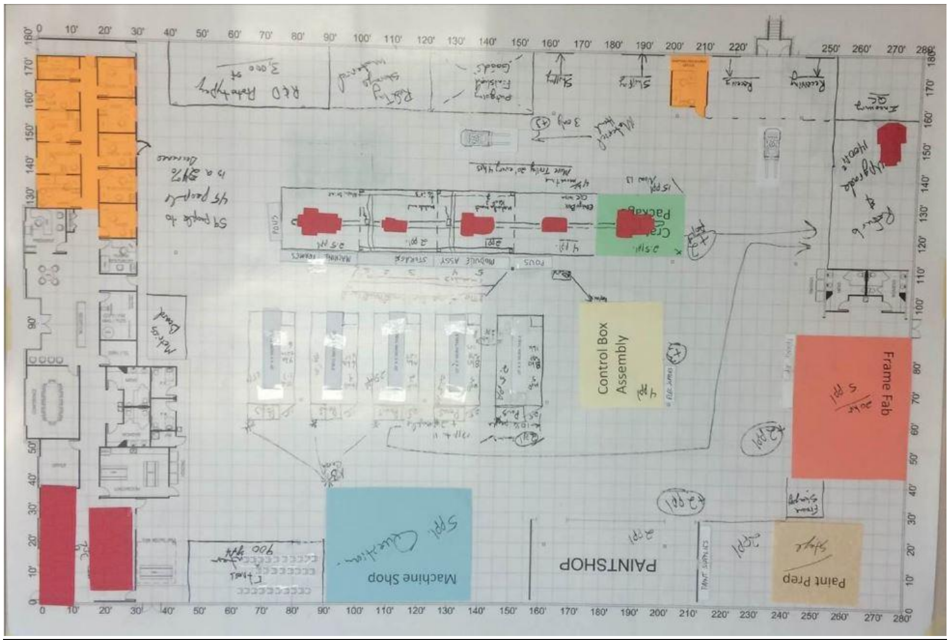

Figure 39: Final Layout of Team K

Figure 39 shows the layout of Team K at the end of the discussion. The module assembly area has been identified. During this time, the team discussed staffing subproblems (S3, S4, and S5). The Figure shows the layout now includes the staffing numbers as well, based on these discussions.

6.3.<u>Team L Layout Discussion</u>

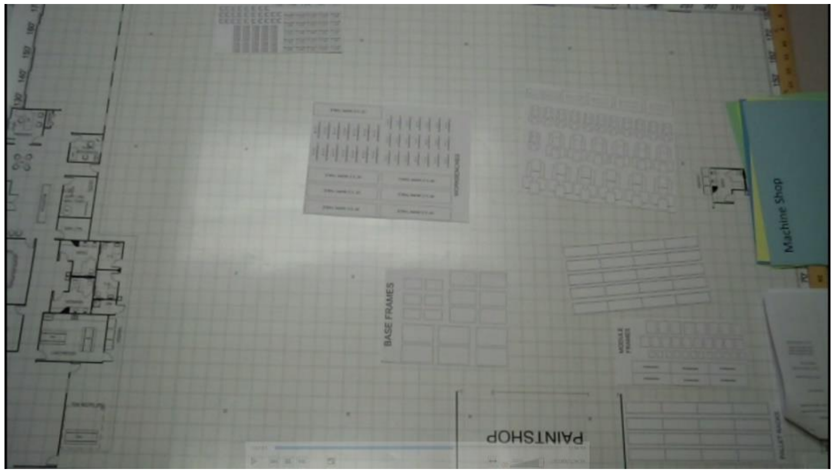

Figure 40: Team L Layout at 62 minutes

Figure 40 shows the layout at the end of 62 minutes. From the timeline, it can be seen that from the start of the discussion until the 62nd minute, the team discussed only the Staffing & Location subproblem (SL1). Even though there was one location variable in this subproblem, the figure shows that there were no changes in the layout. The discussion was focused on calculating how many people per area would be needed and the general layout of the entire facility, before the locations or sizes of any of the areas were decided.

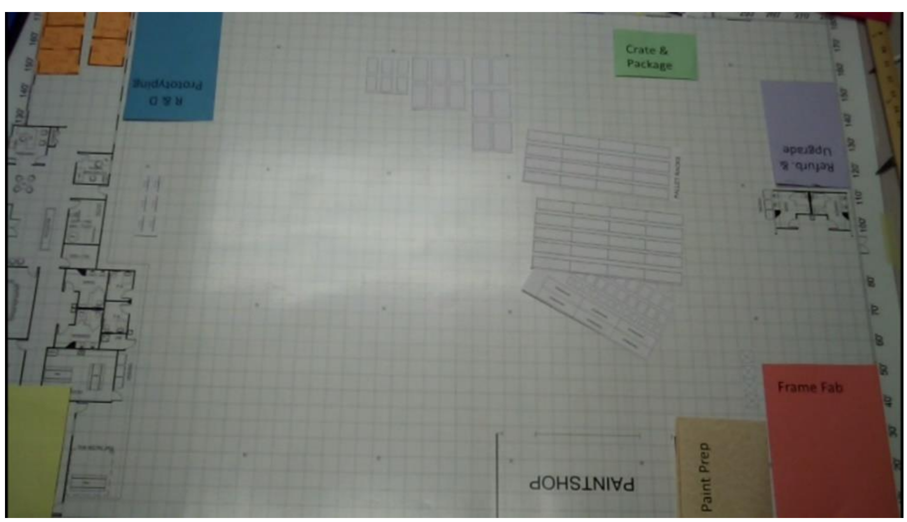

Figure 41: Team L Layout at 128 minutes

Figure 41 shows the layout at the end of 128 minutes. During the time segments 62 – 128, the team discussed Location (Loc3), Staffing (S6), Staffing & Location (SL2), and Location & Size (LSz3) subproblems along with a high-level variable (spatial flow pattern). The resulting layout shows that the location of paint prep, frame fabrication (discussed as Loc3), R&D (discussed as LSz3), Crate & Package, and Refurbishment & Upgrade (not discussed) have been identified.

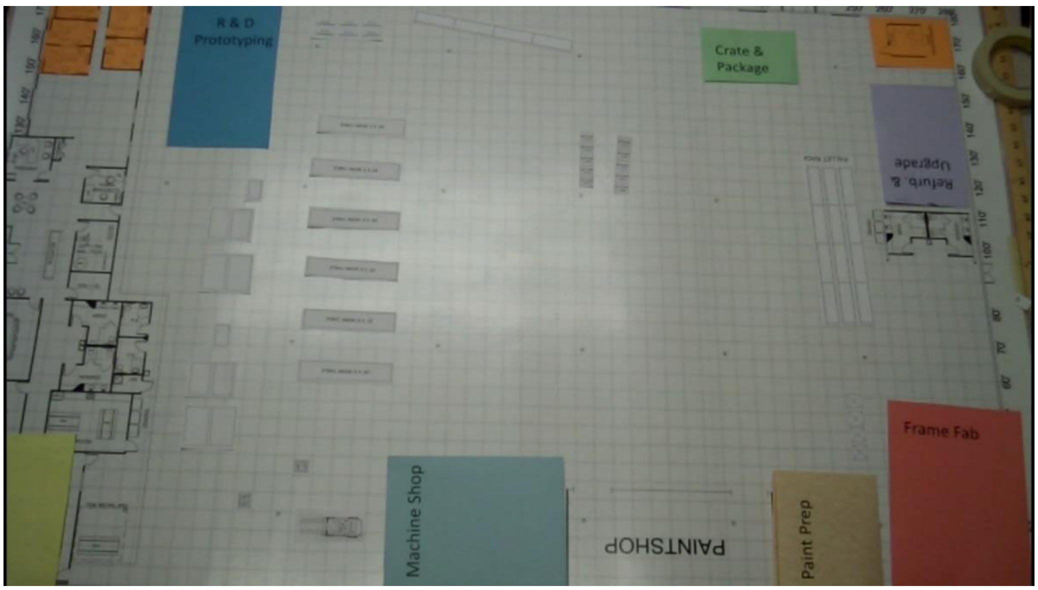

Figure 42: Team L Layout at 170 minutes

Figure 42 shows the layout at 170 minutes. Between minute 128 and 170, the team discussed Assembly Layout (AL1) and Location (Loc3) subproblems. From the figure, the new additions to the layout are the machine shop, and the assembly cell (module and machine assembly areas). The assembly cell appearance is clear, since the AL1 subproblem was discussed. Also, the location and size of machine shop was discussed in previous time segments (LSz3). Thus, the appearance of machine shop is a result of previous discussions.

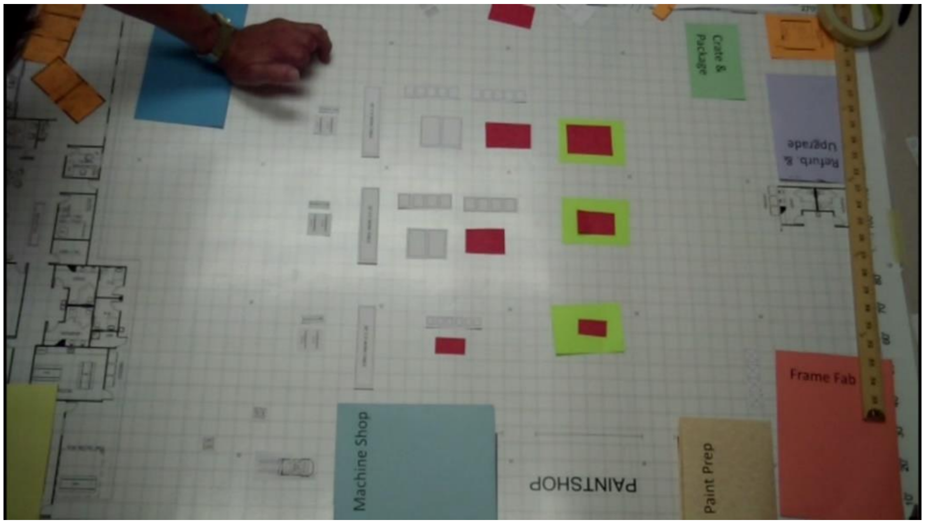

Figure 43: Team L Layout at 216 minutes

Figure 43 shows the layout progress at the end of minute 216. Team L discussed two subproblems between minutes 170-216 along with the spatial flow pattern variable: Assembly Layout (AL1) and Staffing & Location (SL2). The figure shows that in the layout, the assembly cell layout has changed. This is attributed to the extensive discussion of the AL1 subproblem during this time. Also, some inventory areas have been added because of discussion of SL2 subproblem.

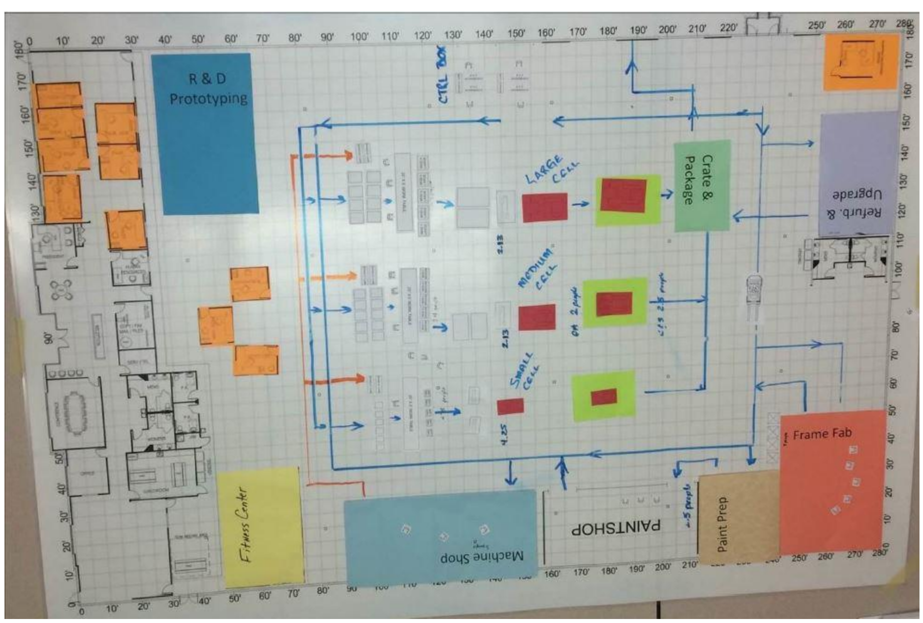

Figure 44: Final Layout of Team L

Finally, Figure 44 shows the final layout of Team L. The timeline does not identify any subproblems discussed between minute 216 till the end of the discussion. However, the layout shows some updates. The assembly cell is complete. The location of crate & package has been adjusted and the gym (fitness center) has also been added. Lines have been drawn to depict the flow of product to and from all areas.

6.4. <u>Team X Layout Discussion</u>

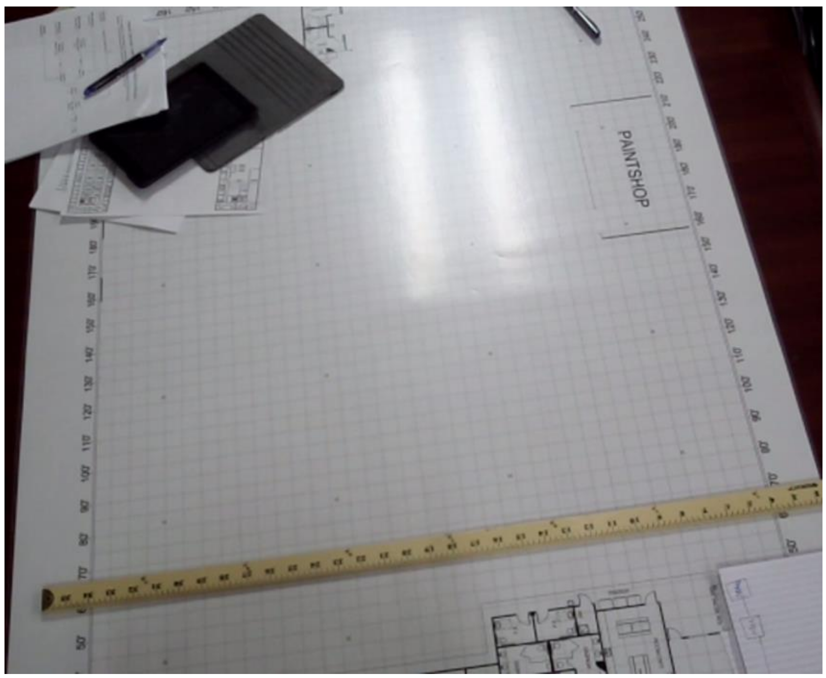

Figure 45: Team X Layout at 60 minutes

Figure 45 shows the layout of Team X at 60 minutes. From the timeline, it can be seen that from the start of the discussion until the 60th minute, the team did not discuss any subproblems. The figure shows that there were no changes in the layout. The discussion was focused on understanding the problem and flow of the facility, before the locations or sizes of any of the areas were decided.

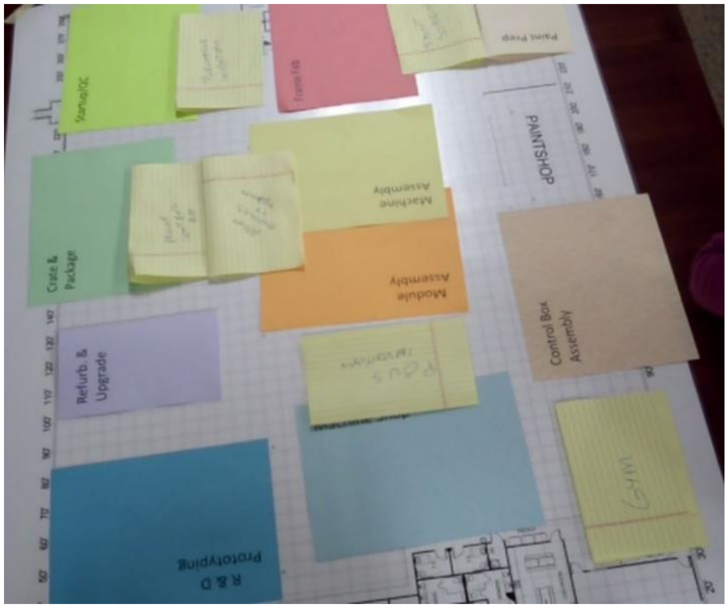

Figure 46: Team X Layout at 82 minutes

Figure 46 shows the layout at the end of 82 minutes. From the timeline, Team X discussed Location and Flow (LF1) and location (Loc4) subproblems from the start of the discussion to minute 82. The corresponding layout progress can be seen in Figure 46. Locations of all areas have been set, because of the discussions being focused mainly on location-based variables.

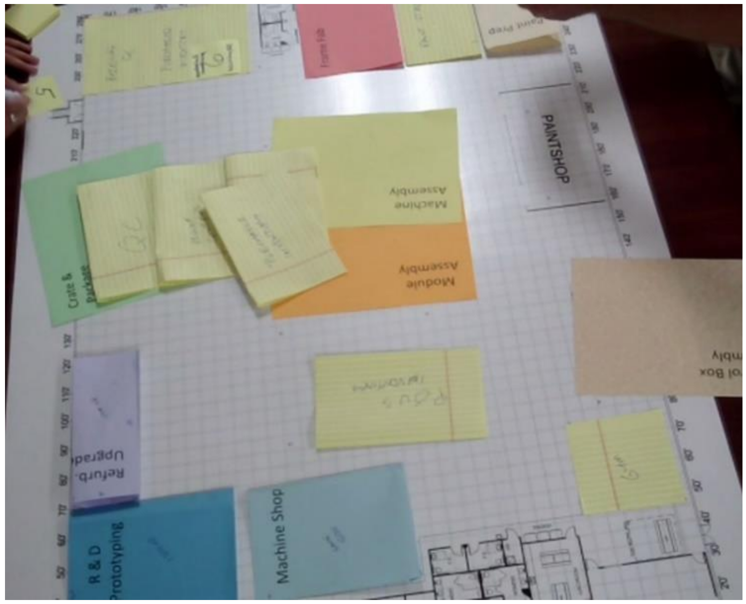

Figure 47: Team X Layout at 122 minutes

Figure 47 shows the progression of layout design in the interval from 82 to 122 minutes. During this time, the team discussed Staffing subproblems; Location, Size, Staff subproblem, and the Location & Flow subproblem. The major changes in the layout are the size of refurbishment and R&D areas, location and size of machine shop, and gym. Even though Location and size related subproblems were discussed during this time, apart from the location machine shop (which was discussed as a part of the LF1 subproblem) the other two areas cannot be attributed to any of the subproblems discussed during this time. This points to decisions being made based on discussion of variables that were either not clustered or were discussed at a previous time. In addition, a QC area has been added which corresponds to the QC1 subproblem discussed in the 82nd time segment.

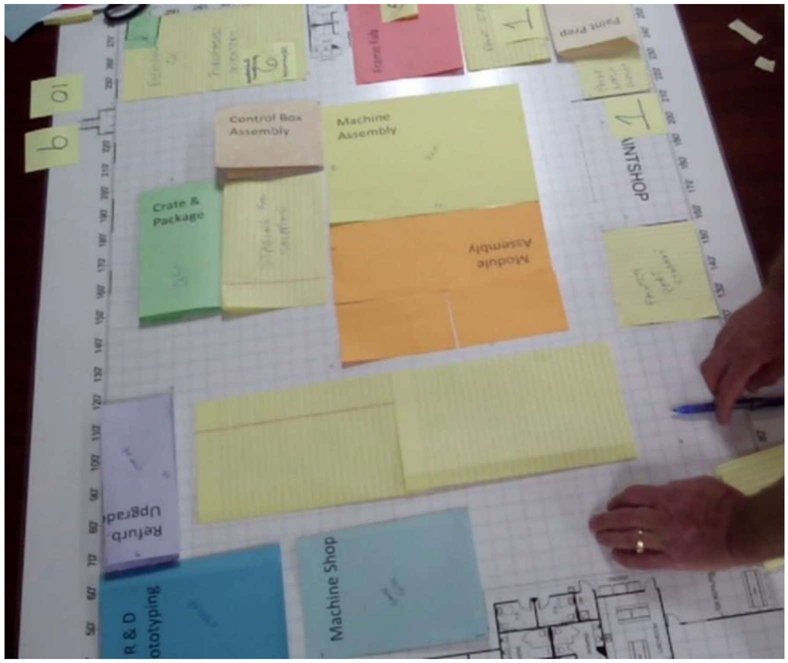

Figure 48: Team X Layout at 140 minutes

Figure 48 shows what the layout looked like after 140 minutes. In the interval between 122 and 140 minutes, the team continued discussing location and flow (LF1), location size and staffing (LSS); and QC (QC1) subproblems during this time. The major updates that can be seen in Figure 48 are the locations of QC area (attributed to QC1 subproblem), Crate and Package, Control Box Assembly (discussed as a part of LF1 subproblem), and Shipping and Receiving (not discussed in any subproblem). Also, the size of Crate and Package, Control Box Assembly, and Inventory have been modified but no corresponding variables were discussed during this time. In addition, the team has also identified new areas – painted parts storage and paint supplies storage (LF1).

Figure 49: Team X Layout at 148 minutes

Figure 49 identifies the layout progress at the end of the 148th minute. From the timeline (minute 140 to minute 148), the team only discussed one notable cluster (miscellaneous subproblem – M1). The POUS inventory has been established, as discussed in the M1 subproblem. However, the layout shows many more change from the previous figure. The layout of the module assembly area has been decided, which was not evident from the timeline observation. The location of gym also seems to have been finalized. The staffing numbers for each area have also been noted, based on previous staffing discussions. Finally, an area at the bottom beside the gym has been assigned for "future use". This makes sense, because the timeline shows that the team discussed allocation of large areas variable during this time.

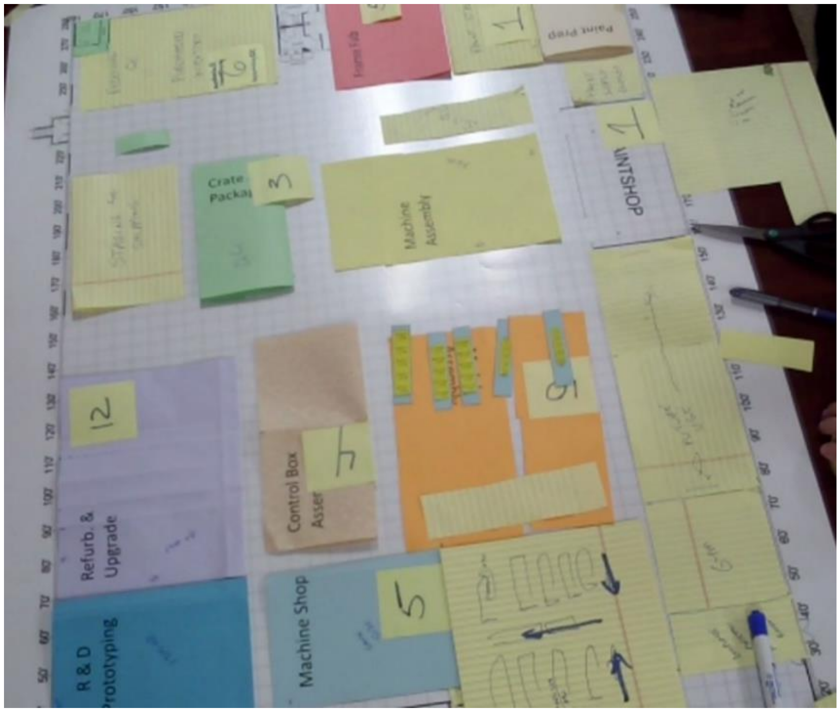

Figure 50: Team X Layout at 162 minutes

After the discussion of a location and flow subproblem (LF1) in the 162nd minute and the high-level variable "assigning products to areas", the layout looks as shown in Figure 50. The locations of the module assembly and control box assembly have changed. This is logical, since the LF1 subproblem has corresponding variables for location of module and control box assembly. It should also be noted that the layout of the module assembly has been modified a bit. Also, the size of control box assembly has changed, even though we don't see a subproblem related to this being discussed in the timeline. There have been additions on the right of the machine assembly for inventory areas, and the painted part storage has been discarded, presumably because of the M1 cluster in the earlier time segments (since M1 contains size of storage variable).

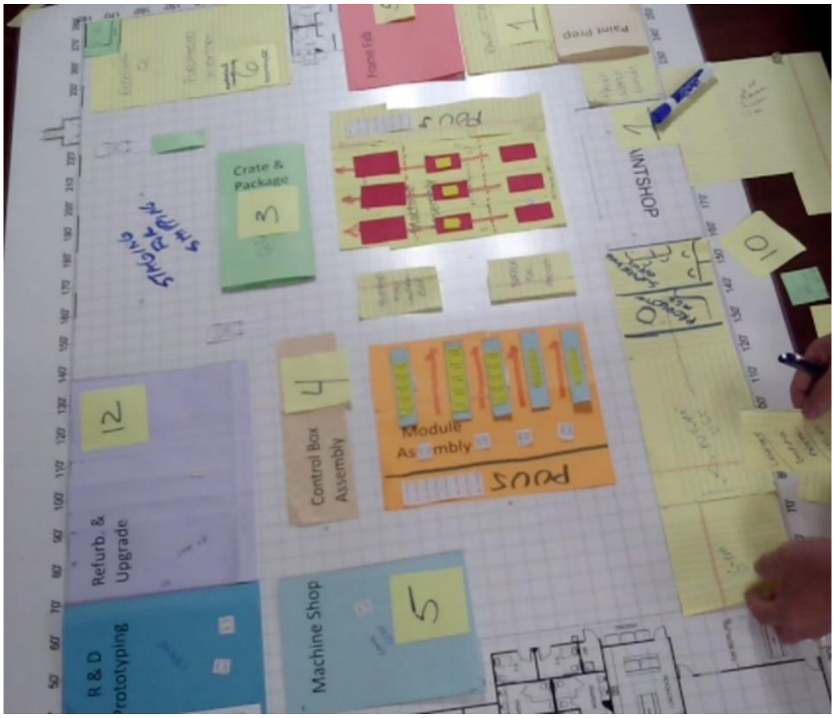

Figure 51: Team X Layout at 192 minutes

Figure 51 shows the layout at the 192nd minute, after the team discussed their last subproblem (Loc5). The subproblem focuses on location of lockers and the employee break room. However, the major change seen here is the layout of the machine assembly cell has been developed. The module assembly cell has also seen some details added. The location of POUS Inventory has also been designated in both these cells. None of these variables are a part of the subproblem discussed.

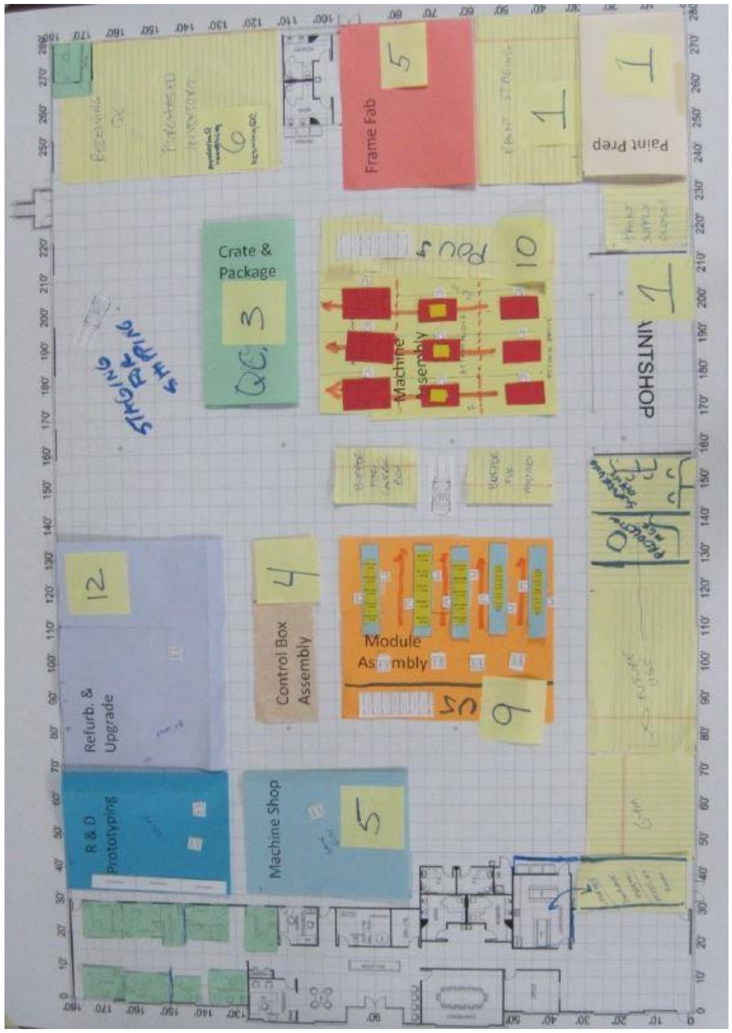

Figure 52: Final Layout of Team X

Figure 52 shows the final layout designed by Team X after the discussion is concluded. It includes a machine assembly area with three assembly lines, and a module assembly area with five assembly lines. These are in the center of the facility. The control box assembly is located above the module assembly, and the Crate and package is located above the machine assembly. Frame fabrication is located to the right of the machine assembly, while the machine shop is located to the left of the module assembly (and control box assembly).

R&D and Refurbishment areas are located on the top left, next to the offices. The top right houses the shipping and receiving office and the inventory area.

6.5.<u>*Team Y Layout Discussion*</u>

Figure 53: Team Y Layout at 40 minutes

Figure 53 shows the layout of Team Y at 40 minutes. From the timeline, it can be seen that until the 40th minute, the team did not discuss any subproblems. The figure shows that there were no changes in the layout. The discussion was focused on understanding the problem and flow of the facility, before the locations or sizes of any of the areas were decided.

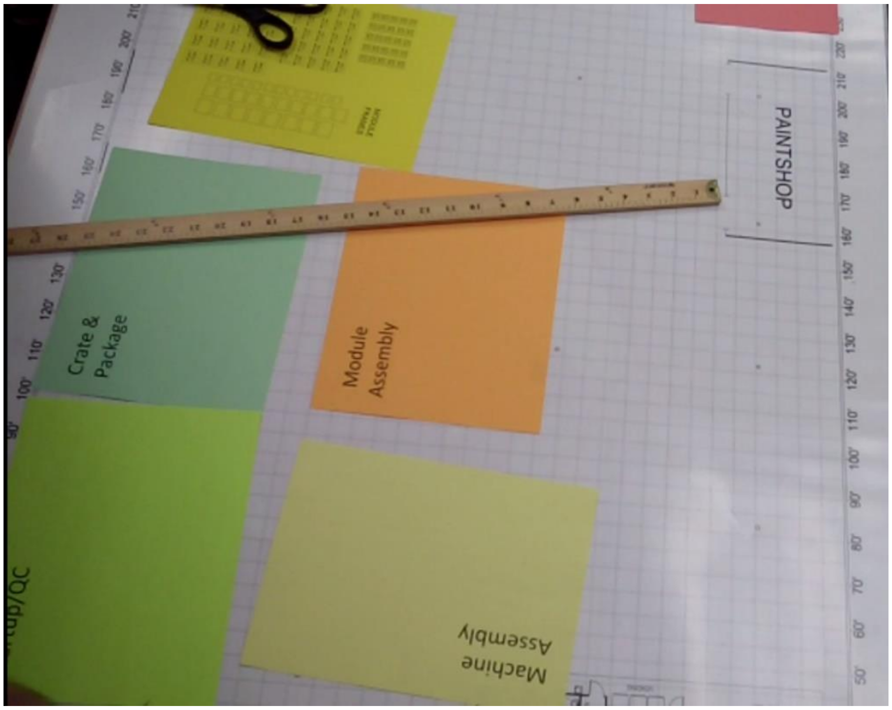

Figure 54: Team Y Layout at 58 minutes

Figure 54 shows the layout at the end of 58 minutes. From the timeline, Team Y discussed Location and Flow (LF2) subproblem between time segments 44 and 46. However, the layout was not worked on during this time segment. It was only after 58 minutes, when the team discussed Location and Size (LSz4, LSz5) subproblems when the team worked on the layout. Figure 54 shows that Locations of frame fabrication, machine shop, inventory, crate and package, machine assembly, module assembly and QC have been set. Out of these, only the location of incoming QC was discussed as a part of a subproblem (LSz4) during this time. On analysis, it was noted that all the location-based variables (though not a part of identified subproblems) were discussed before 58 minutes.

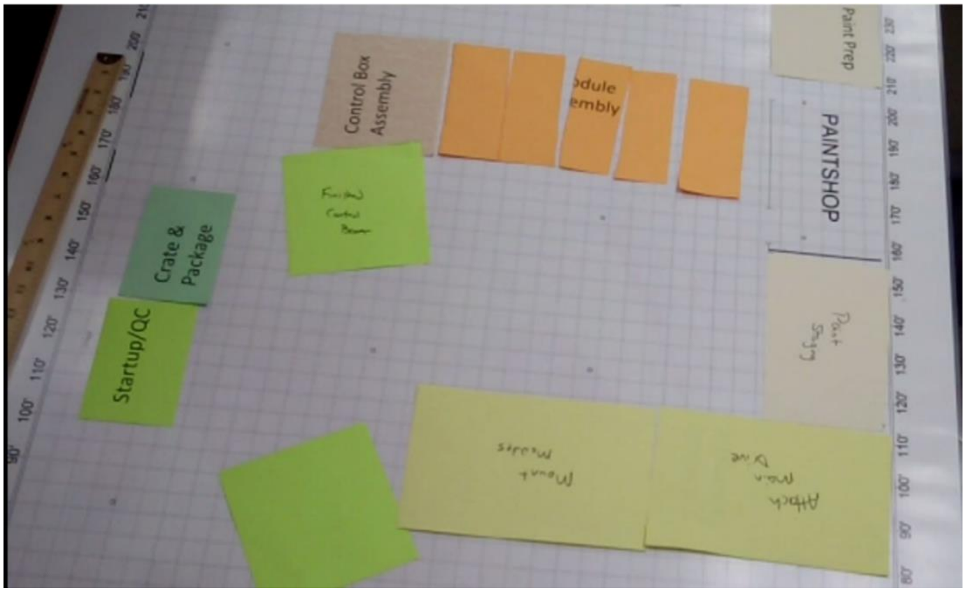

Figure 55: Team Y Layout after 80 minutes

Between the time segments 58 and 80, the team discussed 3 different subproblems: Size (Sz2), Paint (P2), and Staffing (S9) subproblems. Figure 55 shows the progress in the layout during this time. The location of QC, Crate and Package, and Module assembly has been modified even though no location variables were discussed. The size of Crate and package, and control box assembly has been decided because of discussion of the Sz2 subproblem. Size of Incoming QC has been modified, even though there was no discussion of a corresponding variable in any of the subproblems. Also, paint staging and paint prep have been assigned locations and size, owing to the discussion of the P2 subproblem. In addition, the location of attach main drive and mount modules have been assigned too, even though related discussions cannot be found in the timelines.

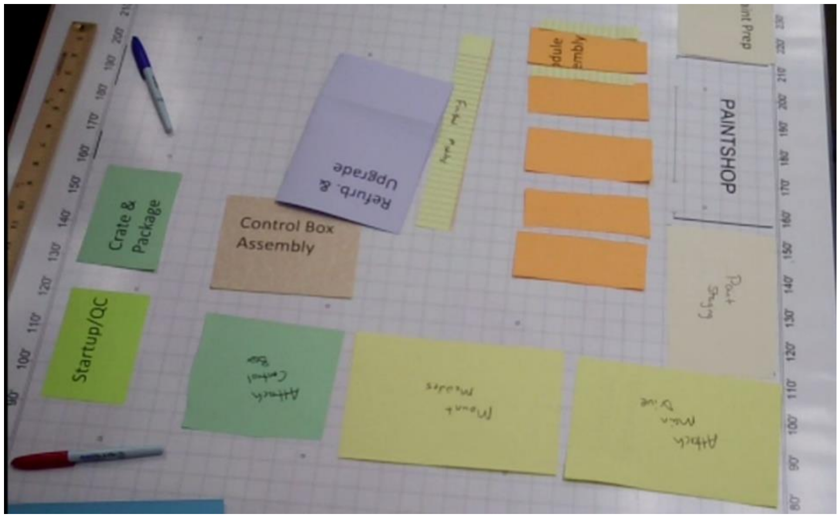

Figure 56: Team Y Layout at 108 minutes

During time intervals 80 – 108, the team discussed just one identified subproblem, layout and size (LAS) subproblem. The corresponding layout (Figure 56) shows that the location of control box assembly has changed, and the location of R&D, refurbish and upgrade and attach control box have been assigned. These are not found on the timelines (no location based subproblems were discussed). The location of module assembly has been modified again, and the area seems to be now divided into sections. This is a result of the layout discussion of machine assembly as a part of the LAS subproblem.

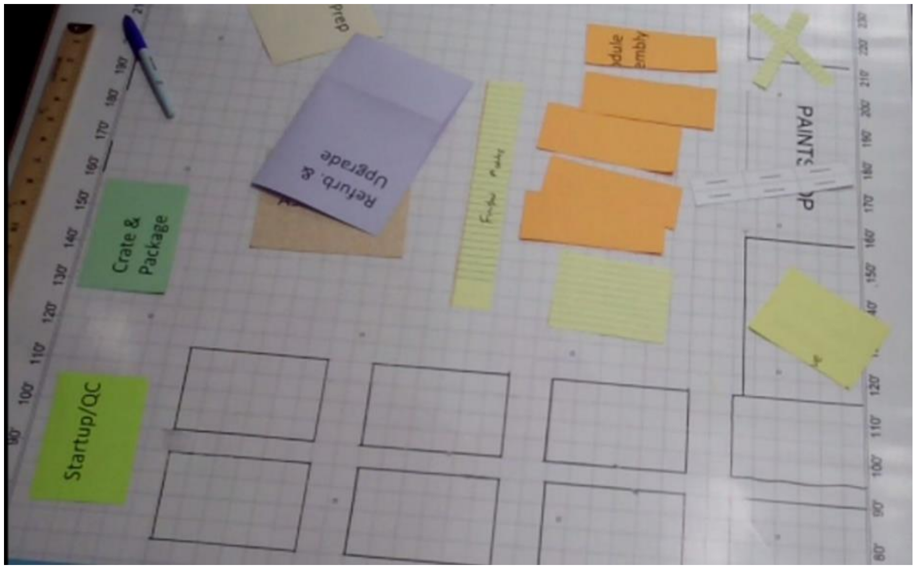

Figure 57: Team Y Layout at 134 minutes

Figure 57 shows the layout of Team Y after 134 minutes. Even though no subproblem was discussed between minutes 108 and 134, the layout is of significance. The team at this point started drawing the areas onto the board replacing the paper cut outs.

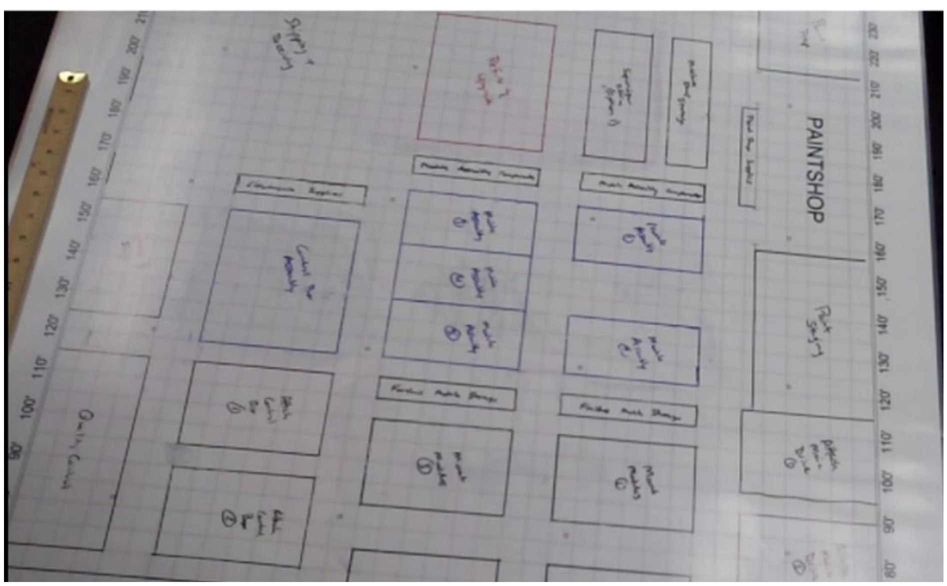

Figure 58: Team Y Layout at 198 minutes

During time interval 134-198, the team only discussed staffing related subproblems (S8, S9, and S10). However, the layout in Figure 58 shows significant changes.

The layout has neared completion, with location of shipping and receiving, module assembly cell, machine assembly cell, gym all finalized. The discussions do not reflect any location subproblems however, as the team only discussed staffing subproblems during this time. Thus, based on analysis of Team Y and comparing the timelines with the layout progress, I conclude that a lot of Team Y's discussion was done early in the process and the layout was updated later. Also, a lot of location variables were not identified as a part of any strong subproblems that would show a clear relationship between the discussion and updating of the layout during any of the time intervals.

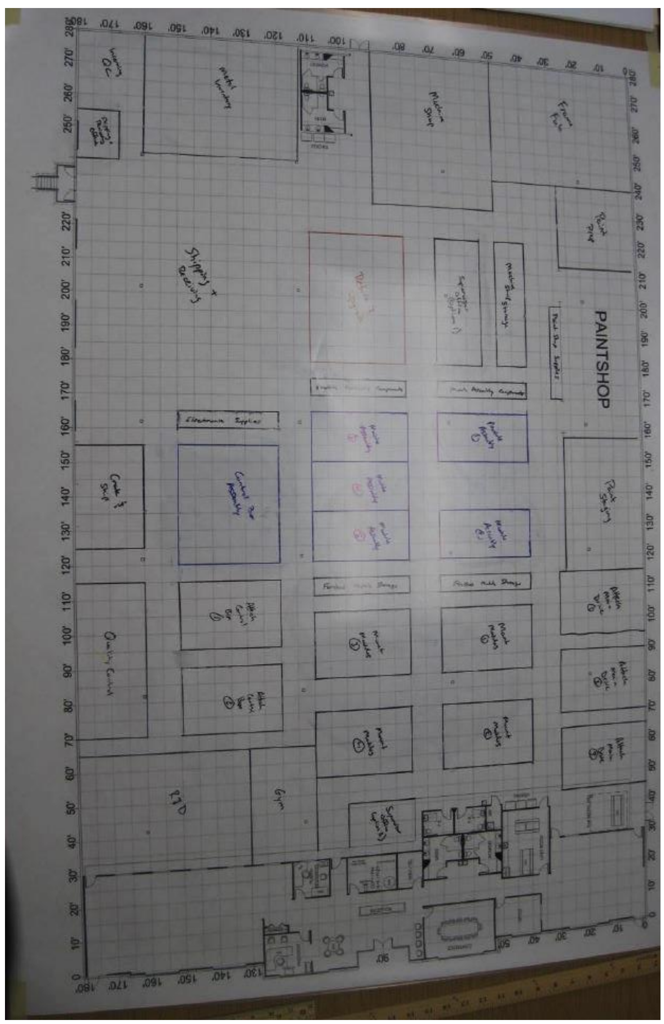

Figure 59: Final Layout of Team Y

Figure 59 shows the final layout designed by Team Y after the discussion is concluded. It includes a machine assembly cell which is broken down into mount module area and attach main drive area, and a module assembly cell with five assembly lines (drawn in blue). These are in the center of the facility.

The control box assembly is located to the left of the module assembly, and the Crate and package is located to the left of the control box assembly. Frame fabrication is in the top-right corner, while the machine shop is located to the left of frame fabrication. Refurbishment area is located above the module assembly cell, near the machine shop. R&D, QC and Gym are located on the bottom left, near the offices. The top left houses the shipping and receiving, S&R office, Incoming QC, and the inventory area.

6.6. <u>Team Z Layout Discussion</u>

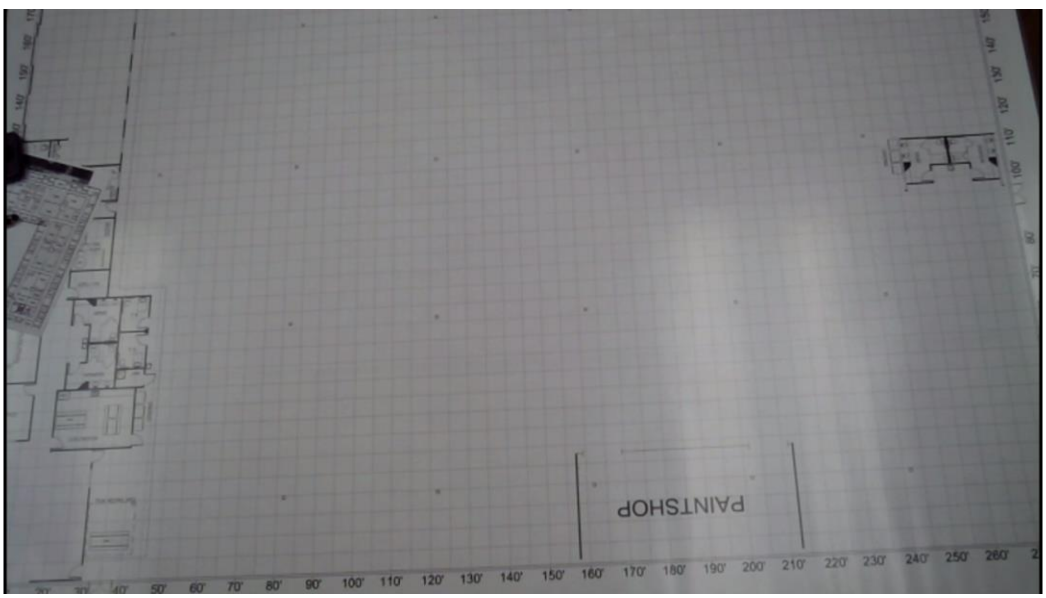

Figure 60: Team Z Layout at 40 minutes

Figure 58 shows the layout of Team Z at 40 minutes. From the timeline, it can be seen that until the 40th minute, the team did not discuss any subproblems. The figure shows that there were no changes in the layout.

The discussion was focused on understanding the problem and flow of the facility, before the locations or sizes of any of the areas were decided.

Figure 61: Team Z Layout at 92 minutes

Figure 61 shows the layout at the end of 92 minutes. From the timeline, Team Z did not start discussion of any subproblems. Thus, the layout was not worked on during this time segment. However, the figure shows that some discussions have indeed taken place.

Figure 62: Team Z Layout at 106 minutes

Figure 62 shows the layout progress after 106 minutes. From the timeline, it is observed that the team discussed two subproblems during this time: Location (Loc6) and Location & Flow (LF3) subproblems. The figure shows that the location of control box assembly, module assembly, machine assembly, R&D, Refurbishment, and Crate & Package have been set. All of these have corresponding variables in LF3 subproblem. In addition, the locations of Paint Prep and Frame Fabrication have also been decided, even though the location variables for these areas were not discussed as a part of the mentioned subproblems. In addition to these subproblems, the high-level variable "spatial flow pattern" was also discussed, which presumably played a part in identifying the layout of the facility before getting into the specific locations of each area.

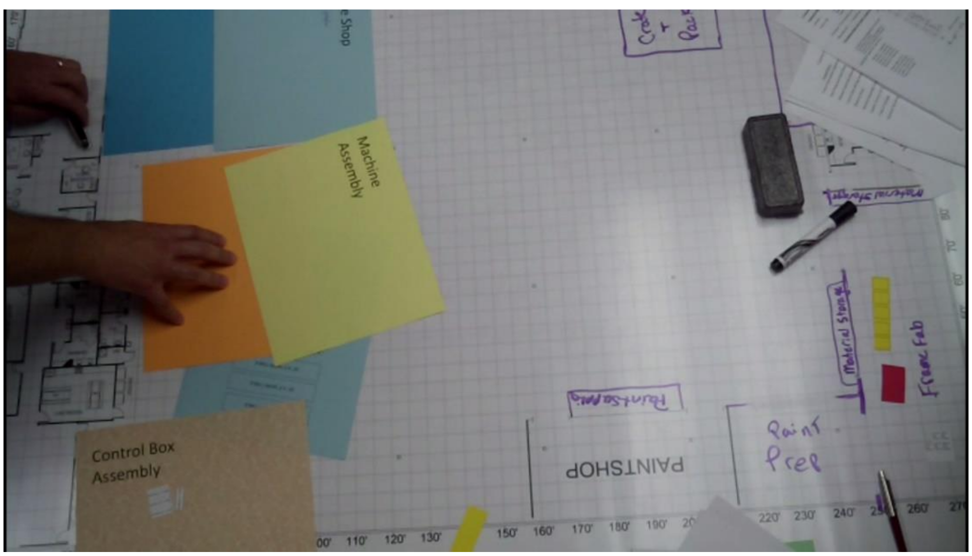

Figure 63: Team Z Layout at 142 minutes

Figure 63 shows the layout after 142 minutes. Between minutes 106 and 142, the team discussed location (Loc6), Location & Flow (LF3), and Layout & Size (LAS2) subproblems.

On comparison with Figure 62, it can be seen that the location of paint prep, frame fabrication, crate and package, and refurbishment have been decided and drawn using a marker. Also, the location of machine shop has been added (not discussed as a part of any subproblem). However, the location of machine assembly, module assembly, and control box assembly are still changing. This is corresponding in the timeline, where the team discussed subproblems containing location variables of control box, module, and machine assemblies. In addition, the team also discussed the layout and size of frame fabrication (LAS2). The same can be seen in Figure 63, where the frame fabrication area has some internal elements added to it. There is a paint storage area added too (above the paint shop). The size of paint storage area is included in one of the subproblems discussed (LAS2) but not the location variable.

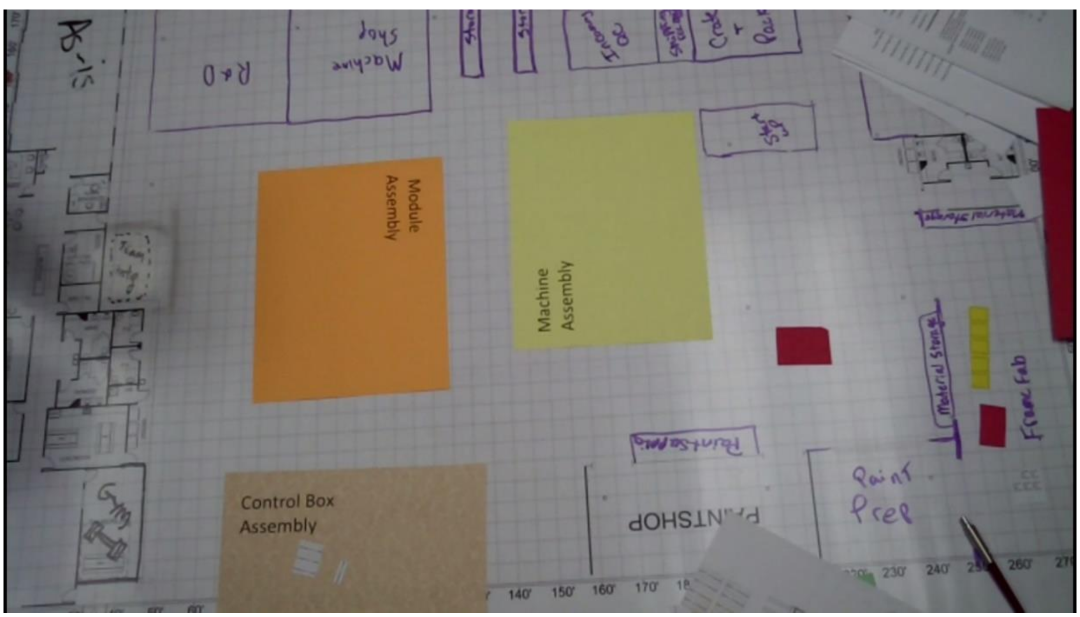

Figure 64: Team Z Layout at 154 minutes

Figure 64 shows the layout at the end of 154 minutes. There are many changes from Figure 63. Two subproblems were discussed between minutes 142-154: Location & Flow (LF3) and Location & Size (LSz6).

The location of R&D, Machine Shop, Incoming QC, and various storage areas have been decided and drawn using a marker. Also, the location and size of gym has been decided (discussed as a part of LSz6 subproblem). The module assembly, machine assembly, and control box assembly are still being discussed, which can be confirmed on observation of the layout and timelines. The Location of these three areas are a part of the LF3 subproblem which is being discussed during this timeframe.

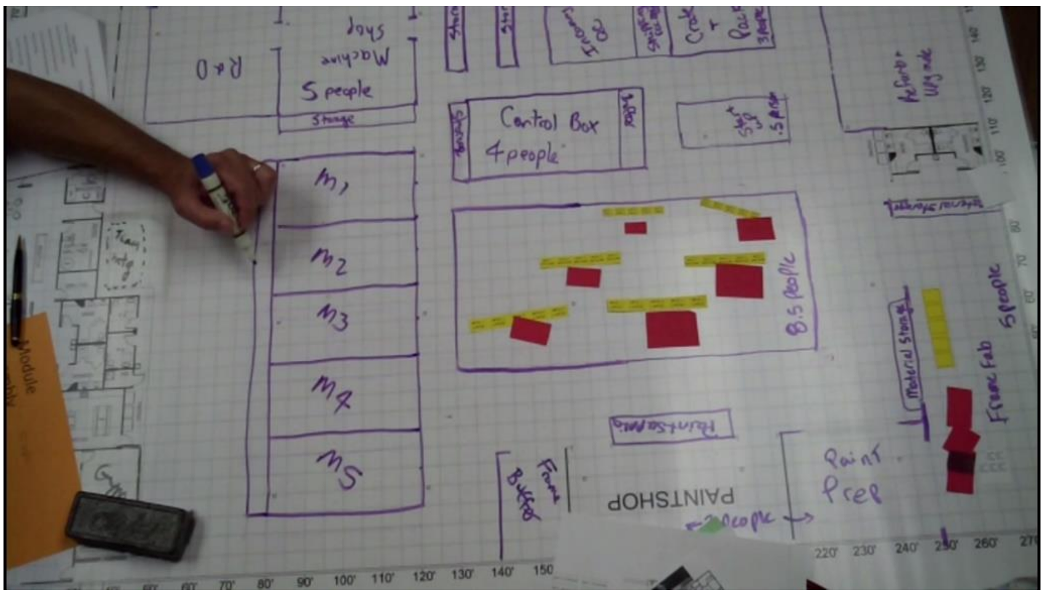

Figure 65: Team Z Layout at 186 minutes

Figure 65 shows the layout at 186 minutes. The only subproblem discussed between minutes 154 and 186 was the Location & Flow subproblem (LF3). The discussion of spatial flow pattern and location of control box, machine assembly, and module assembly has given rise to the layout seen in figure. The locations of all these areas have finally been decided and drawn on the layout board. In addition, the internal layout of module and machine assembly areas have also been decided, even though no variables related to layouts were included in the subproblem discussed during this time.

The staffing information for all areas has also been added (but not discussed in the subproblem identified).

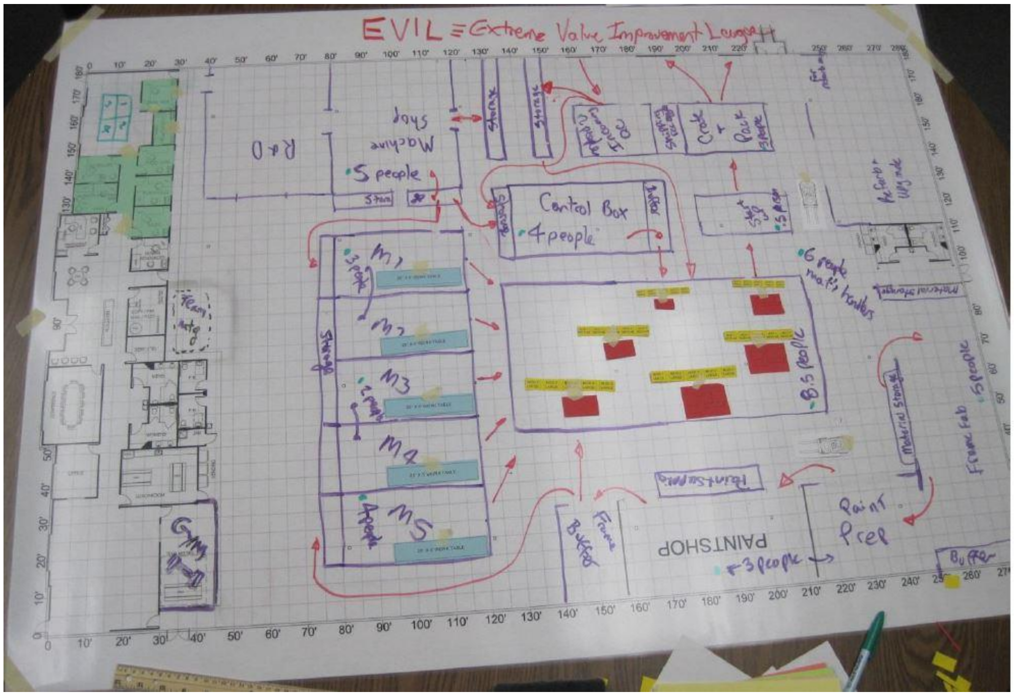

Figure 66: Final Layout of Team Z

Finally, Figure 66 shows the completed layout of Team Z. The timeline does not identify any subproblems being discussed during this time. However, the internal layout of machine assembly has been added to the layout board. Also, the flow directions for the entire facility have been drawn out. This is the final facility layout designed by Team Z.

6.7. *Correspondence Measure of Clusters*

Based on the analysis performed in the previous sections in this chapter, a way was needed to quantify the extent to which the subproblems accurately identified the actual discussions and updates to the layout. To do this, each figure in the previous sections was considered as a "discussion section". Within each of these discussion sections, the subproblems could satisfy one of three categories. The subproblems and discussions (changes in layout) would either:

- Correspond – they were able to explain all (or most) changes in the layout
- Somewhat Correspond – they were able to explain some changes in layout
- Do not Correspond – They were able to explain none of the changes in the layout

All the discussion sections were analyzed and the subproblems that fell into each of these categories were added to identify how often each of these categories occurred. An important thing to note here is that all the discussion sections where no changes occurred were not considered in this exercise. The results for all the teams can be seen in Table 57.

Table 57: Correspondence of Subproblems with Actual Discussions

Section	Corresponds	Somewhat Corresponds	Does Not Correspond	Figure
Team J				
1	1			30
2			1	31
3	1			32
Team K				
1			1	34
2		1		35
3		1		36
4	1			37
5		1		38
6		1		39
Team L				
1	1			41
2	1			42
3	1			43
4			1	44
Team X				
1	1			46
2		1		47
3		1		48
4		1		49
5		1		50
6			1	51
Team Y				
1		1		54
2		1		55
3		1		56
4			1	58
Team Z				
1	1			62
2		1		63
3	1			64
4	1			65
5			1	66
Sum :	**10**	**12**	**6**	

Based on Table 57 and looking at the sum of each of those discussion categories, it can be seen that the subproblems were able to explain the discussions all (or most) changes in the layouts 10 times and were able to explain some of the changes 12 times out of a total of 28 discussion sections. The subproblems were not able to explain the any of the changes in only 6 discussion sections out of 28. So, the conclusion is that the subproblems give a fair idea of the actual discussions and updates in the layout. However, there is scope for improvement.

Chapter 7: Discussion of Results

7.1.<u>Subproblem Selection Results</u>

From the results discussed in Chapters 4, 5, and 6, we conclude that the teams decomposed the design problems differently. As indicated by the similarity values in Tables 9 and 10, no two teams had similar clusters of the common variables. However, some similarities in the teams' timelines were identified. Teams started their discussions gradually and took their time to understand the problem and the current design (Table 53). After the 90-minute mark, almost all the teams (except Team J) discussed location subproblems as indicated in Tables 54 and 55.

However, the differences identified outweigh the similarities. The cluster tables (Tables 41 to 46) indicate that no clusters formed by the teams were identical. Many of the selected clusters include variables of the same type for multiple areas (e.g., location variables). We found fewer clusters with different types of variables for one area: Team K had two such clusters; Teams X, Y, and Z had one such cluster; and Teams J and L had no such clusters. This may reflect the fact that the different areas in the factory were competing for a limited amount of space in the factory. Thus, the locations of the areas were tightly coupled; moving one area required moving others. And the sizes of the areas were tightly coupled; increasing the size of one area required shrinking the size of another. The staffing variables were coupled because each area needed sufficient capacity to meet expected demand. On the other hand, the coupling between variables of different types was not as strong. Teams K, L, and X had different variables clustered by area (Frame Fabrication, Paint, etc.) rather than by function (Location, Size, etc.), which was not exhibited in other teams.

The order of discussion for all the teams was different too, as discussed in Tables 53 to 56. Thus, even though there are some similarities, the conclusion is that all teams approached the factory design problem differently and created a different set of subproblems to tackle the problem.

Discussions about high-level variables can provide insights into whether a team used a top-down or bottom-up design approach. One high-level variable that was discussed by all teams was the spatial flow pattern. Other high-level variables are also identified in Tables 53 to 56.

Although all six teams discussed the spatial flow pattern variable, it was not in a selected cluster for three teams (J, K, and L). For teams X, Y, and Z, it was included in the clusters LF1, LF2, and LF3, which also included location variables for different areas. Although all three teams discussed the variables in these cluster early in their design processes, Team X discussed these repeatedly throughout their design processes. Thus, we conclude that Teams Y and Z followed a top-down approach, while results from Team X discussions did not clearly depict the use of either a top-down or a bottom-up approach. Teams J, K, and L did not have a high-level variable in any cluster, however they still discussed them. Teams J and L discussed spatial flow pattern in the latter stages of their discussion (Table 55).

In addition, Team J also discussed the high-level flow logic. Thus, we conclude that Teams J and L used some form of a bottom-up design approach. Team K discussed the spatial flow pattern repeatedly throughout the discussion, while also discussing assigning operations to areas in the later stages. The results did not clearly depict the use of either a top-down or a bottom-up approach.

Thus, based on the analysis performed, the design teams used different approaches to break down the design problems.

7.2.Layout Comparison Results

From the analysis presented Chapter 6, a few conclusions can be made about the selected subproblems and the corresponding layouts designed by the teams.

For the most part, the subproblems give a fair idea of what the teams are discussing and working on during the corresponding time segment. This can be confirmed by the correspondence values calculated in Table 57. In total, the subproblems were able to explain at least some of the changes in the layout in 22 discussion sections out of 28, which is 78.5% of the times. This is a relatively high value, however, there can be some future work done to increase this number even more.

The discussion sections where the subproblems do not identify the changes that the team make decisions about accounted for 21.5% of the total discussion sections. This scenario occurred because of one of the following reasons: The variable(s) being discussed during this time was not clustered (not similar with any other variables in the design team discussion), or the actual discussion of the variable (or subproblem) took place in a previous segment and the corresponding changes to the layout were made later.

From the analysis, it was identified that all six teams showed instances where the layout showed updates and changes that could not be attributed to corresponding discussion of identified subproblems. Team discussions exhibited both missing subproblems as well as subproblems discussed early and worked upon later in the discussion.

While the second aspect is an acceptable result, the observation of a subproblem being entirely missing when the decisions are made points to deficiencies in the subproblem selection.

Based on these results and results from the cluster selection, the subproblems give a fair picture of the overall design process, but the intricacies are sometimes lost in some parts, owing presumably to the weak pair wise strength of frequently discussed variables. This weakness can also be attributed to the discussion itself, since discussion of variables many times throughout the design process can render the variable as not being a part of any subproblem, but something that is discussed many times across various subproblems. More investigation is needed to identify the root cause of the weakness of missing variables.

Chapter 8: Conclusions and Future Work

This paper described the study of the design processes of six teams of professionals solving a realistic factory redesign problem. To conduct this exploratory research, the teams' discussions were coded, the discussed variables were clustered, the most meaningful clusters were selected, and the teams' design processes were compared based on these variables and clusters. The final layouts of the six design teams were also analyzed and compared with the identified subproblems to see if the subproblems were in accordance with the design developed. The conclusion was that the teams discussed different sets of variables and decomposed the design problem in different ways. The teams formed subproblems that were not similar. This claim is supported by the similarity statistics calculated in Section 5.2. The modified similarity statistic for no two pairs of teams was high in both directions, thus concluding that no two teams had similar subproblems. Another conclusion is that the teams used different design approaches. Based on the analysis of high-level variables in Section 5.3, some teams indicated some form of top-down approach being applied, while some indicated a bottom-up approach. Some other teams indicated a mix of the two, or rather had an unclear approach. There were some similarities, however. These were identified in Section 5.2 and discussed in Section 7.1.

The subproblems were consistent for a majority of the time, shown by the calculations in Table 57. The subproblems were able to explain at least some of the changes in the layout 78.5% of the times, indicating that the subproblems were a fair indicator of the actual discussions.

Regarding the future work and next steps that can be done in this particular thesis, the subproblem selection can be revisited, and investigation is needed to identify the root cause of why the variables that were worked on were missing from the selected subproblems 21.5% of the times. Different clustering techniques that utilize metrics other than the pair-wise distance between variables to identify subproblems can be explored to see if stronger subproblems can be identified, that are able to identify these missing discussions.

Overall, the results presented in this thesis can be further used to provide insight on which problem decomposition strategy is best suited to solve design problems, by analyzing the final design created by each of the teams and establishing a relationship between the decomposition strategy used and the quality of design generated to identify the best decomposition strategies. More generally, the approach used in this study can applied to explore the decomposition of design problems in other domains to gain more insights into the relationship between decomposition and design solution quality.

In addition, the approach identified and employed in this thesis can be applied to design problems in other domains, to see if any similarities and patterns can be identified in the discussions of those design problems.

Appendices

Appendix – A: Design Problem

Current Status of We Assemble Super Terrific Equipment (WASTE) Inc.

\- David Rizzardo

OVERVIEW

WASTE Inc. desires a streamlined facility layout to help save its business. Currently, they are struggling with many problems. Because their capital is tied up in inventory, they have perpetual cash flow problems. They believe that they need this inventory, however, to meet their customers' demands for short delivery times. When an order for a machine hits the production floor, they need to complete it and ship it within five days. They currently keep stockpiles of unpainted and painted module frames (all three sizes), unpainted and painted machine frames (all three sizes), and assembled modules (all three sizes and five types). Despite the current level of inventory, they still have trouble meeting this delivery target due to the various delays and bottlenecks within the operation.

WASTE Inc. currently manufactures and sells three models (small, medium, and large) of their machine. The small machine has an overall footprint of 4 ft. by 7.5 ft; the medium machine has an overall footprint of 7 ft. by 11 ft; and large machine has an overall footprint of 8.5 ft. by 13 ft. Despite the size differences and some minor component variations, all three types require the same assembly steps and have the same labor content.

This fact should help WASTE Inc. create an efficient processing plan, but any simplification gained by the standard labor times among the machines is overwhelmed by the high inventory levels, excessive material handling, and production bottlenecks due to space and personnel constraints.

WASTE Inc. has also started a refurbishment and upgrade business. This began as a service to current customers to refurbish and upgrade WASTE Inc. machines. Their capabilities have attracted the notice of firms who would like to have WASTE Inc. service other machines as well. Because providing this service would bring in significant revenue, it is a major part of their growth plan. Unfortunately, WASTE Inc. has limited space available for the refurbishment and upgrade activities (the current area has 543 sq. ft.). In addition, they hope that the refurbishment and upgrade service would increase productivity (sales per employee), which has been declining. They would like to reassign their current employees from machine assembly to the refurbishment and upgrade operations.

Finally, the R&D Prototyping Area (where engineers and technicians build and test prototypes as part of the product development process) is overcrowded and unorganized, and the staff are wasting time looking for supplies, prototypes, and testing equipment, all of which are often left on the shop floor or back in the Engineering Department office, which is on the other side of the building. (Currently, the area has 1,360 sq. ft.) Occasionally, they make new prototypes because they can't find the ones that they built previously (or they don't want to go back to the office to look for it there).

Overall, WASTE Inc. is in trouble. And they believe that their current facility layout and production management system are major contributing factors to these problems. Thus, they have asked your team to redesign the facility to support their goals.

FACILITY REDESIGN GOALS

The company has the following goals for the new facility layout and production management system:

- Reduce the number of storage racks required to store Frames and Module Assemblies;
- Reduce product travel distance and material handling effort;
- Increase productivity: make available at least 15% of the current production workforce in order to staff anticipated growth opportunities in the refurbishment and upgrade operations along with staffing needs in another company location;
- Increase the space for the refurbishment and upgrade operations from the current 540 sq. ft. to at least 1000 sq. ft.;
- Increase the space of the R&D Prototyping Area from the current 1350 sq. ft. to at least 1500 sq. ft.;
- Increase communication within the Engineering Department;
- Reduce the distance between the Engineering Department and the R&D Prototyping Area;
- Increase the distance between the front office and the noisy Crate/Package Area;

- Open up one of the blocked loading docks for additional capacity in Receiving/Shipping.
- The company would like to have the following item as well, but it has lower priority than the first list of goals:
- Make available space for an employee fitness center: A minimum of 400 sq. ft. would be required for a small fitness center. However, the exercise enthusiasts in the company are lobbying for a 1000 sq. ft. space. (Note: One of those enthusiasts is the CEO.)

Design Constraints

- The Paint Shop cannot be relocated.
- Though there are no restrictions on individual office locations or office design, the current "office area" cannot be modified for additional manufacturing space.
- The building cannot be expanded.
- No new loading docks can be added or relocated, but docks that are currently unutilized can be made available.

When a new, streamlined facility layout is in place, the owners will highlight that the new layout will create in effect a new, better, stronger company, by changing the company's name. This will announce to the world that major transformation has occurred. The new name being considered at the moment is Newly Organized – We Assemble Super Terrific Equipment (NO-WASTE) Inc. Your team has been invited to suggest other new company names for the owners to consider.

PRODUCTION AREAS

The following paragraphs describe the major components of a machine and the processing steps (there are no differences between the three models in these details) and the key departments in the facility. (Please refer to the attachments for further product and processing information.)

- Frame Fabrication
  - This area makes the Machine Frames and the Module Frames. There are three sizes of Machine Frames and three sizes of Module Frames.
  - Machine Frame – Every Machine has a Machine Frame. (The size of the frame varies by model.) (In other processing areas, the Main Drive, five Modules, and the Control Box are attached to the Machine Frame.)
  - Module Frames (5) - Each Module has a Module Frame. Because there are five Modules per Machine, every machine requires five Module Frames. Even though each module assembly is different/unique for a particular machine size, the module frames are identical (i.e., the 5 small module frames are identical, the 5 medium module frames are identical, and the 5 large module frames are identical.)
  - A huge inventory buffer of all types of frames (both painted and unpainted) is maintained. Refer to "Current Production Staffing and Inventory Information" attachment. The production manager wants to be ready for a long-looked-for (but actually unlikely) surge in the demand for frames.

- Currently, identical frames are produced in batches of six because the production manager believes that this is more efficient than producing only what is required. For example, a batch of six medium Machine Base frames is made at the same time to gain "efficiencies."

Note: The terms "Machine Frame" and "Base Frame" are used interchangeably and refers to the main machine structure which the Main Drive, Modules, and Control Box are mounted on.

- Paint Prep and Paint Shop
  - All frames (Machine Frames and Module Frames) get painted in the Paint Shop.
  - Prior to painting, frames are prepared for painting in the Paint Prep area (this is included as part of the total Painting labor time).
  - The inventory of painted frames is stored near the Module Assembly Department and the Machine Assembly Department. WASTE Inc. was very proud of the fact that they placed the mountain of painted frames near the areas that required them. This was their version of *Point of Use Storage*. However, due to their current problems, they definitely are questioning any and all past decisions.
  - The Paint Shop <u>cannot</u> be relocated. Management does not want to incur the costs of relocating the ventilation and other structural components of this area. (The Paint Prep area can be relocated.)

- Module Assembly
  - Modules are assembled in the Module Assembly Department. Here the painted Module Frames are combined with various components and machined parts to produce Modules. Although, per size, all of the Module Frames are identical, there are five different types of Modules. There are three sizes of each module type: small, medium, and large, corresponding to the small, medium, and large machines. A small Machine requires five small Modules, one of each type. A medium Machine requires five medium Modules, one of each type. A large Machine requires five large Modules, one of each type. Thus, there are 15 different modules (five types and three sizes).
  - The Module Assembly Department produces a batch of five Modules of a single type (for example, five medium Type 4 Modules) in order to be more "efficient." If more space were available, they would have used a batch size of six (as the Frame Fabrication Department does). WASTE Inc. is having second thoughts regarding their "efficiency" logic, however, because the setup times are relatively short.
  - A huge inventory of completed Modules of all types and sizes is maintained "just in case" they are needed.
- Control Box Wiring Department – This electronics assembly area assembles and wires the Control Boxes. Every Machine needs one Control Box. All of the Control Boxes are identical.

- Machine Shop – This area fabricates various components for the Modules and Machines. Parts from this area are used in both the Module Assembly and Machine Assembly areas.

- Machine Assembly Department – Employees here attach the Main Drive (a purchased part) on the painted Machine Frame, mount all five Modules, and attach the Control Box, which produces a finished Machine. (Refer to the flowchart to see the sequence of the main assembly steps.)

- Quality Control (QC) – Finished Machines are moved to Quality Control (QC) as soon as possible to make room for working on another Machine. (Some believe that QC staff just prefers that the Machines come to them, rather than them going to the Machines.) When there is no available space in the QC area, Machines are placed in the "Waiting for QC or Crate/Package Area." No special equipment is required for the QC test, however.

- Crate & Package – In this noisy, messy area, employees crate and package Machines that have passed the QC test and refurbished Machines. Company executives are unhappy with its location because this is one of the first areas that visitors on a plant tour see.

- Material Handling – Within each area, items can be easily moved manually. Even a completed large Machine can be moved a short distance within one area. Moving a completed Machine from one area to another requires a forklift truck because the condition of the shop floor is not suitable for moving a Machine on its casters, which would, in any case, be a slow process that requires two employees. Components can be moved manually.
- Refurbishment & Upgrade –Machines needing refurbishment are brought here from the loading dock. Refurbished machines are inspected in this area but are moved to the Crate & Package area before leaving the factory.
- R&D/Prototyping Area – This is a critical area for WASTE Inc. to stay ahead of the competition. However, there are 2 major issues with this area.
  - The distance from Engineering hampers communication which is critical for new product design and development. The new layout must shorten this distance from Engineering to the R&D/Prototyping Area.
  - The space constraints limit the number of projects which can be worked on in a timely manner. It is believed that an increase in this space would directly lead to Sales due to the ability to develop new products faster.

BILL OF MATERIALS

Machine Bill of Materials (for any size). Items that are marked by a "*" come in three different sizes. Items marked with a (p) are purchased. Not included are the metal bars for making frames and the raw material for machined parts; the metal bars and raw materials are also purchased.

- Machine*
  - Machine Frame*
  - Main Drive (p)
  - Type 1 Module*
    - Module Frame*
    - Machined parts
  - Type 2 Module*
    - Module Frame*
    - Machined parts
  - Type 3 Module*
    - Module Frame*
    - Machined parts
  - Type 4 Module*
    - Module Frame*
    - Machined parts
  - Type 5 Module*
    - Module Frame*
    - Machined parts
  - Control Box
    - Control box components (p)
  - Machined parts

Appendix – B: Codebook

Codebook

9 Jan 2014

Updated on 11/26/2017

- **MAJOR CATEGORIES** are in bold caps
- Codes are underlined
- Definitions of codes are indented under the code. The first line of the definition is our current working understanding of this code. Anything below that is a record of earlier understandings, notes on why we changed, etc.
- Sub-codes may be indicated as a bulleted list. If these require further definition, we may need to come up with a better scheme for listing them.
- (This document may become unwieldy. Hopefully we will get funded and purchase Atlas.ti so we can move our codebook into that software, which enables slightly better organization.)

VARIABLES

Variables are generally determined by the researchers' understanding of the key elements of the problem that must be determined by the teams.

Spatial flow pattern

Flow among big blocks and between areas or cells. Shape and location of flow on big layout, such as U-shaped from entry to exit, or flow through big blocks.

Distinguished from "High-level flow design" because this is specifically on the layout shape, and more to do with shape of flow than whether it has cells etc.

High-level flow logic

High-level flow pattern, e.g. number of lines/cells, sizes made in each cell, “big picture”.

This code could be decomposed in an interesting way. We might have sub-headings:

- Cells to make components, then cells to assemble
- Lines based on product size
- Lines/cells that make multiple product sizes
- Flow independent of factory layout (e.g. just flow chart)

Assignment of products to cells

Determining which of the product lines will be produced in each cell.

Related to “high-level flow logic” code, but this is less big picture, and more detailed.

Assignment of operations to cells

Determining which operations (such as control box wiring, main assembly, etc.) will be performed within cells.

Related to “high-level flow logic” code, but this is less big picture, and more detailed.

Allocation of large areas of factory

Setting aside larger than a single block for some set of blocks

Location of blocks

Determining location of “blocks”, meaning the blocks for paint shop, paint prep, machine shop, cells, etc. Includes both setting location and discussing approximately where to locate or what criteria to use in locating.

SUBCODES: Specifically, the big blocks include:

- Raw material storage
- R&D
- Fitness Center
- Incoming QC
- Frame Fab
- Paint Staging
- Paint Prep
- Paint Shop
- Painted frame storage
- Machine shop
- Control Box Assembly
- Module Assembly
- Machine Assembly
- Main Assembly
- QC
- Incoming QC
- Crating and Packing
- Shipping and Receiving
- Production Supervisor Office
- Refurbishment Upgrade
- Cells (location of cells; treated as blocks)
- Buffers

- Storage
- Work in process
- Show room
- Office expansion
- R&D prototypes
- Fitness center
- Materials handling
- Show room
- Part inventory
- Storage of completion
- R&D prototypes
- Office of shipping and receiving

Size of cell/area

Size refers to overall dimensions, area, and size of cells (or blocks).

Code refers to cells in the Lean sense, meaning they contain a series of different operations for a product or product family. Also use this code for production “lines”, which are similar to cells.

Sub-codes:

- Showroom
- R&D
- Refurbish & Upgrade
- Machine Shop
- Fitness Center

- Frame Fabrication
- Paint Staging
- Paint Prep
- Module Assembly
- Machine Assembly
- Assembly Cell
- Control Box Assembly
- Crate & Packaging
- QC
- Storage
- Painted frame storage

<u>Layout of functional area</u>

Layout refers to U-shaped, L-shape, line, etc. and placement of equipment, people, inventory within area. Refers to blocks representing functional areas, not cells.

Sub-codes:

- Showroom
- R&D
- Refurbish & Upgrade
- Machine Shop
- Gym
- Frame Fabrication
- Paint Staging
- Paint Prep

- Module Assembly
- Machine Assembly
- Assembly Cell
- Control Box Assembly
- Crate & Packaging
- QC
- Storage

Layout of cell

Layout refers to U-shaped, L-shape, line, etc. and placement of equipment, people, inventory within cell. Code refers to cells in the Lean sense, meaning they contain a series of different operations for a product or product family. Also use this code for production “lines”, which are similar to cells.

SUBCODES: These sub-codes identify subsets of staffing in functional areas

- Layout of module assembly
- Layout of office
- Machine assembly
- Assembly cell

Staffing in functional area

Determining the number of staff assigned to each functional area.

SUBCODES: These sub-codes identify subsets of staffing in functional areas

- Facility Staffing
- Staffing in module assembly
- Staffing in Frame Fabrication

- Staffing in Paint Prep
- Staffing in Paint Staging
- Staffing in Paint Shop
- Staffing in Control Box Assembly
- Staffing in Machine Shop
- Staffing in Module Assembly
- Staffing in Machine Assembly
- Staffing in QC
- Staffing in Material Handling
- Staffing in Crate and Package
- Staffing in Refurbish and Upgrade

Operation sequencing and balancing

Determining partition of operations among people or workstations.

Include

Determining is a particular area (or function) needs to be included in the layout.

SUBCODES:

- Employee break and meeting room
- R&D Prototype
- Assembly Cell

LEVEL OF ABSTRACTION

Levels of abstraction are from Ho, 2001. Ranges from details through system.

System:

Overall performance, overall flow, overall layout

From Ho: “considering the problem as a whole”

System and Subsystems:

Flow between areas, buffers, definition of area

From Ho: “considering the problem in terms of interactions between the subsystems.”

Subsystems:

Location and shape (boundaries, size) of an area

From Ho: “considering details of the subsystems”

Details:

Anything inside an area, including staffing and layout

From Ho: “considering a subsystem from the point of view of the detailed workings of that subsystem.”

MACRO STRATEGIES

Macro-strategies are from Gero and McNeill, 1988.

Top down

From Gero and McNeill: “Approach of elaborating the desired functions and behaviors and in the process is identifying sub-goals which are then addressed”

Bottom up

From Gero and McNeill: “Trying a number of different configurations of structure and examining their behavior to find a match with the design requirements.”

Decomposing the problem

From Gero and McNeill: “Decomposition of either the overall goals or the potential system prior to top down design.”

Backtracking

From Gero and McNeill: “Designer is not achieving what has been expected [and] goes back over existing work, possibly changing it.” Happens when “designer has identified that a current approach needs to be modified.”

Opportunistic

From Gero and McNeill: “External influence that makes a change of direction advantageous.” Happens when “designer has identified that a current approach needs to be modified.

Identify problems with current layout

Go through current layout and identify challenges, what might need to be changed.

** This needs to be incorporated as a macro-strategy or a component of a macro-strategy

DECISION MAKING PHASES

From Mintzberg et al. 1976.

Original Mintzberg concepts may not fit our problem well, since JWH has already observed that there is little “selection”; instead, teams simply appear to settle implicitly on one proposed solution.

Identification

Identifying that there is a decision to be made.

Sub-processes are:

- Recognition
- Diagnosis (“comprehend the evoking stimuli and determine cause-effect relationships for the decision situation.”)

Development

From Mintzberg: “development of one or more solutions to a problem [or] the elaboration of an opportunity.”

Sub-processes are:

- Search (for solutions)
- Design (modification of solution)

Selection

Fundamentally, selecting an option.

Sub-processes are:

- Screen
- Evaluation-choice, including evaluation of the design
- Authorization

Appendix – C: List of Variables

1. Aisle Space
2. Assigning operations to area
3. High level flow logic
4. Spatial flow pattern
5. Allocation of large areas of factory
6. Assign products to areas
7. Include employee mini-office
8. Include Module Assembly Cell
9. Include machine assembly cell
10. Include combined assembly cell
11. Include employee break area
12. Internal layout of Assembly cell
13. Internal layout of Module Assembly
14. Internal layout of Machine Assembly
15. Internal layout of Control Box Assembly
16. Internal layout of Frame Fabrication
17. Office layout details
18. Facility Staffing
19. Staffing in area - Frame Fab
20. Staffing in area - Paint
21. Staffing in area - Control Box
22. Staffing in area - Machine Shop

23. Staffing in area - Module Assembly
24. Staffing in area - Machine Assembly
25. Staffing in area - refurbish
26. Staffing in area - Crate and Package
27. Staffing in area - QC
28. Staffing in area - S&R
29. Staffing in area - Material Handling
30. Location of Inventory (Storage)
31. Location of Incoming QC
32. Location of Machine Shop
33. Location of Frame Fabrication
34. Location of Paint staging
35. Location of Paint prep
36. Location of Control Box Assembly
37. Location of Assembly Cell
38. Location of Crate & Package
39. Location of R&D
40. Location of Gym
41. Location of QC
42. Location of Production Manager/Supervisor office
43. Location of S&R office
44. Location of Refurbishment & Upgrade
45. Location of show room

46. Location of employee break and meeting room

47. Location of Incoming Material (POUS Inventory)

48. Location of Raw Materials (Supplies)

49. Location of Frame Supplies

50. Location of Painted Frame Storage

51. Location of Staging Modules

52. Location of Electrical Supplies

53. Location of Paint supplies

54. Location of machined parts

55. Location of Module Assembly

56. Location of Machine Assembly

57. Location of Shipping and Receiving

58. Location of Material Handling

59. Location of mounting modules

60. Location of mounting control box

61. Location of lockers

62. Location of attaching main drive

63. Size of R&D

64. Size of Refurbishment & Upgrade

65. Size Machine Shop

66. Size of Gym

67. Size of Frame Fabrication

68. Size of Module Assembly

69. Size of Machine Assembly
70. Size of Control Box Assembly
71. Size of Crate and Packaging
72. Size of Paint Prep
73. Size of QC
74. Size of Storage
75. Size of Assembly Cell
76. Size of Paint Staging
77. Size of painted frame storage
78. Size of lunch room
79. Size of attach main drive
80. Size of attach control box
81. Size of mount module to frame
82. Size of supervisor office

Bibliography

[1] Morency M., Anaparasan A., Herrmann J., Gralla E., “Using Clustering Algorithms to Identify Subproblems In Design Processes,” Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol 2: Design Processes, Vancouver, Canada, August 21-25, 2017.

[2] Tobias C., Herrmann J., Azhar A., Gralla E., “Problem Decomposition by Design Teams”, Fifth International Engineering Systems Symposium, CESUN 2016, Washington, D.C., June 27-29, 2016.

[3] Gralla, E., Herrmann, J., “Team Design Processes and Decompositions in Facility Design”. In: Proceedings of the 2014 Industrial and Systems Engineering Research Conference, Y. Guan and H Liao, eds., Montreal, Canada, June 1-3, 2014.

[4] Morency, Micheal J., “Evaluating Clustering Algorithms to Identify Subproblems in Design Processes”, M.S. Thesis, University of Maryland, College Park, 2017.

[5] Herrmann, Jeffrey W., Michael Morency, Azrah Anparasan, and Erica L. Gralla, "Evaluating Clustering Algorithms for Identifying Design Subproblems," to appear in Journal of Mechanical Design, 2018.

[6] Gralla E., Herrmann J., Morency M., “Design Team Decision Processes in Point of Dispensing Design”, Proceedings of the Industrial and Systems Engineering Research Conference, Anaheim, California, May 22-25, 2016.

[7] Azhar A., Gralla E.L., Tobias C., Herrmann J.W., “Identification of Subproblems in Complex Design Problems: A Study of Facility Design”, ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Volume 7: 28th International Conference on Design Theory and Methodology 2016.

[8] Ahmed S, Wallace K.M, and Blessing L, “Understanding the differences between how novice and experienced designers approach design tasks”, Research in engineering design, 2003.

[9] Ball L.J., Evans J.S.B.T., and Dennis I, “Cognitive processes in engineering design: A longitudinal study”, Ergonomics, 1994.

[10] Hong L. and Page S.E., “Groups of diverse problem solvers can outperform groups of high-ability problem solvers”, Proceedings of the National Academy of Sciences of the United States of America, 2004.

[11] March J., and Simon H., “Organizations”, 2nd edition. Blackwell, Cambridge, Massachusetts, 1993.

[12] Lewis K., and Mistree F., “Collaborative, Sequential, and Isolated Decisions in Design”, Journal of Mechanical Design, Vol. 120, 1998.

[13] Dinar M., Shah J. J., Cagan J., Leifer L., Linsey J., Smith S. M., and Hernandez N. V., “Empirical studies of designer thinking: Past, present, and future”. Journal of Mechanical Design, 2015.

[14] Liikkanen L. A. and Perttula M., “Exploring problem decomposition in conceptual design among novice designers”, Design Studies, Vol. 30, 2009.

[15] Sun G., Yao S., and Carretero J., “An Experimental Approach to Understanding Design Problem Structuring Strategies”, Journal of Design Research, 2016.

[16] Ball L.J., Evans J.S.B.T., Dennis I, and Ormerod T.C, “Problem-solving strategies and expertise in engineering design”, Thinking and Reasoning, 1997.

[17] Gero, J. S., and Mc Neill, T, “An approach to the analysis of design protocols”, Design studies, 1998.

[18] Guindon R., “Designing the design process: Exploiting opportunistic thoughts”, Human-Computer Interaction, 1990.

[19] Glaser B. and Strauss A., “The Discovery of Grounded Theory”, Aldine de Gruyter, 1967.

[20] Corbin J. and Strauss A., “Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory”, Third edition. Sage, 2008.

[21] Langley A., “Strategies for theorizing from process data”, Academy of Management Review, 1999.

[22] Ward J.H. Jr., “Hierarchical grouping to optimize an objective function”, Journal of the American statistical association, 1963.

[23] Sarkar S., Dong A., Henderson J., Robinson P., “Spectral characterization of hierarchical modularity in product architectures”, Journal of Mechanical Design, Vol. 136, 2014.

[24] Rand, William M. "Objective criteria for the evaluation of clustering methods." Journal of the American Statistical association 66, 2012.

[25] Jain A.K. and Dubes R.C., “Algorithms for Clustering Data”, Prentice Hall, Englewood Cliffs, New Jersey, 1988.