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Space Station Functional Relationships Analysis Final Technical Report

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Ames Research Center
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SUMMARY

The Space Station must be designed to facilitate all of the functions that its crew will perform. The Functional Relationships Analysis (FRA) model has been developed as a technique for achieving that goal. In essence, the FRA model is a well-defined method for analyzing Space Station crew functions and detecting relationships among those functions. A clear understanding of these relationships facilitates the design of a Space Station layout that optimizes crew productivity. Further, the FRA model can be used as a tool for quantitatively evaluating the suitability of any Space Station configuration. While the FRA model can be used now for preliminary design and evaluation of Space Station configurations, its more important use will be the continued application of the process to reconfigure Space Station layouts as program objectives and constraints change.

The development of the FRA model involved a ten-step process:

1. <u>Identify Crew Functions</u>

Twenty-seven functions that need to be performed by the Space Station crew were identified. These fell into three conceptual categories: Crew Support (e.g., Eating, Medical Care, Personal Hygiene), Space Station Operations (e.g., Subsystem Monitoring and Control, ORU Maintenance, Proximity Operations), and Mission Operations (e.g., Life Sciences Experiments, Materials Processing Experiments).

2. <u>Identify Required Support Equipment</u>

For each of the 27 crew functions, a list of the equipment required by the crew member to complete the function was derived. This equipment included anything the crew member is likely to use in order to accomplish the function, ranging from the Space Station main computer system to a hand washer.

3. <u>Identify Criteria for Assessing Functional Relationships</u>

Five well-defined criteria for measuring relationships among all pairs of crew functions were identified:

(1) The frequency with which crew members switch from performing one function to another.

(2) The extent to which one function provides the reason (or need) to perform another (i.e., a sequential dependency).

(3) The percentage of support equipment shared by the functions.

(4) The potential for noise generated by one function to interfere with another function.

(5) The similarity of privacy requirements for the functions (both audio and visual)

These criteria were chosen because they tap functional relationships that could be enhanced by the interior layout of the Space Station. A matrix reflecting the relationships of each function with every other function can then be developed for each of these five criteria.

4. <u>Identify Tools for Analyzing Functional Relationship Matrices</u>

Two related statistical analysis tools were used to analyze the functional relationship matrices: hierarchical clustering and multidimensional scaling. Hierarchical clustering is a technique that identifies clusters of related functions at a variety of levels, from very strongly associated functions to very weakly associated functions. Multidimensional scaling, or MDS, is a technique that takes a matrix of distances among a set of functions and derives an optimum configuration of those functions in one-, two-, or three-dimensional space. The distances among the functions in that spatial configuration are designed to closely approximate the distances in the original matrix.

5. Conduct Analysis of Crew Transition Frequency

The frequencies with which the crew will switch from performing one function to another were derived from fourteen sample sequences of crew functions. Each sequence covered a 24-hour period for one crew member. The most frequent crew transitions were those involving meals and personal hygiene. The MDS analysis revealed a configuration in which crew support functions tended to fall together in one area while Station and mission operations tended to fall in another area.

6. Conduct Analysis of Sequential Dependencies

Sequential dependencies among all crew functions were assessed using a rating scale of how often one crew function provides the reason (or need) to perform another function. The scale ranged from 0 (always) to 4 (never). Two clusters of dependent functions were identified: (1) three functions associated with mealtimes, and (2) two functions associated with EVA operations. These two clusters themselves, however, were not particularly dependent upon each other. As with transition frequency, the MDS analysis revealed a configuration in which the crew support functions fell in one area while the Station and mission operations fell in another.

7. Conduct Analysis of Support Equipment Requirements

For all pairs of crew functions, a percentage was calculated representing what proportion of the total equipment items required by both functions is shared between them. This percentage could range from 0 (no equipment in common) to 100 (all equipment in common). Both the cluster analysis and MDS analysis revealed four very strong clusters of functions based on support equipment: (1) all Space Station and mission operations, as well as some crew support functions; (2) personal cleanliness functions (e.g., full-body cleansing); (3) urination/defecation; and (4) sleep.

8. Conduct Analysis of Potential for Noise Interference

A noise interference potential was derived for every pair of functions by estimating the noise generation level and noise tolerance level for each crew function. The analyses resulted in eleven closely related functions that are not likely to be disrupted by noise (mostly crew support functions, such as exercise) and two loosely related groups of functions that are more likely to be disrupted by noise. One of those two groups was composed of basically "quiet" functions (e.g., sleep) while the other group was composed of "noisier" functions (e.g., ORU maintenance).

9. Conduct Analysis of Need for Privacy

The desire for audio privacy was assessed for each function by estimating the percentage of words spoken that should be understood by a listener. The desire for visual exposure was assessed by estimating the optimum percentage of visual exposure appropriate to the activity. These were then combined to form an overall privacy index. The analyses indicated a continuum of functions from "private" (e.g., urination/defecation, sleep, private recreation) to "public" (e.g., subsystem monitoring, meal preparation).

10. Conduct Analysis of Overall Compatibility of Functions

The five functional relationship matrices derived from the assessments of the individual matrices were combined, in an equal-weighted manner, to form an overall compatibility matrix. The MDS analysis revealed two dimensions that can be used to describe the configuration of functions. The primary dimension was a "Public-Private" continuum. At the extreme "Private" end were sleep and private recreation; at the extreme "Public" end were many of the Station operations. The secondary dimension, orthogonal to the first, was a "Group-Individual" continuum. At the "Group" end were meeetings, teleconferences, and eating; at the "Individual" end were sleep, medical care (presumably self-care), and experiments.

The following implications for Space Station interior layout were derived from the analyses:

1. Facilities supporting "private" functions, such as sleep and private recreation, need to be clearly separate from the facilities supporting the more "public" Station operations.

2. Facilities for meal preparation, eating, and meal clean-up should be close together.

3. At least two kinds of meeting spaces are needed: a larger facility for on-duty entire-crew meetings and a smaller facility for off-duty small-group meetings.

4. The two functions associated with health maintenance -- medical care and exercise -- should be performed separately.

5. Facilities supporting the hygiene-related functions (cleansing, personal hygiene, changing clothes, urination/defecation) should be co-located.

6. Facilities for experiments and payload support should be separate from the facilities for crew support and Station operations.

7. Facilities for training should be provided in more than one location.

The FRA model can also be used to quantitatively evaluate any Space Station interior layout. An example of using the model in this manner to evaluate a sample configuration is described. The approach involves calculating distances between all functional areas in the proposed configuration and correlating those distances with the overall compatibility matrix derived in this study.

INTRODUCTION

The United States has embarked upon a course of action leading to the establishment of a permanent manned facility in low Earth orbit early in the next decade. When NASA initiated the current Space Station Phase B effort, eight characteristics were identified that must be included as an integral part of the overall Space Station program. These characteristics were NASA System Engineering and Integration; Evolutionary Growth; Effective Utilization of Man's Presence in Orbit; a "Customer-Friendly" Perspective; Maintainability; Commonality; Test and Verification Concepts; and the Need for Increased Productivity. Three of these eight characteristics, Evolutionary Growth, Utilization of Man's Presence, and Increased Productivity, establish the basic philosophy that the Space Station must be designed as a facility capable of supporting meaningful functions over an extended period of time as effectively as possible.

To achieve this goal, a functional requirements model of the Space Station is mandatory. It is essential that preliminary design approaches consider the Station as a composite of functional requirements and consider the interrelationships among those requirements in such a way that an optimum configuration results. Understanding the Space Station as a functional system is critical to projecting a corresponding physical system.

DESCRIPTION AND USE OF THE MODEL

The Space Station Habitability Research Group of the Space Human Factors Office at NASA Ames Research Center asked the McDonnell Douglas Astronautics Company (MDAC), Huntington Beach, CA, to conduct a "Functional Relationships Analysis" (FRA) as an extension of an existing contract involving "Human Performance Issues Arising From Manned Space Missions". The purpose of the study was to analyze the operational system proposed for the Space Station in terms of mission functions, crew activities, and functional relationships. The most advanced information available for projecting functions and activities was used as input data to this model. The initial results of this analysis can be used to optimize the layout of the Initial Operating Capability (IOC) Space Station interior. The greatest benefit of this model, however, will be the continued use of the FRA process to configure and reconfigure Space Station layouts as the design of the Station evolves, with concomitant changes in mission objectives, functions, crew activities, and physical support elements.

The development of the Functional Relationships Analysis model included a ten-step process, as illustrated in Figure 1. Each step can be iterated a number of times as appropriate based upon changes in requirements or objectives. The ten steps defined in this study are as follows:

1. Identify Crew Functions

A list of the functions that need to be performed by the Space Station crew at IOC was developed. These functions, which are listed in Table 1, are divided into three main areas: Crew Support, Space Station Operations, and Mission Operations.

In general, Crew Support includes those functions required to maintain the crew's physical and psychological well-being and their productivity. Space

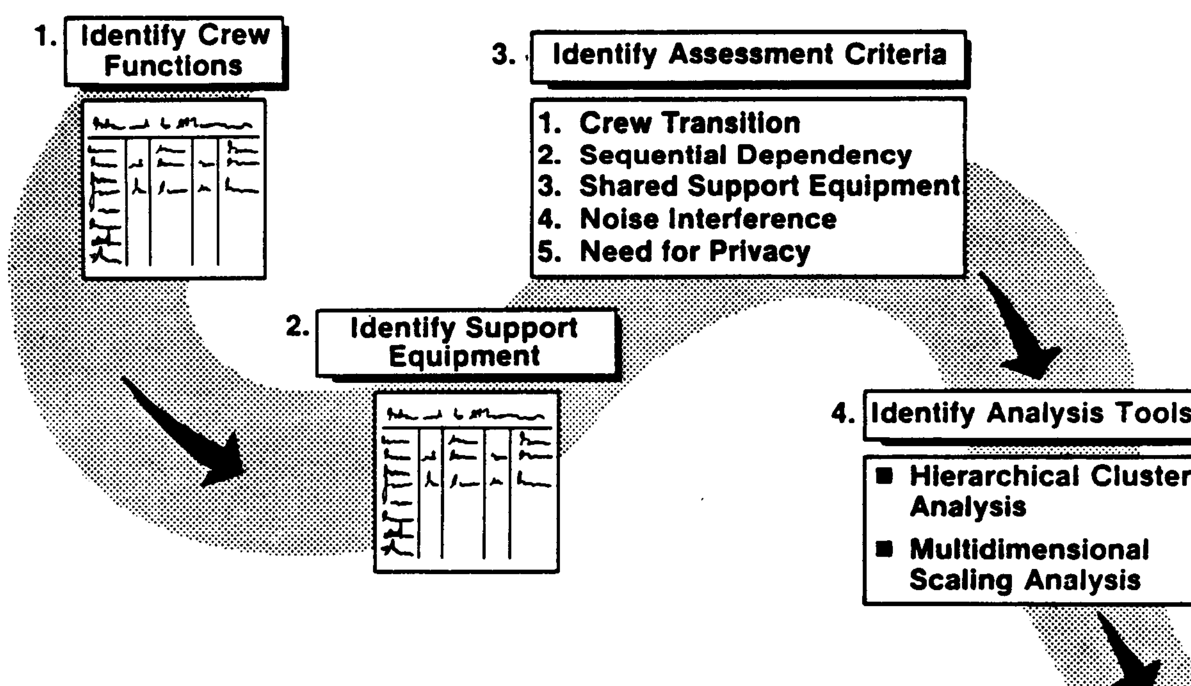

Figure 1. Functional Relationship Analysis (Steps 1-4)

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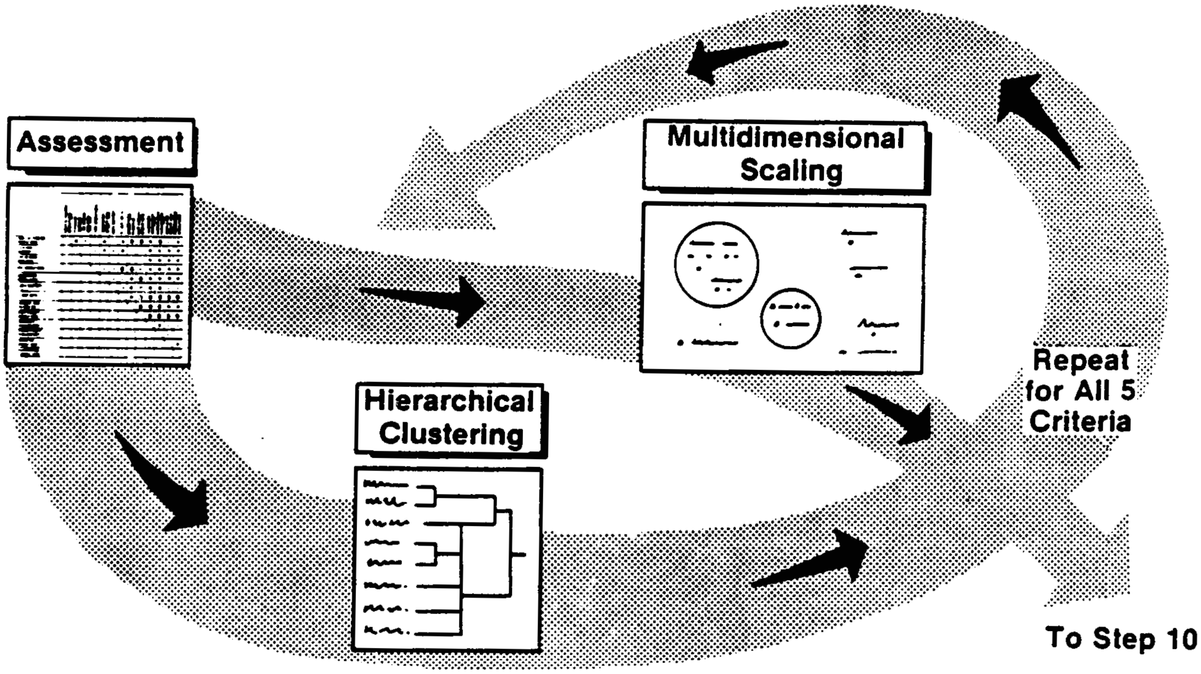

Figure 1. Functional Relationship Analysis. Steps 5-9 Analysis of Each Criterion (Cont)

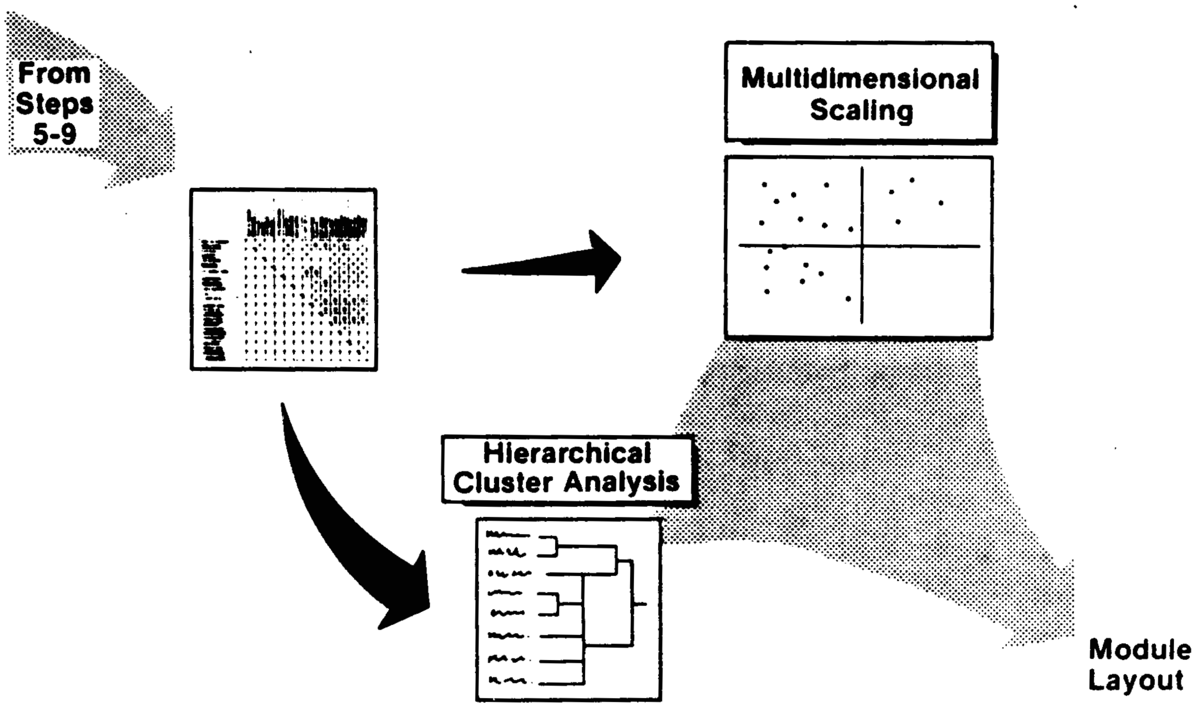

Figure 1. Functional Relationship Analysis. Step 10 Analysis of Combined Data (Cont)

Table 1. Space Station Crew Functions

Crew Support
Meal Preparation
Eating
Meal clean-up
Exercise
Medical Care
Full-body Cleansing
Hand/Face Cleansing
Personal Hygiene
Urination/Defecation
Training
Sleep
Private Recreation and Leisure
Small-group Recreation and Leisure
Dressing/Undressing
Clothing Maintenance
Station Operations
Meetings and Teleconferences
Planning and Scheduling
Subsystem Monitoring and Control
Pre/Post-EVA Operations
IVA Support of EVA Operations
Proximity Operations
General Space Station Housekeeping
ORU Maintenance and Repair
Logistics and Resupply
Mission Operations
Payload Support
Life Sciences Experiments
Materials Processing Experiments

Station Operations include those crew functions required to keep the Station and all of its components operating properly. Mission Operations include those crew functions required to achieve the objectives of specific missions.

Crew Support functions are identified to a somewhat lower level of detail than the others. This approach seems appropriate given the overall focus of this study on habitability and the current level of detail of the information about Space Station Operations and Mission Operations. As the design of the Space Station evolves, the Space Station and Mission Operations crew functions can be expanded.

The main criteria for defining what constitutes a crew function were as follows:

- The function has a clear objective and a well-defined beginning and end.

- One crew member can reasonably be expected to perform the function from beginning to end. This does not preclude the possibility that several crew members could each be performing the function, in its entirety, simultaneously (e.g., a group meeting), but this definition does preclude a "function" that would require one person to begin it and another to end it.

- Under ideal circumstances, the function could be performed in one place.

2. Identify Required Support Equipment

For each of the crew functions, a list of the equipment required by the crew member to complete the function was derived. This list is shown in Table 2. "Equipment" was defined as being anything the crew member is likely to use (e.g., manipulate, look at, etc.) in order to accomplish the function. Certain types of equipment were identified as being sufficiently generic that they are not listed, even though they are used during performance of many of the functions. These include crew restraints at work areas, stowage facilities, loose equipment restraints, and lighting controls.

3. Identify Criteria for Assessing Functional Relationships

To provide data about what functions should be performed where in the Space Station, it is necessary to identify the appropriate criteria for assessing relationships between the functions. In a general sense, the goal is to identify those functions that are more closely associated with each other and those that are less closely associated.

TABLE 2. REQUIRED SUPPORT EQUIPMENT FOR EACH FUNCTION

---

1. Meal Preparation
   - Main computer system (for menu selection and inventory control)
   - Food
   - Dishes and utensils
   - Food heating equipment

2. Eating
   - Food (prepared)
   - Dishes and utensils
   - Group meeting place (e.g., table)

3. Meal Clean-up
   - Food (leftover)
   - Dishes and utensils (soiled)
   - Trash disposal equipment
   - Dish washing equipment
   - Cleaning equipment (e.g., wipes, vacuum)

4. Exercise
   - Exercise equipment (e.g., treadmill)
   - Physiological monitoring equipment
   - Books
   - TV and video playback equipment
   - Audio playback equipment

5. Medical Care
   - Main computer system (for medical history, procedures, etc.)
   - Physiological monitoring equipment
   - Medical supplies (e.g., pharmaceuticals, bandages)
   - Emergency medical treatment equipment (e.g., defibrillator)
   - Medical laboratory equipment
   - Minor surgery equipment

6. Full-body Cleansing
   - Shower
   - Soap and shampoo
   - Wash cloth and towel

7. Hand/face Cleansing
   - Hand washer
   - Soap and shampoo
   - Wash cloth and towel

TABLE 2. REQUIRED SUPPORT EQUIPMENT FOR EACH FUNCTION (Continued)

8. Personal Hygiene	
	Hand washer
	Toothpaste and toothbrush
	Shaving equipment
	Mirror
	Comb or hairbrush
	Miscellaneous personal hygiene equipment
9. Urination/Defecation	
	Toilet/urinal
	Sanitary wipes
10. Training	
	Main computer system (for computer-assisted instruction)
	TV and video playback equipment
	Task-specific simulation equipment (e.g., MRMS simulator)
11. Sleep	
	Sleep restraint
12. Private Recreation and Leisure	
	Books
	TV and video playback equipment
	Audio playback equipment
	Writing equipment
	Audio communications facilities (for communications with family)
	Window (for recreational viewing)
13. Small-group Recreation and Leisure	
	Games
	TV and video playback equipment
	Audio playback equipment
	Window (for recreational viewing)
14. Dressing/Undressing	
	Mirror
	Clothes
15. Clothing Maintenance	
	Clothes
	Clothes washer
	Clothes dryer
16. Meetings and Teleconferences	
	Group meeting place (e.g., table)
	Video cameras
	TV and video playback equipment
	Writing equipment

TABLE 2. REQUIRED SUPPORT EQUIPMENT FOR EACH FUNCTION (Continued)

---

17. Planning and Scheduling
    - Main computer system (for schedules, tasks, etc.)
    - Group meeting place (e.g., table)
    - Audio communications facilities (with ground personnel)

18. Subsystem Monitoring and Control
    - Main computer system (for display of status and subsystem control)
    - Dedicated subsystem displays (e.g., warning lights)
    - Dedicated subsystem controls
    - Window (for direct viewing of SS structure)
    - Remote-control TV camera (for indirect viewing of SS structure)

19. Pre/Post-EVA Operations
    - Extravehicular Mobility Unit (EMU) (suit and life support)
    - Extravehicular Excursion Unit (EEU)
    - EMU and EEU service and checkout equipment
    - Decontamination provisions
    - Main computer system (for checklists, etc.)

20. IVA Support of EVA Operations
    - Audio communications facilities (with EVA crewmember)
    - Window (for direct visual contact)
    - Remote-control TV camera (for indirect visual contact)
    - Main computer system (for task-specific information)

21. Proximity Operations
    - Window (for direct visual contact with other vehicle)
    - Remote-control TV camera (for indirect visual contact with other vehicle)
    - Audio communications facilities (with piloted vehicle)
    - Controls for remotely operated vehicle
    - Main computer system (for proximity traffic displays, etc.)

22. General Space Station Housekeeping
    - Cleaning equipment (e.g., wipes, vacuum)
    - Trash disposal equipment

23. ORU Maintenance and Repair
    - Tools (e.g., hammer, screwdriver)
    - Diagnostic equipment (e.g., volt/ohm meter)
    - Spare parts
    - Contamination containment equipment
    - Main computer system (for procedures, spares information, etc.)

24. Logistics and Resupply
    - Main computer system (for inventory management)
    - Food
    - Non-food consumables

TABLE 2. REQUIRED SUPPORT EQUIPMENT FOR EACH FUNCTION (Continued)

25. Payload Support
    - Dedicated payload status displays
    - Dedicated payload controls
    - Main computer system (for data capture and analysis)
    - MRMS controls/displays

26. Life Sciences Experiments
    - Life sciences experiment-specific displays
    - Life sciences experiment-specific controls
    - Life sciences experiment racks
    - Main computer system (for data capture and analysis)

27. Materials Processing Experiments
    - Materials processing experiment-specific displays
    - Materials processing experiment-specific controls
    - Materials processing experiment racks
    - Main computer system (for data capture and analysis)

We have identified two classes of criteria for measuring the degree of association between any pair of functions:

1. Circulation criteria - these measure the association between functions by studying the "trips" that crew members would have to make when switching from performing one function to another.

2. Zoning criteria - these measure the association between functions by studying various kinds of compatibilities among them, the goal being to detect groups of functions ("zones") that are compatible with each other.

In considering each class of criteria in detail, we have identified two specific circulation criteria and three specific zoning criteria:

- Circulation Criteria

    1. The frequency with which crew members switch from performing one function to another.

2. The extent to which one function provides the reason (or need) to perform another function (i,e., a sequential dependency).

- Zoning Criteria

1. The percentage of support equipment shared by the functions.

2. The potential for noise generated by crew activities and support equipment associated with one function to interfere with the performance of another function.

3. The similarity of privacy requirements for the functions (both audio and visual).

These five specific criteria were chosen because they tap functional relationships that could be enhanced by the interior layout of the Space Station (i.e., by placing facilities that support certain functions closer together or further apart than others). Other criteria tapping relationships that could best be addressed by other means (e.g., skill levels of crew members, scheduling) were excluded from the analysis.

A matrix reflecting the relationships of each function with every other function can then be developed for each of the five criteria. The development of these matrices will be described in detail in later steps devoted to each criterion.

4. Identify Tools Necessary for Analyzing Functional Relationship Matrices

The matrices of functional relationships provide important raw data, but they are difficult to use directly for drawing conclusions about which functions should be performed where. Techniques for visually summarizing the data in the matrices are needed. Two related statistical analysis tools can help in this process: hierarchical clustering and multidimensional scaling.

Hierarchical clustering is a technique that identifies clusters of related functions. The analysis is done for a range of "clustering levels", from the lowest possible level (where every function falls in its own cluster) to the highest possible level (where all the functions fall in one large cluster). The more interesting clustering levels are those that come between these two extremes. At those intermediate clustering levels, the functions that are more closely related combine into clusters at lower levels than do the functions that are less closely related.

The computer program used to perform the hierarchical cluster analysis was based upon the "minimum method" algorithm described by Johnson (1967). This program has been used before to conduct an analysis of relationships between functions performed by a large computer operating system (Tullis, 1985).

As an illustration of hierarchical clustering, consider the matrix given in Table 3, which provides the airline distances between ten U.S. cities (from Kruskal and Wish, 1978). The output of a hierarchical cluster analysis of this matrix is shown in Figure 2. The values across the top of the figure indicate the distances at which the cities combine into clusters. Notice that New York and Washington combine into a cluster first, followed by Los Angeles and San Francisco. At subsequent levels, the other "eastern" cities combine into a cluster while the other "western" cities combine into another cluster.

Table 3. Airline Distances Between 10 U.S. Cities (from Kruskal and Wish, 1978)

CITIES	Atlanta	Chicago	Denver	Houston	Los Angeles	Miami	New York	San Francisco	Seattle	Washington
Atlanta		587	1212	701	1936	604	748	2139	2182	543
Chicago			920	940	1745	1188	713	1858	1737	597
Denver				879	831	1726	1631	949	1021	1494
Houston					1374	968	1420	1645	1891	1220
Los Angeles						2339	2451	347	959	2300
Miami							1092	2594	2734	923
New York								2571	2408	205
San Francisco									678	2442
Seattle										2329
Washington										

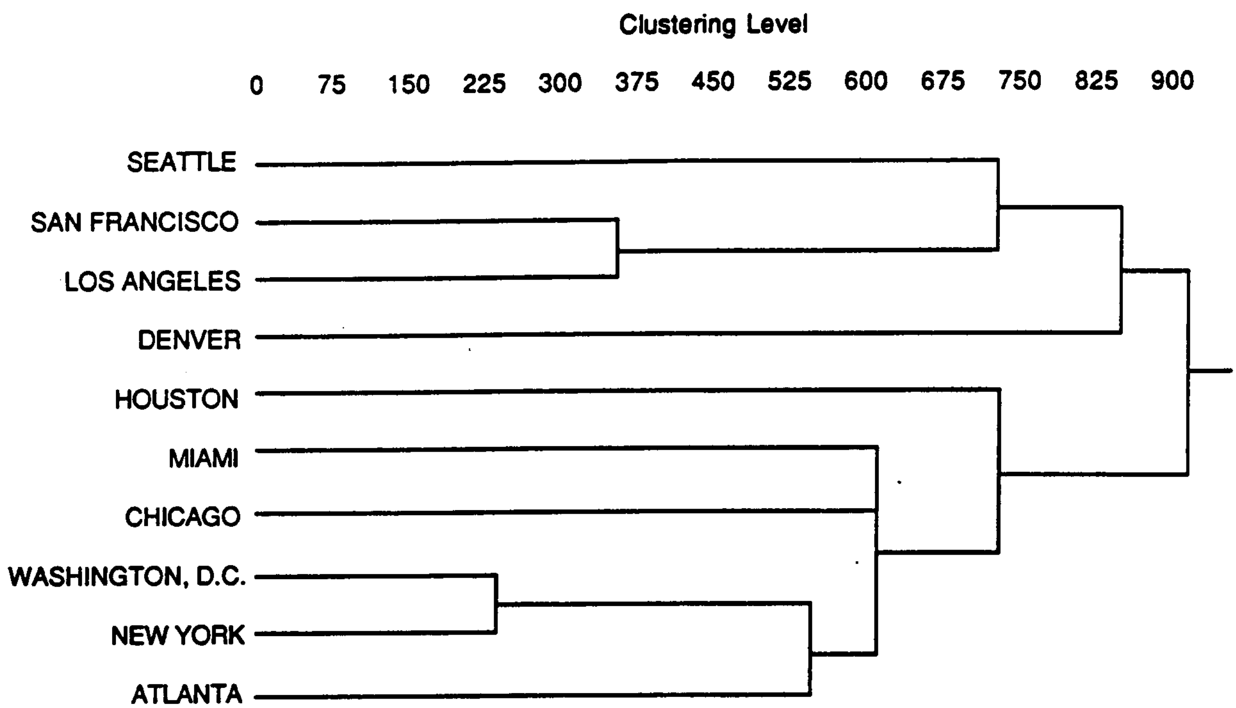

Figure 2. Hierarchical Cluster Analysis of Airline Distances

Notice that Denver is the last city to join a cluster due to its position somewhat near the "middle" of the country. Finally, as is always the case in hierarchical clustering, the two main clusters combine into one at the last level.

Multidimensional scaling, or MDS, is a process whereby a matrix of distances (either psychological or physical) among a set of objects can be translated into a representation of those objects in space. Typically, the representation is in one-, two- or three-dimensional space. The goal is to have the distances between the objects in the spatial representation accurately reflect the distances in the original matrix.

MDS can also be illustrated using the airline distances shown in Table 3. MDS can convert those distances into a map showing the relative geographic locations of the cities. Figure 3 shows the result of an MDS analysis of the distances from Table 3 in two-dimensional space. The traditional axes ("North-South", "East-West") have been added for clarity;

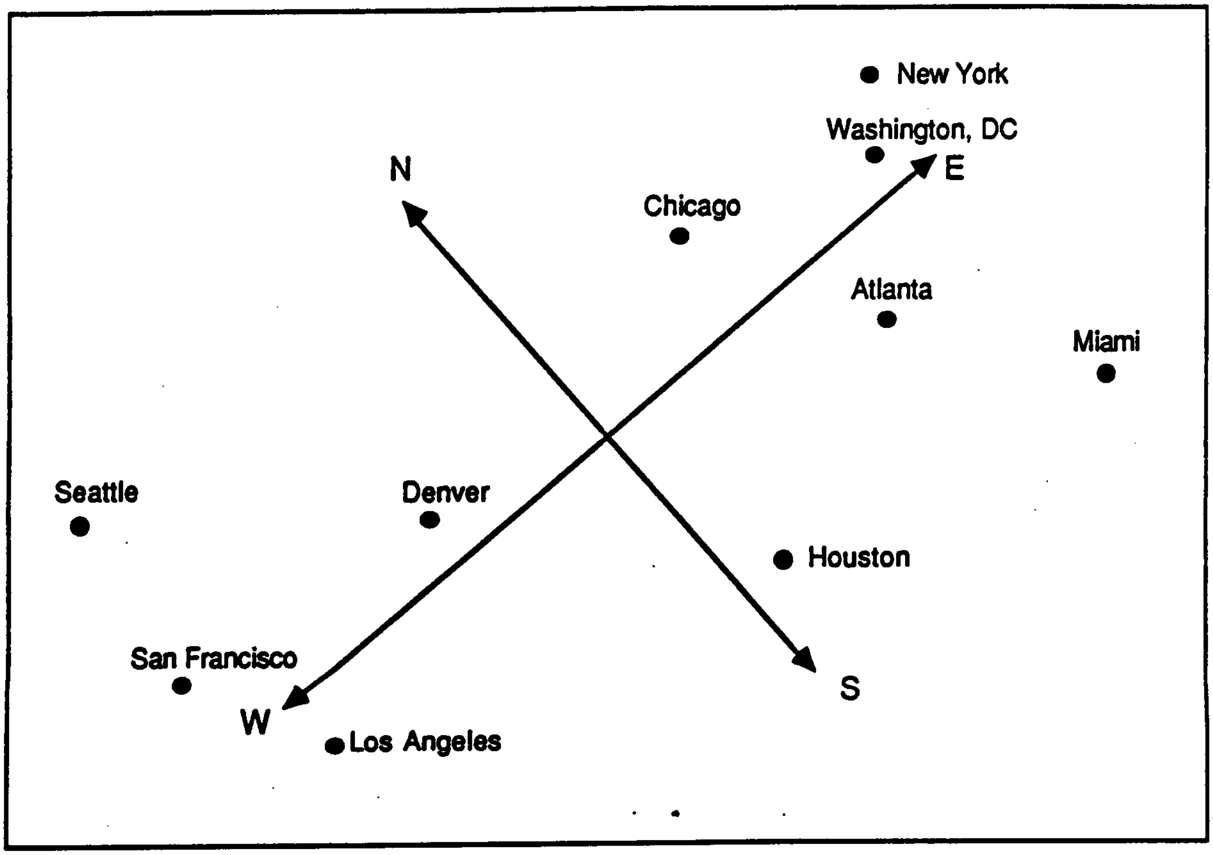

Figure 3. Configuration Obtained by Applying MDS to Airline Distances Shown in Table 3 (from Kruskal and Wish, 1978)

these are not an inherent part of MDS. In fact, there is no way that MDS can detect these axes given only the inter-city distances.

MDS has been used for a wide variety of applications. For example, Bobko, Bobko, and Davis (1984) used MDS to represent the perceived similarity of ten commercial video games, while Hooley (1984) used it to represent the perceived similarity of eight cigarette brands. In a study more closely related to our current use, Nathan (1984) used MDS to identify the optimal arrangement of seven facilities within a manufacturing plant. His technique involved having managers make judgements (on a six-point scale) of the need for closeness between all pairs of facilities. The managers were provided with matrices of volume flow and handling cost for use in making their judgements.

Since the computer program for performing the MDS analysis is a general-purpose tool, it was developed under MDAC's Independent Research and Development (IR&D) activity. The program was based upon techniques for non-metric MDS described by Shepard (1962), Kruskal (1964), and Young and Torgerson (1967). "Non-metric" MDS is a particular type of MDS that is generally used when the distances being submitted to analysis are psychological rather than physical (i.e., they were not directly "measured").

An important point about MDS is that, for any matrix of distances, there may not be a perfect solution in any given space. If the original matrix is composed of distances actually measured in two-dimensional space, there should be a near-perfect MDS solution in two-dimensional space (except for measurement error). However, in many cases the original matrix is composed of distances that are more psychological in nature (e.g., subjective ratings of similarities among objects). In these cases, there probably will not be a perfect solution in any given space. In this situation, various measures can be used to express the goodness of fit between the MDS solution and the original matrix. (See Kruskal, 1977, p. 306-308, for a discussion of these measures.) In general, all the goodness-of-fit measures reflect how accurately the distances between the objects in the MDS configuration correspond to the distances in the original matrix.

For this study, Kruskal's "stress" was used as the measure to describe the correspondence between the distances in the MDS solution and the distances in the original matrix. Specifically, stress is computed as follows:

$$\text{Stress} = \frac{\Sigma(d_{ij}-\hat{d}_{ij})^2}{\Sigma\, d_{ij}^2}$$

where: d_{ij} = distances between all pairs of i and j objects (functions) in the MDS configuration

$\hat{d}_{ij}$ = disparities between the distances in the MDS configuration and the order of the distances in the orginal matrix

As the goodness of fit for a particular MDS configuration improves, the values of $\hat{d}_{ij}$ will approach the corresponding values of d_{ij}, thus causing stress to approach zero. As an example, the stress for the MDS configuration shown in Figure 3 is 0.0007. Thus, the solution is near-perfect, which is what would be expected since the original distances were actually measured in two-dimensional space. In applications dealing with "psychological" distances, however, the values of stress for the best configurations are usually not so small.

For the FRA, all of the analyses were performed in one, two and three dimensions. Although it is theoretically possible to calculate MDS configurations using more than three dimensions, it is probably not warranted by the data nor particularly useful. As suggested by McGrath (1984, p. 123) and others, the use of more than three dimensions is primarily fitting noise, in most cases. One way of determining the "optimum" number of dimensions to use in a particular case is to plot some measure of goodness fo fit, such as stress, as a function of the number of dimensions. The optimum number of dimensions then usually appears as the "elbow" of the curve, after which increasing dimensionality has limited payoff. These kinds of plots will be shown along with the discussions of the individual criteria.

Another way of visualizing the goodness of fit of any MDS configuration is to plot the distances in the MDS configuration versus the distances in the original matrix. Such plots are shown in Appendix A for all of the MDS configurations derived in this study. If these distances are perfectly correlated (reflecting a very good fit), the data points will lie along a straight, diagonal line (e.g., the three-dimensional configuration for the privacy data). On the other hand, if the distances are not highly correlated (reflecting a poor fit), the data points will be more scattered (e.g., the one-dimensional configuration for noise interference). There are situations, however, where the relationship between the original distances and the distances in the MDS configuration is not linear, but is still highly monotonic (e.g., the three-dimensional configuration for transition frequency). In these cases, the value of the correlation coefficient may be low (reflecting a poor fit), but the value of stress may also be low (reflecting a good fit). This is because stress is calculated based only upon the order of the original distances, so no assumption of linearity is made.

A final point about the analysis tools that warrants some discussion is the use of both hierarchical clustering and MDS. A comparison of Figures 2 and 3, which show analyses of the airline distances in Table 3, indicates that there is some redundancy between the hierarchical cluster analysis and the MDS analysis. In many ways, the main difference between the two techniques is simply that they provide different ways of graphically representing the same data. In this particular example, the MDS analysis (Figure 3) provides a much more familiar representation, due to our familiarity with maps of the United States. In other cases, however, the cluster analysis can add to our interpretation of the data. This use of both MDS and cluster analysis (as well as other tools) for interpreting distance matrices has been advocated by Shepard (1980).

In the cluster and MDS analyses of the five criteria for assessing functional relationships, we focused on the MDS analysis. Generally, MDS is a more sensitive technique than cluster analysis. As appropriate, however, features of the cluster analysis will be pointed out to clarify functional relationships.

5. Conduct Analysis of Crew Transition Frequency

As mentioned earlier, one of the five criteria for assessing functional relationships involves the frequency with which the crew members shift from performing one function to performing another function. Such a shift between functions may be referred to as a crew transition between functions. The assumption is that the Space Station facilities should be arranged in such a manner as to facilitate transitions that occur frequently. This is clearly consistent with traditional time-and-motion approaches to facilities layout (e.g. Chapanis, 1959, p. 23-62).

Sample sequences of crew functions provided the basis for estimating frequency of crew transitions. Sample sequences were developed showing the order in which individual crew members might perform the functions listed in Table 1. Each sequence covered a 24-hour period for one crew member. A total of fourteen sequences were developed: six for Space Station Specialists, six for Mission Specialists, and two for off-duty days. The sample sequences are shown in Appendix B. These fourteen sequences can be viewed as representing the sequence of functions that one "composite" crew member might perform over a two-week period (assuming one day off per week).

The individual crew sequences were actually built by listing the function numbers from a master list of functions (with the ability to add comments, if needed). A computer program was then used to read all of these sequence files and calculate the frequency of all possible transitions between functions. The result was a matrix of crew transition frequencies for all pairs of functions, shown in Table 4.

Since MDS and hierarchical clustering both require that the values to be analyzed represent distances of some sort, it was necessary to first reverse the scale of the values in Table 4. That is, higher values need to represent

Table 4. Matrix of Crew Transition Frequency

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		42	0	1	1	0	12	3	3	0	0	0	3	5	0	2	3	1	0	0	0	2	0	1	0	2	2
Eating			41	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Meal Clean-up				5	1	0	1	2	1	2	0	1	6	2	1	1	7	0	0	0	1	2	1	0	4	2	1
Exercise					1	3	2	1	5	0	0	1	1	2	0	2	0	1	0	0	0	0	0	0	1	0	0
Medical Care						0	1	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
Full-body Cleaning							0	9	4	0	1	1	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Hand/Face Cleaning								1	21	1	2	1	2	1	0	0	1	3	0	1	0	1	1	0	0	3	1
Personal Hygiene									13	0	6	2	1	7	0	0	1	0	0	0	0	0	0	0	0	0	0
Urination/Defecation										3	2	8	2	8	0	4	2	4	3	0	2	0	3	3	4	2	4
Training											0	2	1	0	0	0	3	0	0	0	0	0	0	1	0	3	0
Sleep												1	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0
Private Recreation													5	3	2	1	0	0	0	0	0	0	0	0	0	1	0
Small-grp Recreation														1	0	1	0	1	0	0	0	0	0	0	0	1	0
Changing Clothes															1	0	2	0	0	0	0	0	0	0	0	0	0
Clothing Maint.																0	0	0	0	0	0	0	0	0	0	0	0
Meetings & Teleconf																	2	1	0	0	0	2	0	0	1	1	2
Planning & Sched.																		3	1	1	0	0	0	2	2	1	1
Subsys Monitoring																			0	1	0	1	3	1	0	0	0
Pre/Post-EVA																				0	0	0	0	0	0	0	0
IVA Support of EVA																					1	0	0	0	0	0	0
Prox Operations																						0	0	0	0	0	0
Gen. Housekeeping																							0	2	0	0	0
ORU Maintenance																								0	1	0	0
Logistics, Resupply																									0	0	0
Payload Support																										0	1
Life Sciences Exp.																											2
Mtl. Proc. Exper.																											

a more distant relationship between functions instead of a closer relationship as the transition frequencies currently do. The scale was reversed by simply subtracting all of the entries in Table 4 from the maximum value in the table (42%).

The result of the cluster analysis of the reversed matrix is shown in Figure 4. Likewise, the values of stress for the one-, two-, and three-dimensional MDS configurations are shown in Figure 5. The "elbow" of this curve obviously occurs at two dimensions, since the use of three dimensions did not significantly reduce stress further. Figure 6 shows this two-dimensional MDS configuration.

The cluster analysis (Figure 4) shows that there are really only two clusters of functions that are very closely related at all: (1) Meal Preparation, Eating, and Meal Clean-up; and (2) Urination/Defecation and Hand/Face Cleansing. Further, these two clusters themselves are fairly closely related to each other. Obviously, these clusters are quite logical.

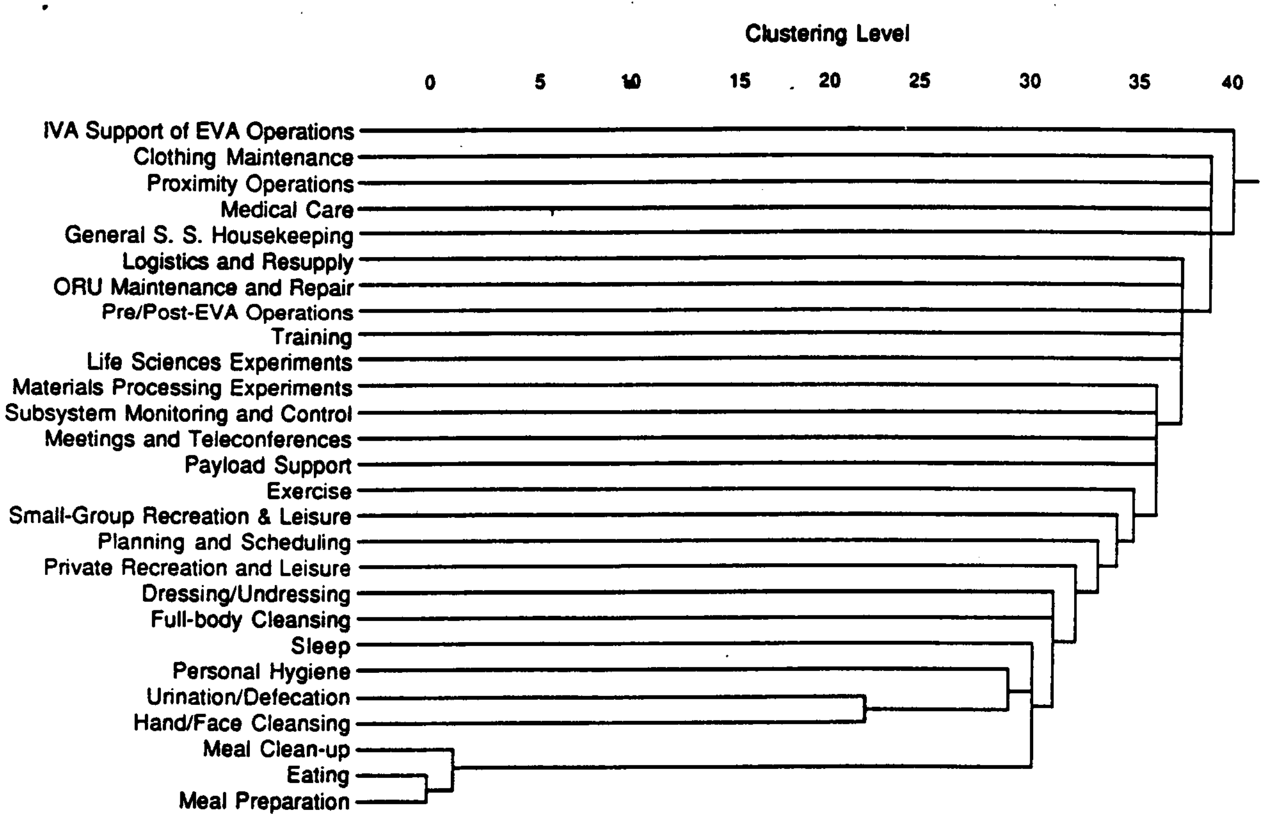

Figure 4. Hierarchical Cluster Analysis of Crew Transition Frequency

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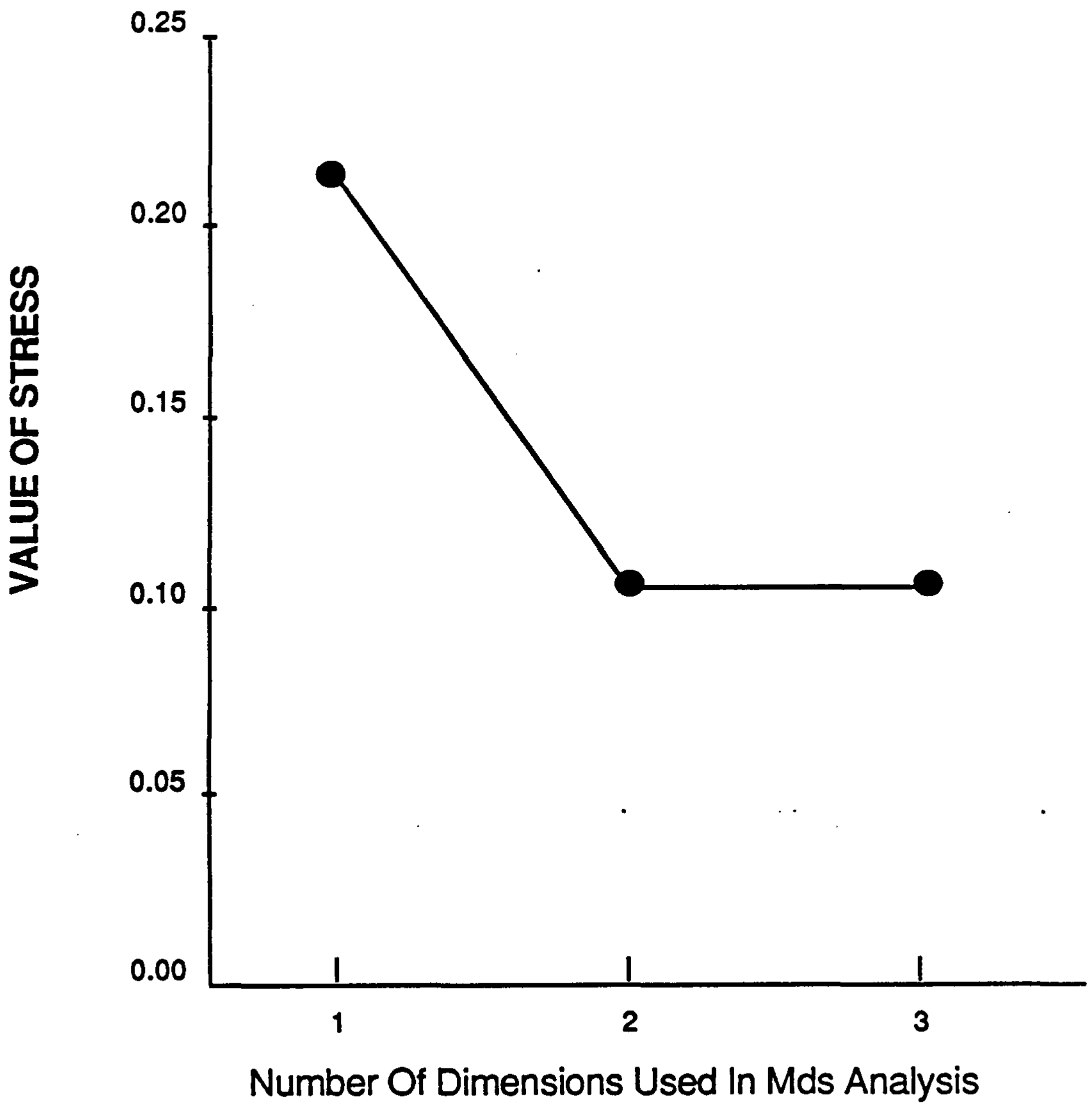

Figure 5. Stress for 1-, 2-, and 3-Dimensional MDS Configurations for Crew Transition Frequency

These two clusters are also apparent from the MDS configuration (Figure 6), where they appear near the center of the plot.

The frequency of crew transitions between most of the other functions is sufficiently low that they do not combine into clusters until relatively high levels in the cluster analysis. In the MDS analysis, this causes these other functions to be distributed around the periphery, while the two clusters discussed before fall near the center. In general, the more frequently

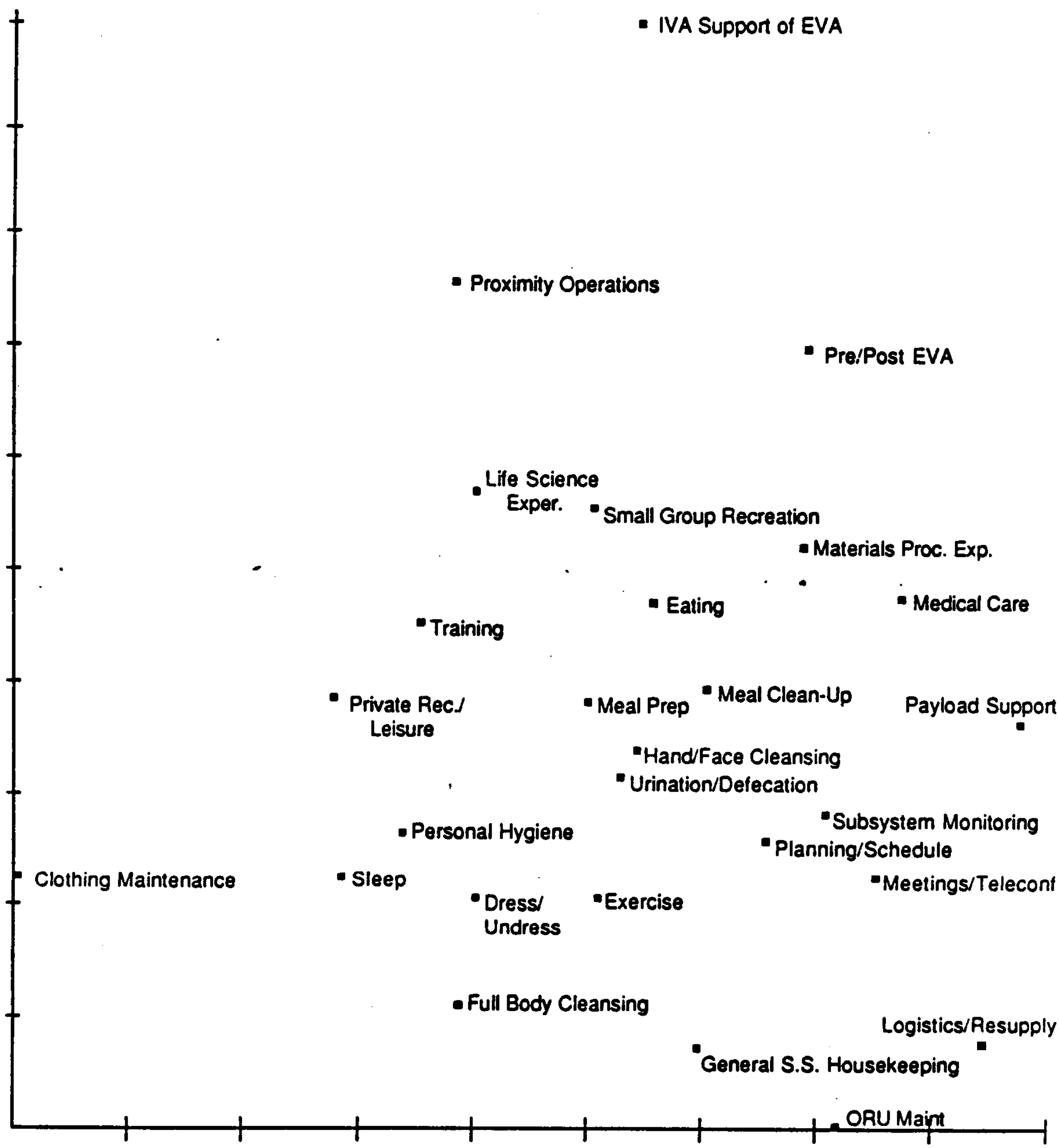

Figure 6. Two-Dimensional MDS Configuration for Crew Transition Frequency

performed functions fall near the center of the MDS configuration while the less frequently performed functions fall around the periphery. In addition, the crew support functions tend to fall in the bottom and left portions of Figure 6, (e.g., Clothing Maintenance, Full-body Cleansing) while the Space Station and mission operations functions tend to fall in the top and right (e.g., IVA Support of EVA, Payload Support).

6. Conduct Analysis of Sequential Dependencies

Some of the functions listed in Table 1 depend upon other functions for their input. An obvious example of this kind of sequential dependency is that "Eating" depends upon "Meal Preparation" for its input. A somewhat less obvious example is that "Exercise" may occasionally generate the need for "Full-body Cleansing" or "Hand/Face Cleansing" as a result of perspiration.

The type of flow between functions that these sequential dependencies generate can take on various forms: material (e.g., food), changes in the state of the crew (e.g., the need to urinate or defecate), or information (e.g., an update to the inventory system as a result of food consumed). As with crew transition between the functions, traditional techniques of facilities layout suggest that this kind of flow between functions should be optimized by locating those facilities that support dependent functions close together. This analysis of sequential dependencies is somewhat related to traditional "link" analysis (e.g., Chapanis, 1959, p. 51-62).

As the above examples illustrate, these dependencies are not necessarily all-or-none. Consequently, the following rating scale was developed to quantify the degree of sequential dependency between all pairs of functions:

How often does one function provide the reason (or need) to perform another function?

0 = always
1 = often
2 = occasionally
3 = rarely
4 = never

Due to the subjective nature of these judgements, three people familiar with Space Station crew functions were asked to rate, independently, all possible pairs of functions using this scale. The values submitted to analysis were then the averages of the three independent ratings, as shown in Table 5.

To assess the amount of agreement between the three independent sets of ratings, correlations between them were calculated. The results were as follows:

	Rater #1	Rater #2	Rater #3
Rater #1	-	.50	.34
Rater #2		-	.31
Rater #3			-

Table 5. Matrix of Sequential Dependencies

(Values shown are 10 times actual values)

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		0	4	37	34	40	17	34	34	40	40	40	40	40	40	40	34	40	40	40	40	30	40	34	40	40	40
Eating			0	34	34	40	10	20	20	40	37	34	27	40	40	37	37	40	40	40	40	40	40	40	40	40	40
Meal Clean-up				34	37	30	17	30	27	40	30	30	30	37	40	40	37	34	37	34	34	34	34	34	34	34	34
Exercise					37	7	14	24	24	40	30	27	27	24	30	30	30	34	34	34	34	34	34	34	34	30	34
Medical Care						30	17	30	30	30	30	30	30	34	34	34	34	34	30	34	30	30	34	34	34	30	34
Full-body Cleaning							14	20	27	37	27	27	27	14	30	27	30	34	20	30	34	30	30	34	34	27	30
Hand/Face Cleaning								17	14	40	24	30	30	27	34	30	30	24	34	34	34	30	30	34	30	27	27
Personal Hygiene									20	40	17	27	27	27	27	27	27	27	24	27	27	27	30	27	27	30	30
Urination/Defecation										40	17	24	24	27	30	27	27	30	24	27	27	27	27	27	27	27	27
Training											37	37	37	37	37	37	27	27	27	27	30	37	24	30	30	27	30
Sleep												34	34	20	30	34	27	30	34	34	34	34	34	34	34	34	34
Private Recreation													34	27	30	30	30	34	34	34	34	30	34	34	30	34	34
Small-grp Recreation														34	30	30	30	34	34	34	34	34	34	34	34	34	34
Changing Clothes															14	37	37	37	27	37	34	37	37	37	34	37	37
Clothing Maint.																37	37	37	37	37	37	34	37	37	37	34	37
Meetings & Teleconf																	14	30	34	34	34	34	37	30	34	34	34
Planning & Sched.																		27	27	17	20	20	20	17	20	20	20
Subsys Monitoring																			24	27	27	37	20	27	24	27	27
Pre/Post-EVA																				0	34	37	34	40	37	40	40
IVA Support of EVA																					40	34	30	34	30	34	34
Prox Operations																						37	30	30	27	40	40
Gen. Housekeeping																							27	27	30	34	34
ORU Maintenance																								30	30	30	30
Logistics, Resupply																									30	30	30
Payload Support																										30	30
Life Sciences Exp.																											40
Mtl. Proc. Exper.																											

While all of these correlations are significant (p <.01), they indicate that the raters did not totally agree on the sequential dependencies among the functions.

The result of the cluster analysis of Table 5 is shown in Figure 7. The values of stress for the one-, two-, and three-dimensional MDS configurations are plotted in Figure 8. Since the "elbow" clearly falls at two dimensions, the two-dimensional configuration is shown in Figure 9.

The cluster analysis resulted in two main clusters that formed at a very low level: (1) Meal Preparation, Eating, and Meal Clean-up, and (2) Pre/post-EVA Operations and IVA Support of EVA. These are indicated on the MDS configuration as well. However, these two clusters were not very closely related to each other.

A close inspection of the MDS configuration reveals some other interesting information as well. In general, most of the Crew Support functions fell in the top and left of Figure 9 (e.g., Eating, Clothing

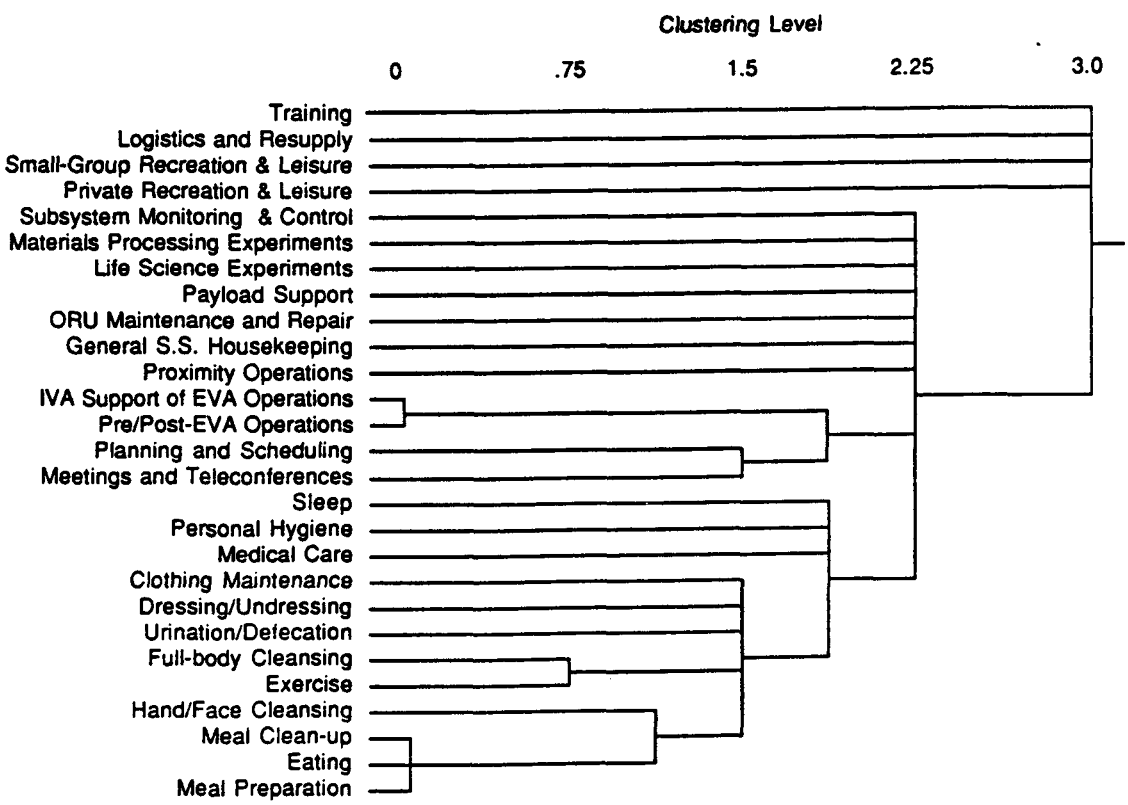

Figure 7. Hierarchical Cluster Analysis of Sequential Dependencies

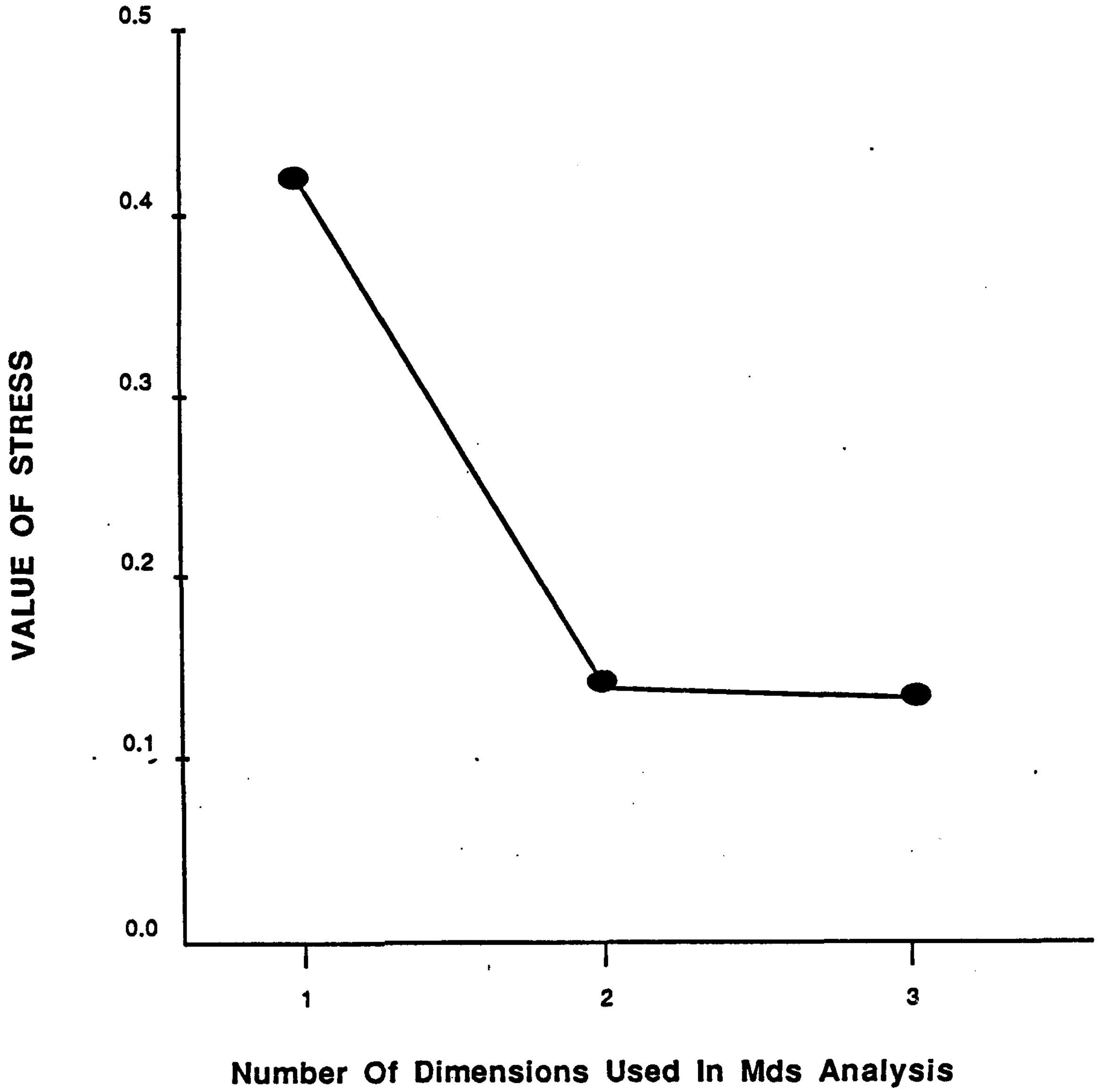

Figure 8. Stress for 1-, 2-, and 3-Dimensional MDS Configurations for Sequential Dependencies

Maintenance, Small-group Recreation), while most of the Space Station and Mission Operations functions fell in the bottom and right (e.g., Materials Processing Experiments, Proximity Operations, ORU Maintenance). An interesting exception to this is Training, which is commonly viewed as being a Crew Support function, but which clearly fell in with the Station and Mission Operations functions. The apparent reason for this is that many Station and Mission functions are dependent upon the crew being properly trained.

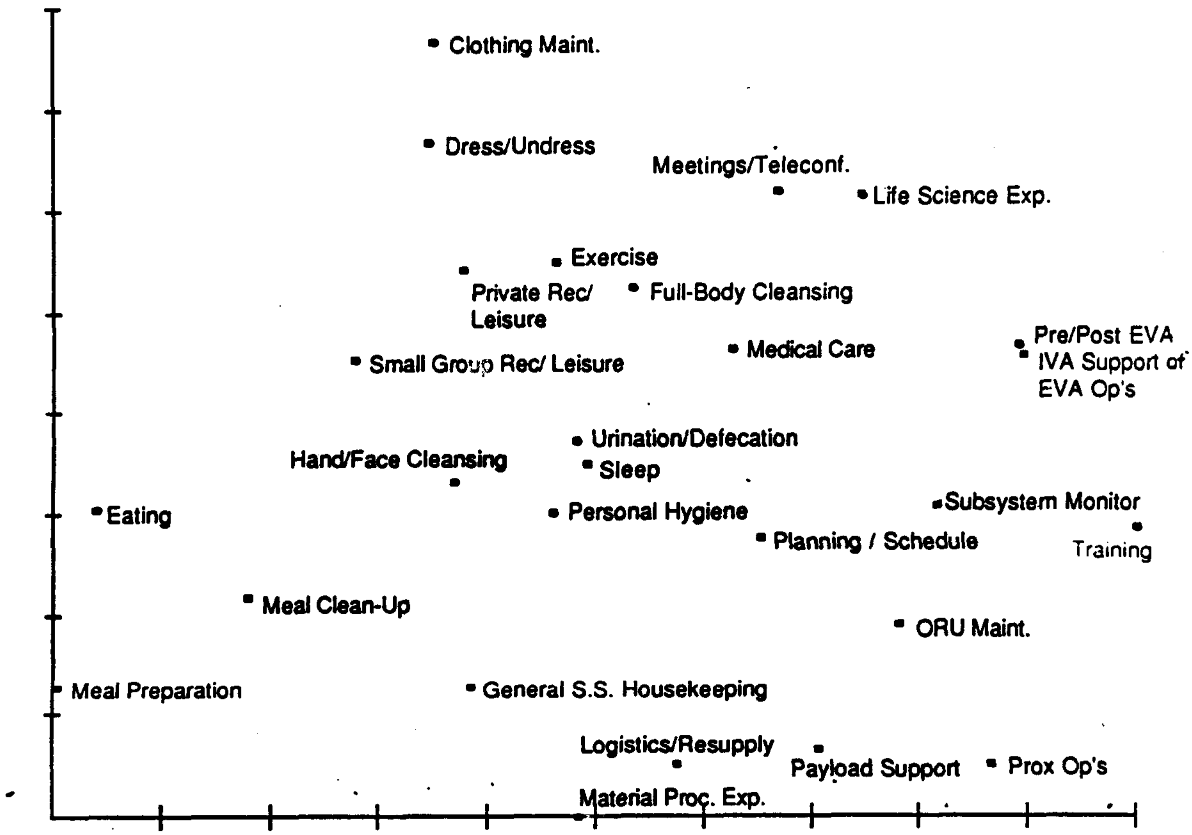

Figure 9. Two-Dimensional MDS Configuration for Sequential Dependencies

7. Conduct Analysis of Support Equipment Requirements

One of the zoning-type criteria for measuring the relationships between crew functions on the Space Station involves the extent to which the functions require similar support equipment. The implicit assumption is that functions that share similar support equipment are more compatible than those that do not. Taken to the extreme, if two crew functions require precisely the same set of support equipment, then those functions might reasonably be performed at the same place. The assumption that increasing similarity of support equipment corresponds to increasing compatibility of crew functions seems reasonable since the nature of the crew's activities is largely shaped by the equipment they are manipulating.

The most straight-forward measure of the extent to which two functions require similar support equipment appears to be a percentage representing what proportion of equipment is shared by the functions. Specifically, for each pair of functions, a list of the total equipment items required by either is compiled (with items required by both functions listed only once). Then the number of equipment items that are shared by both functions is determined. This number of shared items is then divided by the total number of items to get the percentage. If two functions have no equipment items in common, the percentage will be 0. If two functions have precisely the same equipment items, the percentage will be 100.

As an example of calculating this measure, consider the support equipment listed in Table 2 for the first two crew functions: Meal Preparation and Eating. "Meal Preparation" requires four different support items. "Eating" adds only one new item to that list (a group meeting place), for a total of five items. Two items are shared between the functions: "Food" and "Dishes and Utensils". Thus, the percentage of shared equipment is 2/5 or 40%.

To ensure consistent identification of equipment items across functions, a master list of support equipment was built (Table 6). The support equipment associated with each function was then identified by number from this list (with the ability to add comments, if needed, describing how a piece of equipment would be used by a given function). By identifying the equipment in this manner, it was possible to write a computer program to calculate the percentages of shared equipment for all pairs of functions. The resulting matrix of these percentages is shown in Table 7.

As with the data on transition frequency discussed in an earlier section, the scale of the values shown in Table 7 must be reversed (so that higher numbers reflect a more distant relationship) before submitting the matrix to cluster and MDS analysis. This was done using the same technique as before (subtracting each value from the maximum value in the matrix, 80).

The result of the cluster analysis of the reversed matrix is shown in Figure 10. The values of stress for the one-, two-, and three-dimensional configurations are plotted in Figure 11. Note that all three of these MDS configuratons provided extremely good fits to the data. (All values of stress were under 0.012.) For all practical purposes, then, these data can be fit by

TABLE 6. MASTER EQUIPMENT LIST

Main computer system
Food
Dishes and utensils
Food heating equipment
Group meeting place (e.g., table)
Trash disposal equipment
Dish washing equipment
Cleaning equipment (e.g., wipes, vacuum)
Exercise equipment (e.g., treadmill)
Physiological monitoring equipment
Books
TV and video playback equipment
Audio playback equipment
Medical supplies (e.g., pharmaceuticals, bandages)
Emergency medical treatment equipment (e.g., defibrillator)
Medical laboratory equipment
Minor surgery equipment
Shower
Soap and shampoo
Washcloth and towel
Hand washer
Toothpaste and toothbrush
Shaving equipment
Mirror
Comb or hairbrush
Miscellaneous personal hygiene equipment
Toilet/urinal
Sanitary wipes
Task-specific simulation equipment (e.g., MRMS simulator)
Sleep restraint
Writing equipment
Audio communications facilities
Window
Games
Clothes
Clothes washer
Clothes dryer
Video cameras
Dedicated subsystem displays (e.g., warning lights)
Dedicated subsystem controls
Remote-control TV camera
Controls for remotely operated vehicle
Tools (e.g., hammer, screwdriver)
Diagnostic equipment (e.g., volt/ohm meter)
Spare parts
Contamination containment equipment
Non-food consumables
Dedicated payload status displays

TABLE 6. MASTER EQUIPMENT LIST (Continued)

Dedicated payload controls
MRMS controls/displays
Life sciences experiment-specific displays
Life sciences experiment-specific controls
Life sciences experiment racks
Materials processing experiment-specific displays
Materials processing experiment-specific controls
Materials processing experiment racks
Extravehicular Mobility Unit (EMU) (suit and life support)
Extravehicular Excursion Unit (EEU)
EMU and EEU service and checkout equipment
Decontamination provisions

Table 7. Matrix of Shared Support Equipment

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		40	29	0	11	0	0	0	0	17	0	0	0	0	0	0	17	12	12	14	12	0	12	40	14	14	14
Eating			33	0	0	0	0	0	0	0	0	0	0	0	0	17	20	0	0	0	0	0	0	20	0	0	0
Meal Clean-up				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	14	0	0	0
Exercise					10	0	0	0	0	14	0	37	29	0	0	12	0	0	0	0	0	0	0	0	0	0	0
Medical Care						0	0	0	0	12	0	0	0	0	0	0	12	10	10	11	10	0	10	12	11	11	11
Full-body Cleaning							50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hand/Face Cleaning								12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Personal Hygiene									0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0
Urination/Defecation										0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Training											0	12	17	0	0	17	20	14	14	17	14	0	14	20	17	17	17
Sleep												0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Private Recreation													43	0	0	25	12	10	0	25	22	0	0	0	0	0	0
Small-grp Recreation														0	0	14	0	12	0	14	12	0	0	0	0	0	0
Changing Clothes															25	0	0	0	0	0	0	0	0	0	0	0	0
Clothing Maint.																0	0	0	0	0	0	0	0	0	0	0	0
Meetings & Teleconf																	17	0	0	0	0	0	0	0	0	0	0
Planning & Sched.																		14	14	40	33	0	14	20	17	17	17
Subsys Monitoring																			11	50	43	0	11	14	12	12	12
Pre/Post-EVA																				12	11	0	11	14	12	12	12
IVA Support of EVA																					80	0	12	17	14	14	14
Prox Operations																						0	11	14	12	12	12
Gen. Housekeeping																							0	0	0	0	0
ORU Maintenance																								14	12	12	12
Logistics, Resupply																									17	17	17
Payload Support																										14	14
Life Sciences Exp.																											14
Mtl. Proc. Exper.																											

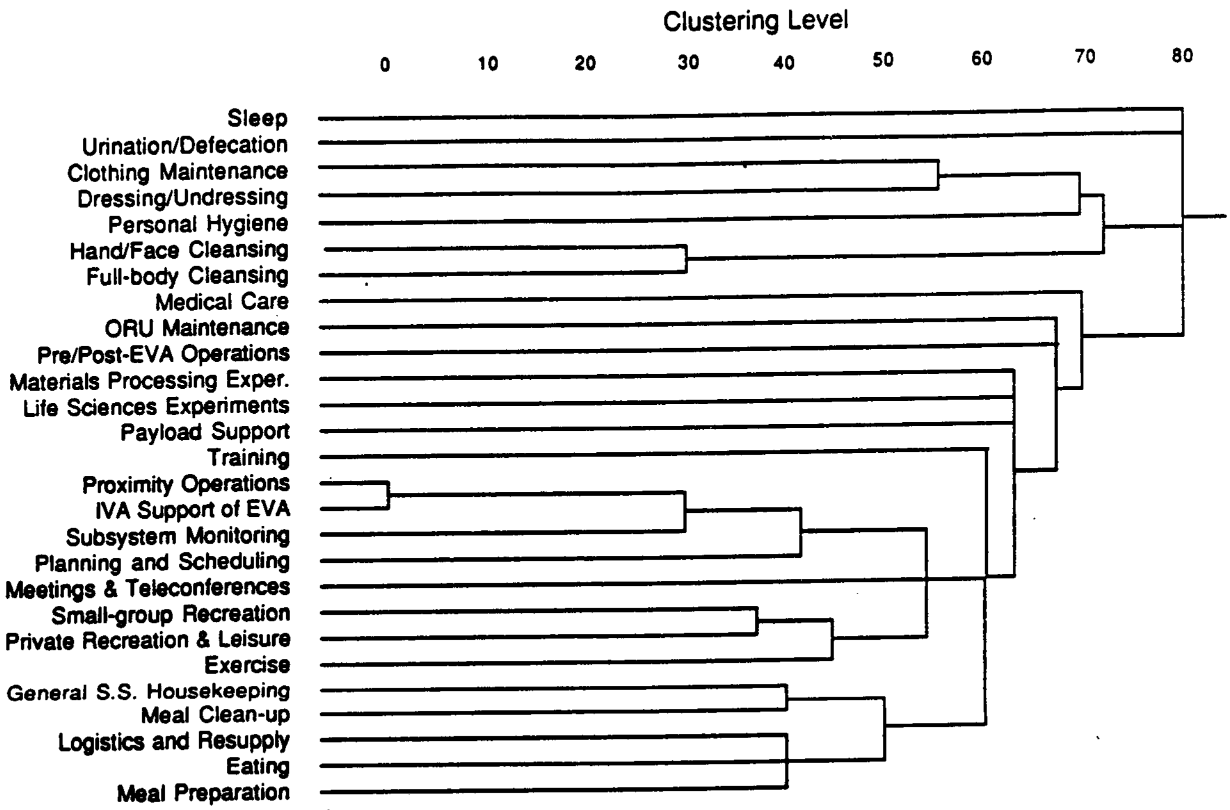

Figure 10. Hierarchical Cluster Analysis of Shared Support Equipment

a one-dimensional MDS configuration. Although the two-dimensional configuration, shown in Figure 12, reduced stress slightly, the resulting MDS solution was still essentially one-dimensional.

The obvious result from the MDS analysis shown in Figure 12 is that there are four clear groupings of functions based upon the shared support equipment. Inspection of the cluster analysis shown in Figure 10 reveals the same four clusters joining at the highest clustering level (80). One of the groups, shown on the left in Figure 12, consists of the majority of the crew functions, including such functions as Subsystem Monitoring, IVA Support of EVA, and Proximity Operations. All of the functions directly related to Space Station Operations and Mission Operations fell in this group, indicating that they share much of the same support equipment (e.g., all of the functions requiring access to the main computer system are in this group). To the right

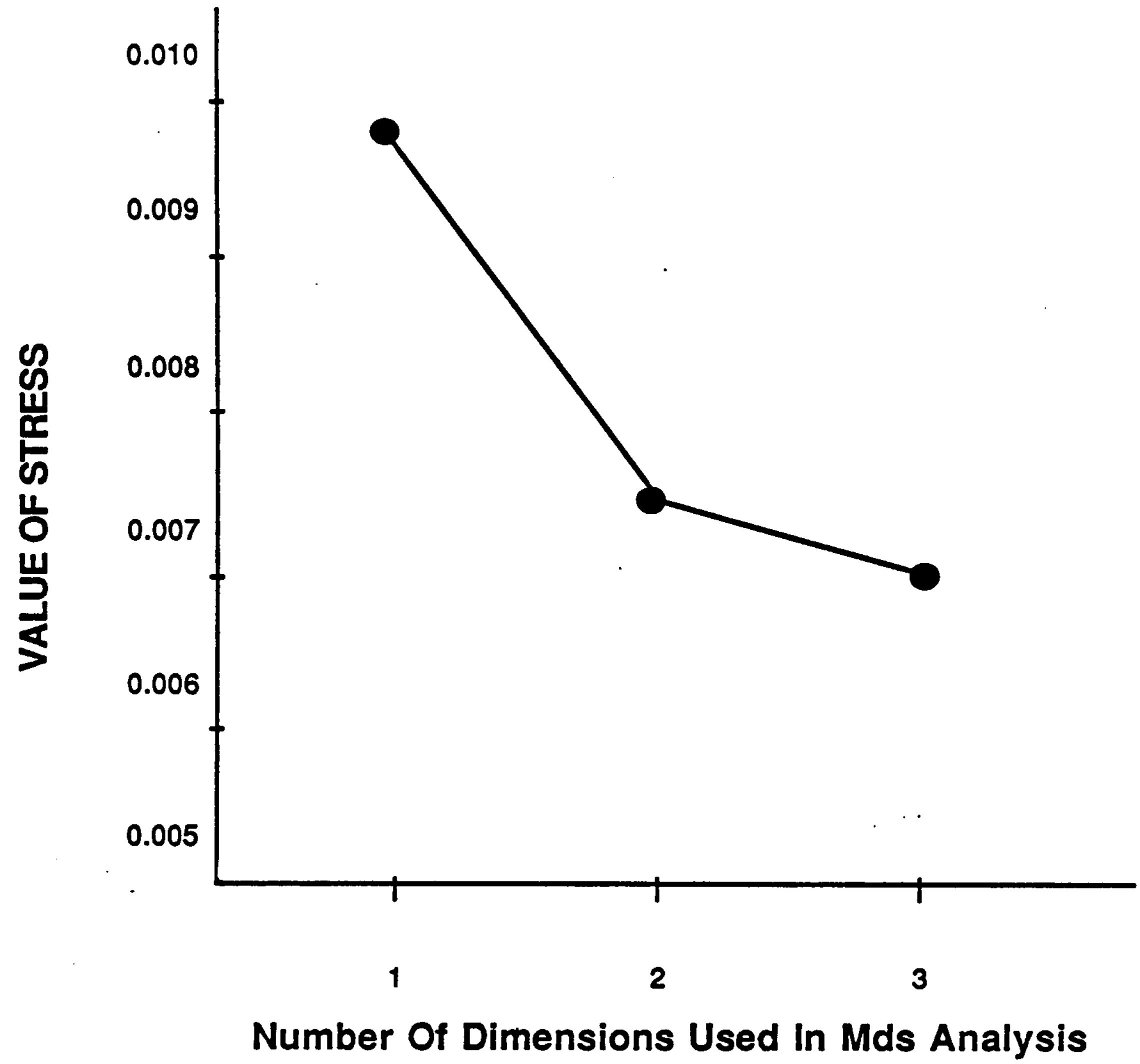

Figure 11. Stress for 1-, 2-, and 3-Dimensional MDS Configurations for Shared Support Equipment

of the main cluster in Figure 12 is another cluster consisting of five functions related to hygiene (Personal Hygiene, Changing Clothes, Hand/Face Cleansing, Full-body Cleansing, and Clothing Maintenance). These five functions do not share equipment with any other functions. Finally, apart from the two clusters are the last two functions: Sleep and Urination/ Defecation. Both of these functions are relatively isolated since neither of them shares support equipment with any other function.

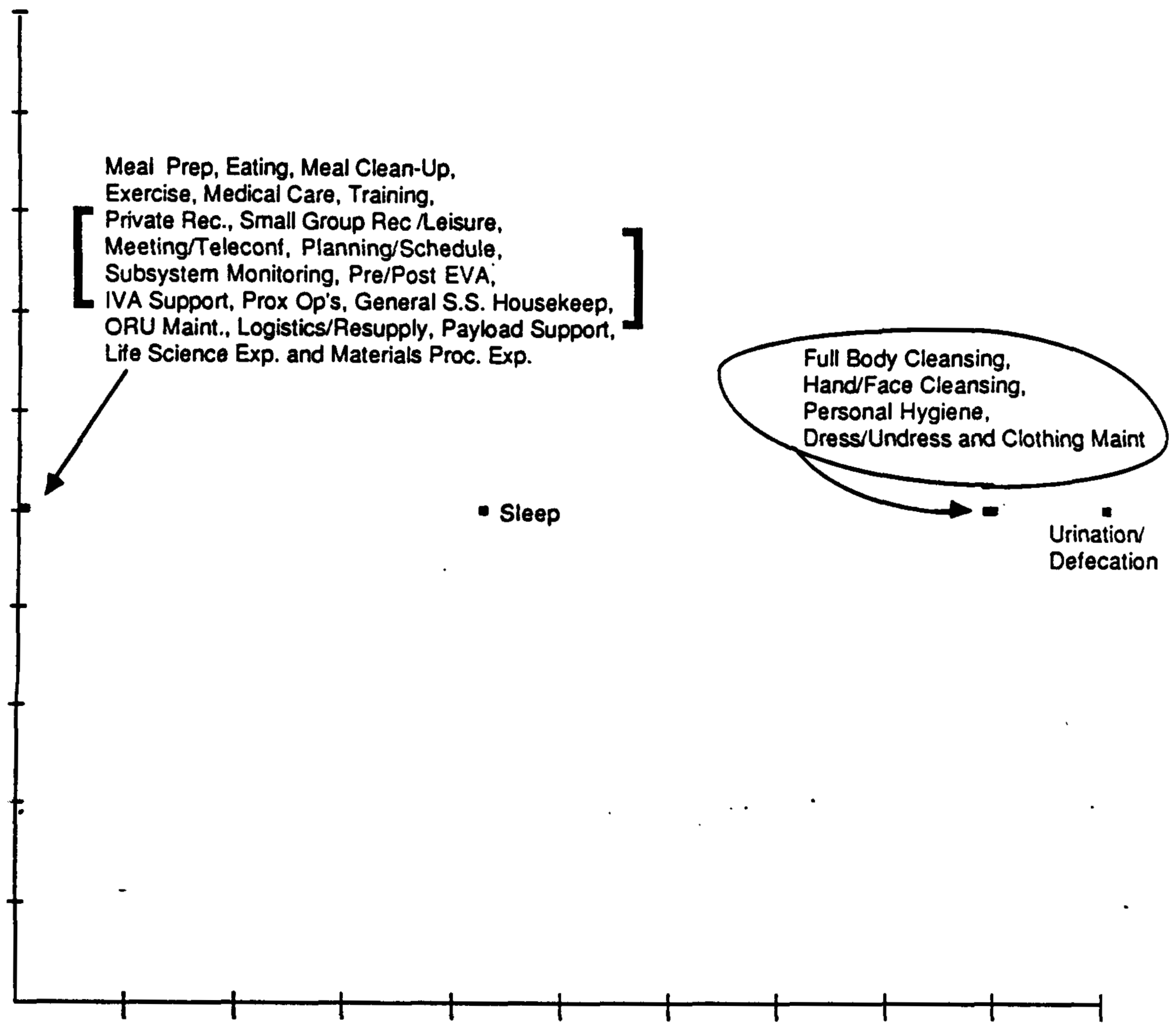

Figure 12. Two-Dimensional MDS Configuration for Shared Support Equipment

8. <u>Conduct Analysis of Potential for Noise Interference</u>

Another zoning criterion involves the potential for noise generated by the performance of one function to interfere with the performance of another function. These interference potentials were derived from a combination of two factors:

(1) The potential for each function to generate noise, either due to the crew activities or due to the support equipment.

(2) The potential for the crew activities associated with each function to be disrupted by noise.

The obvious assumption is that functions having a high potential for generating noise should not be co-located with functions having a high potential for being disrupted by noise.

A noise generation potential was assigned to each function by having raters estimate the Noise Criterion Curve (NCC) (see Figure 13) that would just <u>cover</u> the noise curve generated by the function. (For a discussion of Noise Criterion Curves see, for example, McCormick, 1970, p. 207-208). The acceptable range of NCC values was 15 (extremely quiet) to 70 (extremely loud). The noise generation ratings were assigned on the basis of the types of support equipment that might generate noise (e.g., rotating motors, air duct noises, showers, hammer, drill) and the associated crew activities (e.g., large-group discussions). These assessments were made independently by the same three people who did the earlier sequential dependency ratings. The resulting average noise generation potentials are shown in Table 8.

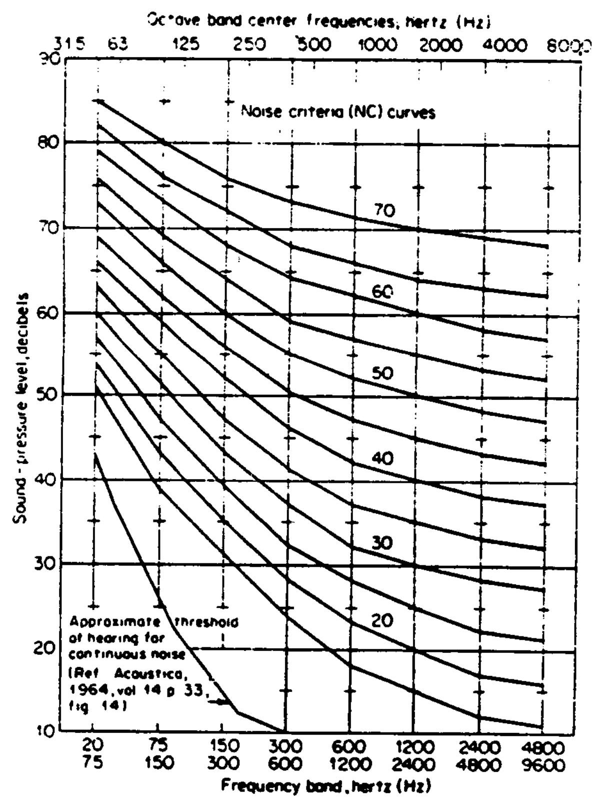

Figure 13. Noise Criteria Curves (from McCormick, 1970, p. 207)

Table 8. Average Ratings for Noise Generation, Noise Tolerance, and Noise Disruption (Noise Disruption = 52.7 - Noise Tolerance)

Function	Noise Generation	Noise Tolerance	Noise Disruption
Meal Preparation	37.0	50.7	2.0
Eating	41.7	41.3	11.4
Meal Clean-up	45.0	51.0	1.7
Exercise	50.0	50.0	2.7
Medical Care	26.7	29.7	23.0
Full-body Cleansing	42.7	46.0	6.7
Hand/Face Cleansing	34.7	46.0	6.7
Personal Hygiene	35.7	48.3	4.4
Urination/Defecation	33.7	48.3	4.4
Training	31.3	30.3	22.4
Sleep	19.7	21.3	31.4
Private Recreation and Leisure	26.7	23.0	29.7
Small-group Recreation and Leisure	35.3	32.0	20.7
Dressing/Undressing	27.0	49.3	3.4
Clothing Maintenance	35.3	48.7	4.0
Meetings and Teleconferences	47.7	26.7	26.0
Planning and Scheduling	38.3	31.0	21.7
Subsystem Monitoring and Control	39.0	27.3	25.4
Pre/Post-EVA Operations	42.3	34.7	18.0
IVA Support of EVA Operations	40.0	34.0	18.7
Proximity Operations	37.7	25.7	27.0
General Space Station Housekeeping	47.3	52.7	0.0
ORU Maintenance and Repair	52.3	40.7	12.0
Logistics and Resupply	44.0	50.0	2.7
Payload Support	36.3	31.0	21.7
Life Sciences Experiments	35.0	31.3	21.4
Materials Processing Experiments	44.7	31.0	21.7

A noise tolerance level was then established for each function by asking the raters to select the Noise Criterion Curve that represents the maximum level of noise that could be tolerated by a crew member without disrupting performance of the function. Again, these values could range from 15 to 70. The resulting average noise tolerance levels are shown in Table 8.

The correlations between the estimated noise generation levels for the three raters were as follows:

	Rater #1	Rater #2	Rater #3
Rater #1	-	.72	.78
Rater #2		-	.81
Rater #3			-

The correlations between the estimated noise tolerance levels were as follows:

	Rater #1	Rater #2	Rater #3
Rater #1	-	.86	.83
Rater #2		-	.88
Rater #3			-

All of the correlations were significant (p <.01) and relatively high, indicating general agreement among the raters on the noise generation and noise tolerance levels for each of the functions.

To arrive at a noise-interference potential for each pair of functions, the basic approach was to combine the corresponding noise generation and noise tolerance levels. However, before combining them it was necessary to rescale the noise tolerance levels so that higher numbers represent a greater potential for the function to be disrupted by noise. This was done by subtracting each of the noise tolerance levels from the highest tolerance level found (52.7). The resulting values, which will be called noise disruption potentials, are shown in Table 8. The noise generation levels and noise disruption potentials were then multiplied together to form a full matrix. This approach, however, results in an asymmetric matrix. For example, "Sleep" has a noise disruption potential of 31.4 and a noise generation potential of 19.7; the corresponding values for "Exercise" are 2.7 and 50.0. Thus, the two products are 53.2 (19.7 x 2.7) and 1570 (31.4 x 50.0).

Since it is physically impossible for the distance from area "A" to area "B" to be different from the distance from area "B" to area "A", then one number must be chosen to represent the noise interference potential between each pair of functions. Since these numbers represent a type of incompatibility between the functions, it was decided that the appropriate number to use in each case is the sum of the two values. Following the example given before, the noise interference potential between "Sleep" and "Exercise" would be 1623.2 (53.2 + 1570). These resulting noise interference potentials are shown in Table 9, where they have been divided by 10 and rounded to the nearest whole number for ease of representation.

The result of the cluster analysis of Table 9 is shown in Figure 14. The values of stress for the one-, two-, and three-dimensional MDS configurations are plotted in Figure 15. Since the "elbow" seems to occur at two dimensions, the two-dimensional MDS configuration is shown in Figure 16.

The MDS configuration (Figure 16) very clearly shows one main cluster of functions near the center of the plot. This same group appears as the bottom eleven functions in the cluster analysis (Figure 14). This cluster is composed almost entirely of crew support functions (e.g., Dressing/Undressing, Meal Preparation, Exercise). The functions in this cluster are those functions that are the least likely to be disrupted by noise. In fact, inspection of Table 8 reveals that the noise disruption potentials for these eleven functions ranged from only 0 to 6.7. The next-lowest disruption potential is 11.4 (for Eating), reflecting the clear separation between the central cluster and the other functions.

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Table 9. Matrix of Noise Interference Potentials

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Telecon.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		50	15	20	90	33	32	23	23	89	120	115	84	18	22	106	88	102	75	77	107	9	55	19	87	86	89
Eating			58	68	126	76	67	58	56	129	153	154	126	44	57	162	134	150	123	123	155	54	109	61	131	129	141
Meal Clean-up				20	108	37	36	25	25	106	144	138	99	20	24	125	104	120	88	91	128	8	63	19	104	102	105
Exercise					122	45	43	31	31	120	162	155	113	24	29	143	119	137	101	104	145	13	74	25	118	116	120
Medical Care						116	98	94	89	132	129	140	136	71	92	179	146	157	145	142	159	109	152	108	141	137	161
Full-body Cleaning							52	42	41	116	147	144	112	32	41	143	118	134	105	106	140	32	86	41	117	114	122
Hand/Face Cleaning								39	37	98	122	121	95	30	37	122	101	114	91	91	119	32	76	39	99	97	105
Personal Hygiene									30	93	120	117	89	24	30	113	94	107	83	84	113	21	65	29	93	91	97
Urination/Defecation										89	114	111	85	23	29	108	90	102	79	80	107	21	63	28	89	87	92
Training											142	153	144	71	91	188	153	166	151	148	169	106	154	107	149	145	168
Sleep												142	151	91	119	200	163	172	168	162	171	148	188	143	156	152	183
Private Recreation													160	89	115	211	171	183	174	168	184	140	187	138	166	161	190
Small-grp Recreation														68	87	190	156	170	151	149	173	98	151	100	152	148	169
Changing Clothes															23	86	71	81	63	64	85	16	50	22	71	69	73
Clothing Maint.																111	92	105	81	82	110	19	63	27	91	89	94
Meetings & Teleconf																	203	222	196	193	227	123	193	127	198	193	219
Planning & Sched.																		182	161	158	185	103	159	106	162	158	180
Subsys Monitoring																			177	174	201	120	179	122	177	172	198
Pre/Post-EVA																				151	182	85	145	90	157	153	172
IVA Support of EVA																					178	86	146	93	154	151	170
Prox Operations																						128	186	129	180	175	202
Gen. Housekeeping																							57	13	103	101	103
ORU Maintenance-																								67	157	154	167
Logistics, Resupply																									105	103	107
Payload Support																										153	175
Life Sciences Exp.																											171
Mtl. Proc. Exper.																											

The remaining functions are scattered around the periphery of the MDS configuration. In general, the quieter functions that are susceptible to noise disruption fall in the top and right (e.g., Sleep, Private Recreation) while the noisier functions that are also somewhat susceptible to disruption fall in the bottom and left (e.g., Meetings and Teleconferences, ORU Maintenance).

9. <u>Conduct Analysis of Need for Privacy</u>

Some of the functions listed in Table 1 are inherently more "private" than others (e.g., Sleep). In general, privacy may be defined as the ability to control or regulate information about oneself that is available to others.

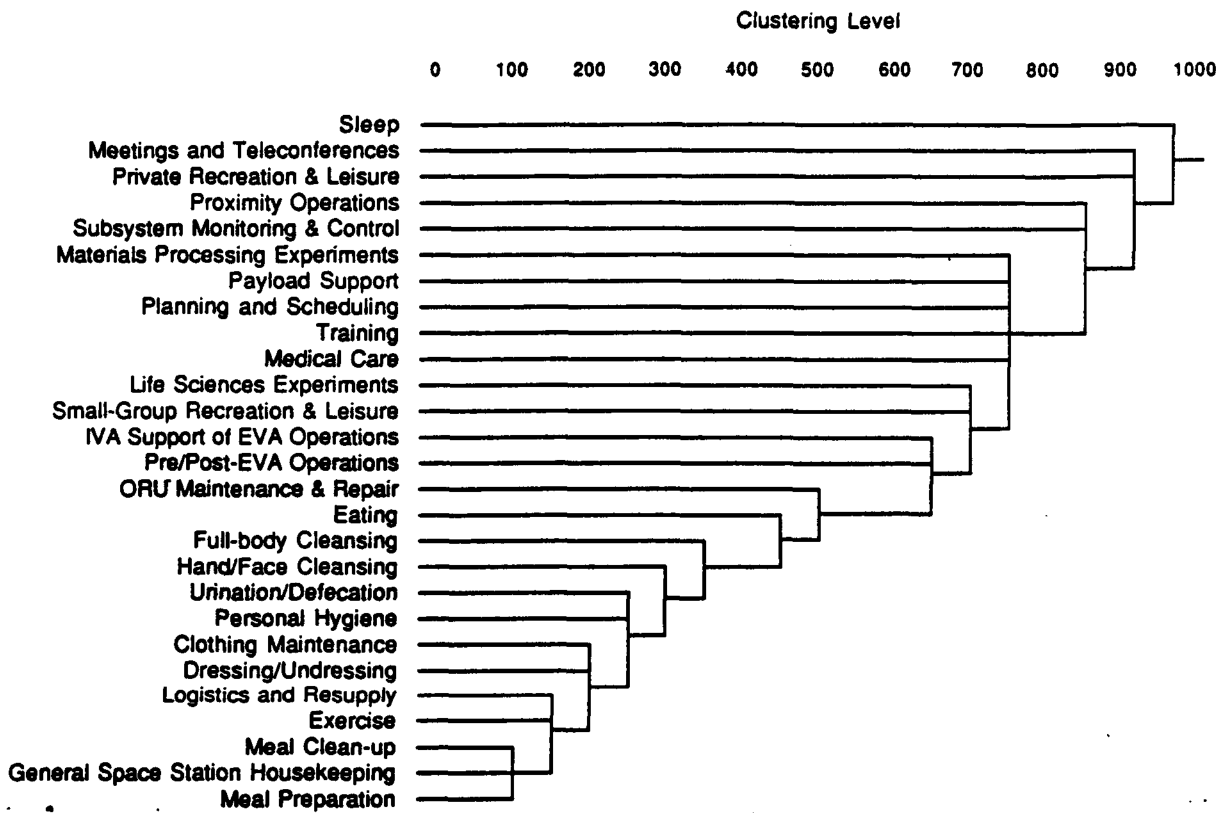

Figure 14. Hierarchical Cluster Analysis of Noise Interference

This regulation can occur for two main sensory channels: audio and visual (i.e., you wish to regulate how much others can hear about what you are doing and how much they can see). Neither type of privacy regulation is an all-or-none affair. Consequently, methods for rating both types of desired privacy were developed.

Audio privacy was operationally defined for each function as the optimum percentage of words spoken by someone performing the function that could be understood by a listener. These percentage assessments where made independently by three raters. The resulting averages are shown in Table 10.

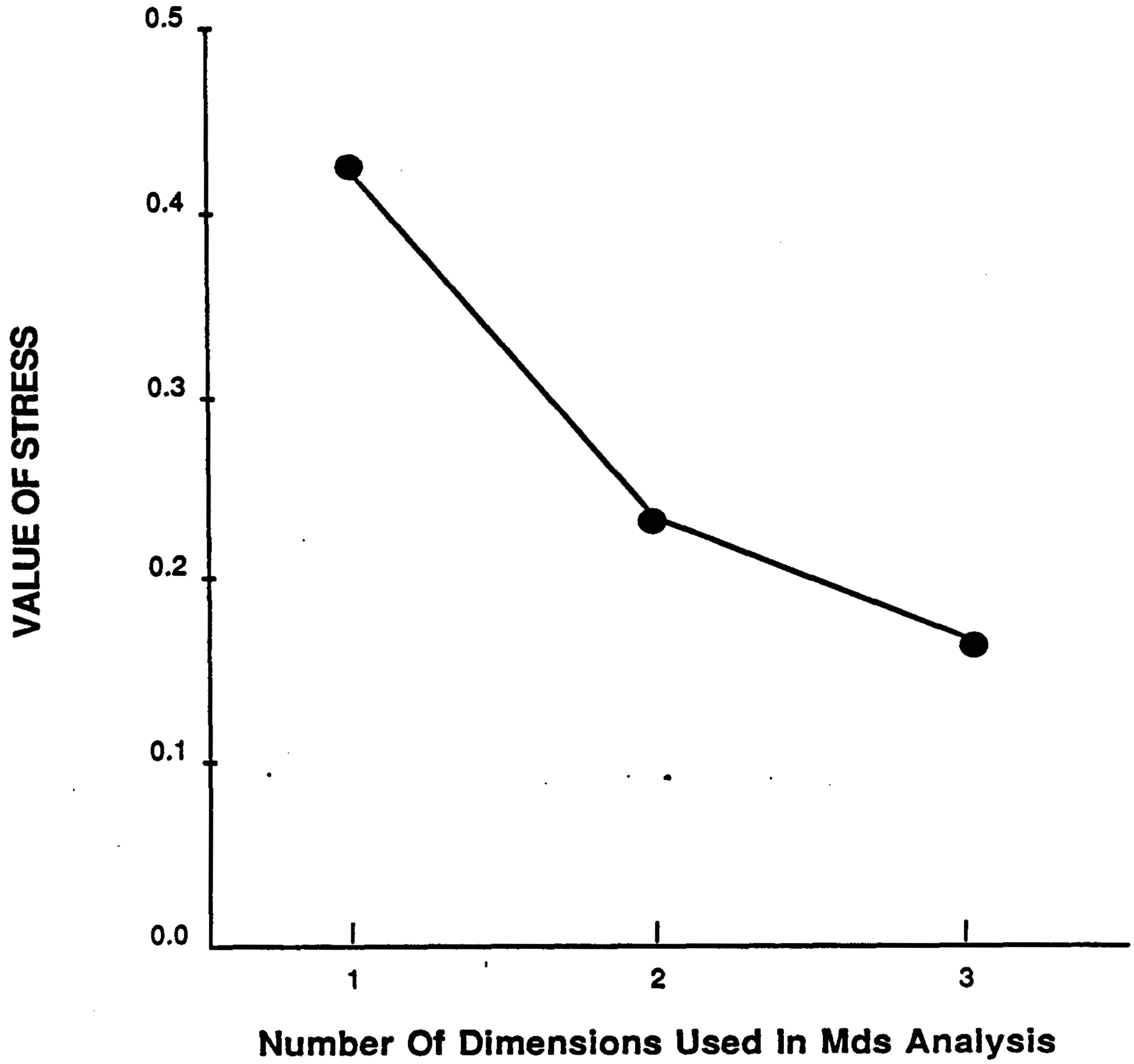

Figure 15. Stress for 1-, 2-, and 3-Dimensional MDS Configurations for Noise Interference

Visual privacy was operationally defined for each function as the optimum percentage of visual exposure appropriate to the activity. The raters were given the following examples of visual exposure:

Total exposure	=	•	=	100
1 visual barrier	=	•|	=	75
2 visual barriers	=	|•| or ⌉•⌉	=	50
3 visual barriers	=	⌈•⌉	=	25
4 visual barriers	=	[•]	=	0

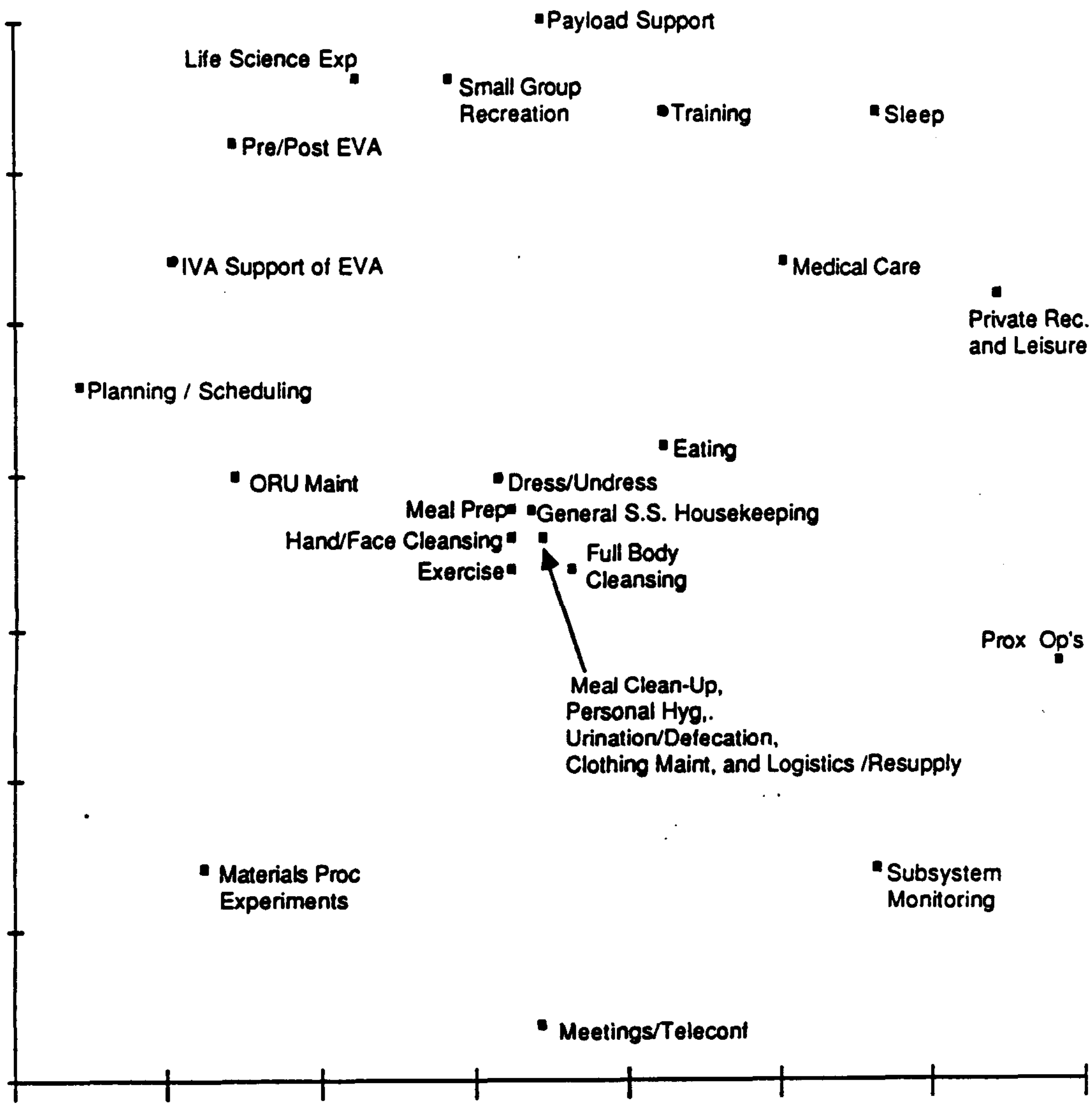

Figure 16. Two-Dimensional MDS Configuration for Noise Interference

They were told, however, that they could use intermediate values as well. The resulting averages are shown in Table 10.

The correlations among the three raters for the audio privacy assessments were as follows:

	Rater #1	Rater #2	Rater #3
Rater #1	-	.87	.62
Rater #2		-	.53
Rater #3			-

Table 10. Average Ratings for Audio and Visual Privacy Needs

Function	Audio	Visual
Meal Preparation	97	100
Eating	93	93
Meal Clean-up	97	92
Exercise	82	67
Medical Care	52	43
Full-body Cleansing	10	0
Hand/face Cleansing	50	67
Personal Hygiene	7	0
Urination/Defecation	0	0
Training	67	83
Sleep	0	25
Private Recreation and Leisure	5	15
Small-group Recreation	35	62
Dressing/Undressing	8	58
Clothing Maintenance	65	85
Meetings and Teleconferences	70	92
Planning and Scheduling	75	100
Subsystem Monitoring and Control	100	100
Pre/Post-EVA Operations	100	100
IVA Support of EVA Operations	100	100
Proximity Operations	100	93
General Space Station Housekeeping	100	83
ORU Maintenance and Repair	100	83
Logistics and Resupply	92	93
Payload Support	75	68
Life Sciences Experiments	67	67
Materials Processing Experiments	67	67

The correlations for the visual privacy assessments were as follows:

	Rater #1	Rater #2	Rater #3
Rater #1	-	.68	.57
Rater #2		-	.35
Rater #3			-

Interestingly, not all of the correlations are particularly high, reflecting some individual differences among the raters with regard to privacy perceptions. In fact, Rater #3 (for whom the correlations with Raters 1 and 2 were rather low) volunteered that she is probably a more "public" person than many other people are.

For both the audio and visual privacy assessments, a matrix was formed by calculating the differences (unsigned) between the respective ratings. This resulted in lower values ("distances") for pairs of functions with similar privacy requirements and higher values for pairs of functions with dissimilar privacy requirements. The resulting matrices are shown in Table 11 for audio privacy and Table 12 for visual privacy. To get a composite privacy matrix, these two matrices were simply added together. The resulting matrix is shown in Table 13.

The result of a cluster analysis of Table 13 is shown in Figure 17. The values of stress for the one-, two-, and three-dimensional MDS configurations are plotted in Figure 18. Since the "elbow" seems to occur at two dimensions, the two-dimensional MDS configuration is shown in Figure 19.

Table 11. Matrix of Audio Privacy Needs

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Expts.	Mtl. Proc. Exper.
Meal Preparation		4	0	15	45	87	47	90	97	30	97	92	62	89	32	27	22	3	3	3	3	3	3	5	22	30	30
Eating			4	11	41	83	43	86	93	26	93	88	58	85	28	23	18	7	7	7	7	7	7	1	18	26	26
Meal Clean-up				15	45	87	47	90	97	30	97	92	62	89	32	27	22	3	3	3	3	3	3	5	22	30	30
Exercise					30	72	32	75	82	15	82	77	47	74	17	12	7	18	18	18	18	18	18	10	7	15	15
Medical Care						42	2	45	52	15	52	47	17	44	13	18	23	48	48	48	48	48	48	40	23	15	15
Full-body Cleaning							40	3	10	57	10	5	25	2	55	60	65	90	90	90	90	90	90	82	65	57	57
Hand/Face Cleaning								43	50	17	50	45	15	42	15	20	25	50	50	50	50	50	50	42	25	17	17
Personal Hygiene									7	60	7	2	28	1	58	63	68	93	93	93	93	93	93	85	68	60	60
Urination/Defecation										67	0	5	35	8	65	70	75	100	100	100	100	100	100	92	75	67	67
Training											67	62	32	59	2	3	8	33	33	33	33	33	33	25	8	0	0
Sleep												5	35	8	65	70	75	100	100	100	100	100	100	92	75	67	67
Private Recreation													30	3	60	65	70	95	95	95	95	95	95	87	70	62	62
Small-grp Recreation														27	30	35	40	65	65	65	65	65	65	57	40	32	32
Changing Clothes															57	62	67	92	92	92	92	92	92	84	67	59	59
Clothing Maint.																5	10	35	35	35	35	35	35	27	10	2	2
Meetings & Teleconf																	5	30	30	30	30	30	30	22	5	3	3
Planning & Sched.																		25	25	25	25	25	25	17	0	8	8
Subsys Monitoring																			0	0	0	0	0	0	25	33	33
Pre/Post-EVA																				0	0	0	0	0	25	33	33
IVA Support of EVA																					0	0	0	0	25	33	33
Prox Operations																						0	0	0	25	33	33
Gen. Housekeeping																							0	0	25	33	33
ORU Maintenance																								8	25	33	33
Logistics, Resupply																									17	25	25
Payload Support																										8	8
Life Sciences Exp.																											0
Mtl. Proc. Exper.																											

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Table 12. Matrix of Visual Privacy Needs

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		7	8	33	57	100	33	100	100	17	75	85	38	42	15	8	0	0	0	0	7	17	17	7	32	33	33
Eating			1	26	50	93	26	93	93	10	68	78	31	35	8	1	7	7	7	7	0	10	10	0	25	26	26
Meal Clean-up				25	49	92	25	92	92	9	67	77	30	34	7	0	8	8	8	8	1	9	9	1	24	25	25
Exercise					24	67	0	67	67	16	42	52	5	9	18	25	33	33	33	33	26	16	16	26	1	0	0
Medical Care						43	24	43	43	40	18	28	19	15	42	49	57	57	57	57	50	40	40	50	25	24	24
Full-body Cleaning							67	0	0	83	25	15	62	58	85	92	100	100	100	100	93	83	83	93	68	67	67
Hand/Face Cleaning								67	67	16	42	52	5	9	18	25	33	33	33	33	26	16	16	26	1	0	0
Personal Hygiene									0	83	25	15	62	58	85	92	100	100	100	100	93	83	83	93	68	67	67
Urination/Defecation										83	25	15	62	58	85	92	100	100	100	100	93	83	83	93	68	67	67
Training											58	68	21	25	2	9	17	17	17	17	10	0	0	10	15	16	16
Sleep												10	37	33	60	67	75	75	75	75	68	58	58	68	43	42	42
Private Recreation													47	43	70	77	85	85	85	85	78	68	68	78	53	52	52
Small-grp Recreation														4	23	30	38	38	38	38	31	21	21	31	6	5	5
Changing Clothes															27	34	42	42	42	15	35	25	25	35	10	9	9
Clothing Maint.																7	15	15	15	15	8	2	2	8	17	18	18
Meetings & Teleconf																	8	8	8	8	1	9	9	1	24	25	25
Planning & Sched.																		0	0	0	7	17	17	7	32	33	33
Subsys Monitoring																			0	0	7	17	17	7	32	33	33
Pre/Post-EVA																				0	7	17	17	7	32	33	33
IVA Support of EVA																					7	17	17	7	32	33	33
Prox Operations																						10	10	0	25	26	26
Gen. Housekeeping																							0	10	10	16	16
ORU Maintenance																								10	15	16	16
Logistics, Resupply																									25	26	26
Payload Support																										1	1
Life Sciences Exp.																											0
Mtl. Proc. Exper.																											

As is apparent from Figure 19, the MDS configuration is mostly one-dimensional. The functions on the left side of the plot are basically "public" (e.g., Subsystem Monitoring, Meal Preparation), while the functions on the right side are basically "private" (e.g., Urination/Defecation, Private Recreation). A few "semi-private" functions fall near the middle (e.g., Medical Care, Small-group Receation). This "public vs. private" dichotomy is also apparent in the cluster analysis (Figure 17), where the five "private" functions, shown on the right in the MDS configuration, do not join the other more "public" functions until the last clustering level.

Table 13. Matrix of Combined Privacy Needs

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		11	8	48	102	187	80	190	197	47	172	177	100	131	47	35	22	3	3	3	10	20	20	12	54	63	63
Eating			5	37	91	176	69	179	186	36	161	166	89	120	36	24	25	14	14	14	7	17	17	1	43	52	52
Meal Clean-up				40	94	179	72	182	189	39	164	169	92	123	39	27	30	11	11	11	4	12	12	6	46	55	55
Exercise					54	139	32	142	149	31	124	129	52	83	35	37	40	51	51	51	44	34	34	36	8	15	15
Medical Care						85	26	88	95	55	70	75	36	59	55	67	80	105	105	105	98	88	88	90	48	39	39
Full-body Cleaning							107	3	10	140	35	20	87	60	140	152	165	190	190	190	183	173	173	175	133	124	124
Hand/Face Cleaning								110	117	33	92	97	20	51	33	45	58	83	83	83	76	66	66	68	26	17	17
Personal Hygiene									7	143	32	17	90	59	143	155	168	193	193	193	186	176	176	178	136	127	127
Urination/Defecation										150	25	20	97	66	150	162	175	200	200	200	193	183	183	185	143	134	134
Training											125	130	53	84	4	12	25	50	50	50	43	33	33	35	23	16	16
Sleep												15	72	41	125	137	150	175	175	175	168	158	158	160	118	109	109
Private Recreation													77	46	130	142	155	180	180	180	173	163	163	165	123	114	114
Small-grp Recreation														31	53	65	78	103	103	103	96	86	86	88	46	37	37
Changing Clothes															84	96	109	134	134	134	127	117	117	119	77	68	68
Clothing Maint.																12	25	50	50	50	43	37	37	35	27	20	20
Meetings & Teleconf																	13	38	38	38	31	39	39	23	29	28	28
Planning & Sched.																		25	25	25	32	42	42	24	32	41	41
Subsys Monitoring																			0	0	7	17	17	15	57	66	66
Pre/Post-EVA																				0	7	17	17	15	57	66	66
IVA Support of EVA																					7	17	17	15	57	66	66
Prox Operations																						10	10	8	50	59	59
Gen. Housekeeping																							0	18	40	49	49
ORU Maintenance																								18	40	49	49
Logistics, Resupply																									42	51	51
Payload Support																										9	9
Life Sciences Exp.																											0
Mtl. Proc. Exper.																											

10. Conduct Analysis of Overall Compatibility of Functions

As the preceding discussions have indicated, the conclusions that one might draw about facilities layout differ somewhat depending upon which of the five criteria is being considered. This is to be expected: facilities layout is inherently a process of making trade-offs between these various criteria. For example, a high frequency of crew transition between two functions would lead the designer to locate the associated facilities close together. However, the same two functions might have a high noise interference potential, thus leading the designer either to locate them further apart or to erect a sound barrier between them. A systematic technique for making these kinds of trade-offs is needed.

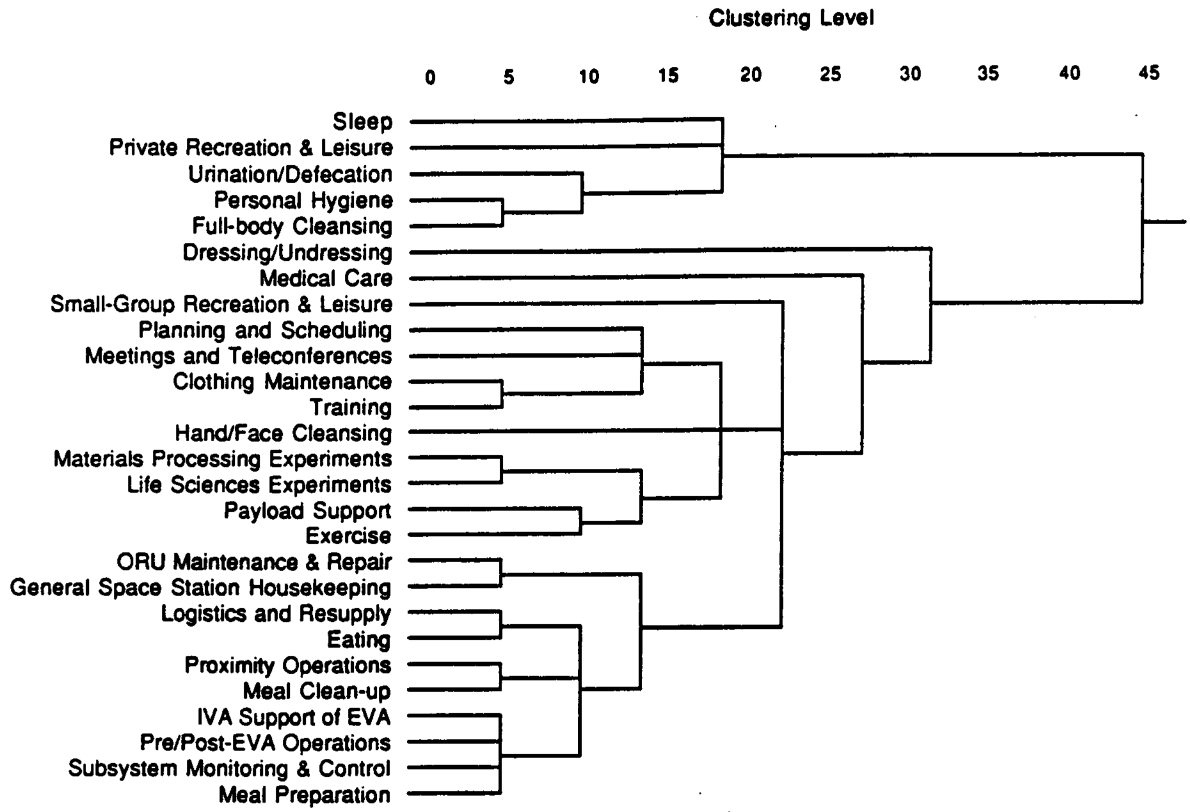

Figure 17. Hierarchical Cluster Analysis of Need for Privacy

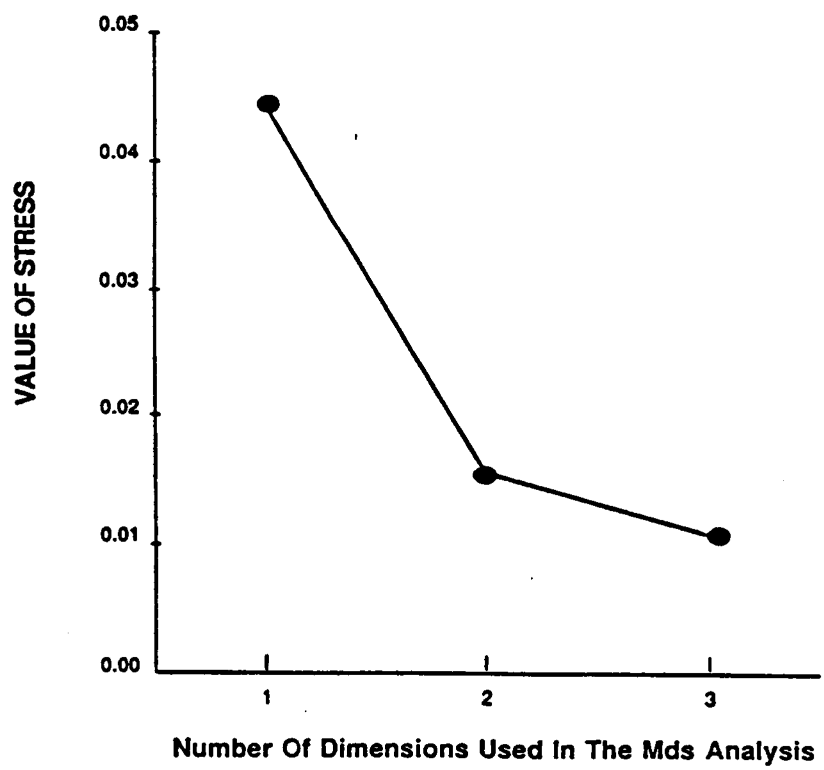

Figure 18. Stress for 1-, 2-, and 3-Dimensional MDS Configurations for Need for Privacy

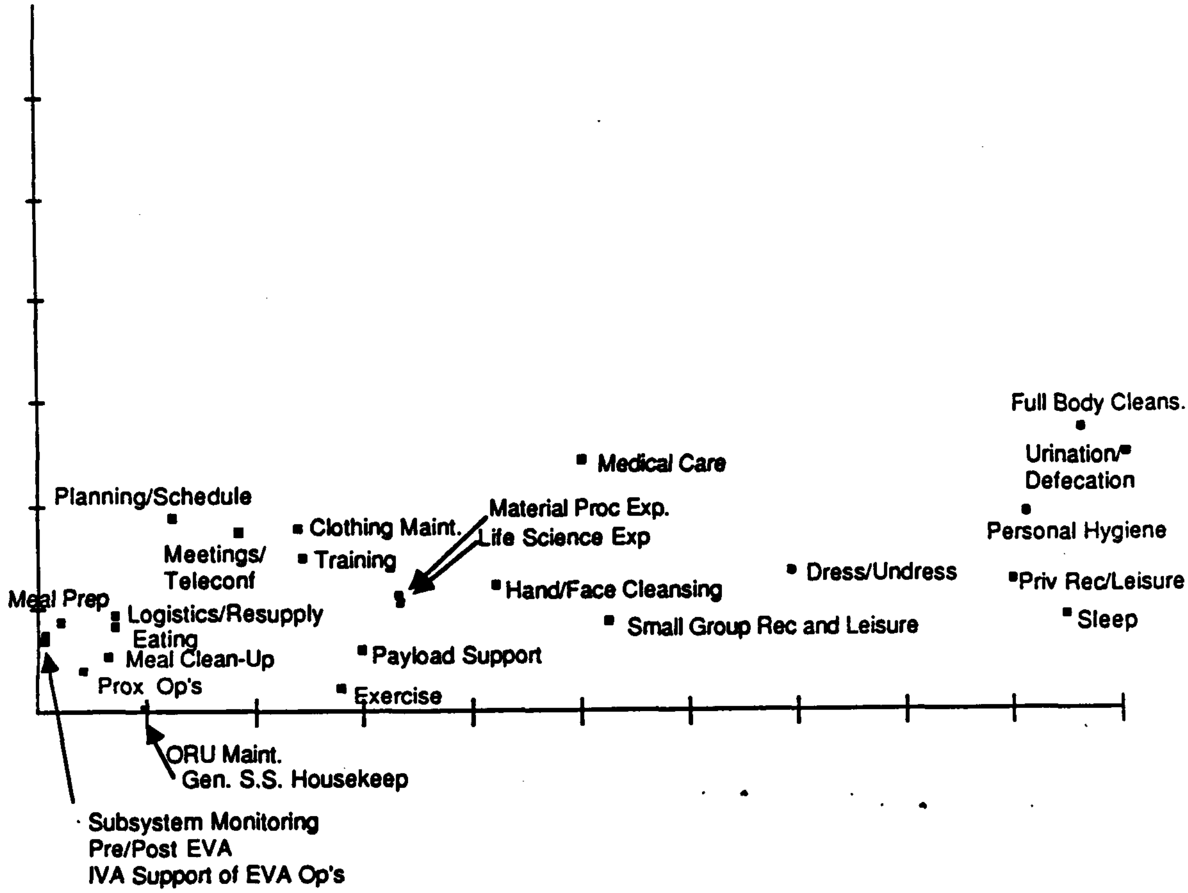

Figure 19. Two-Dimensional MDS Configuration for Need for Privacy

One technique for approaching these trade-offs is to compare the "circulation" matrices (i.e., crew transition frequency and sequential dependencies) to the "zoning" matrices (i.e., shared equipment, noise interference, privacy needs). This can be done by combining the two circulation matrices into one matrix and the three zoning matrices into another matrix. If each of the five matrices had used exactly the same scale for their entries, one approach to combining them could be to simply add the corresponding matrices together. In reality, however, the five matrices did not use the same scale. This problem can be solved by rescaling each of the matrices to a common scale. Arbitrarily, a scale that ranges from 0 to 50 was chosen. Each matrix was then rescaled by multiplying its entries by the ratio of 50 over the maximum value in the matrix. In the cases of the shared equipment matrix and the crew transition matrix, the "reversed" matrix was used. In this way, higher numbers mean a more distant relationship for all five matrices.

After rescaling, the crew transition and sequential dependency matrices were added together to yield a "circulation" matrix, shown in Table 14, and the shared equipment, noise interference, and privacy matrices were added together to yield a "zoning" matrix, shown in Table 15.

The result of the cluster analysis of Table 14 is shown in Figure 20. The values of stress for the one-, two- and three-dimensional MDS configurations are plotted in Figure 21. Since the "elbow" appears to fall at two dimensions, the two-dimensional MDS configuration is shown in Figure 22. The result of the cluster analysis of Table 15 is shown in Figure 23. The values of stress for the one-, two-, and three-dimensional MDS configurations are plotted in Figure 24. Since the "elbow" falls at two dimensions, the two-dimensional MDS configuration is shown in Figure 25.

Table 14. Matrix of Combined Circulation Data

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		0	54	95	90	100	57	88	88	100	100	100	96	94	100	98	88	99	100	100	100	85	100	90	100	98	98
Eating			1	92	92	100	63	75	74	100	96	90	82	100	100	96	96	100	100	100	100	100	100	100	100	100	100
Meal Clean-up				86	95	88	70	85	82	98	88	86	80	93	99	99	88	92	96	92	90	89	90	92	87	89	90
Exercise					82	55	64	78	73	100	88	82	82	77	88	85	88	90	92	92	92	92	92	92	90	88	92
Medical Care						88	70	88	85	88	88	88	88	90	92	92	92	92	88	92	88	88	88	90	92	88	92
Full-body Cleaning							67	64	79	96	82	82	83	62	88	83	88	92	75	88	92	88	88	92	92	83	88
Hand/Face Cleaning								70	42	99	77	86	85	82	92	88	86	84	79	90	92	86	86	92	88	80	82
Personal Hygiene									60	100	64	81	82	75	83	83	82	83	79	83	83	83	88	83	83	88	88
Urination/Defecation										96	57	70	77	74	88	79	81	83	76	83	81	83	80	80	79	81	79
Training											96	93	95	96	96	96	80	83	83	83	88	96	79	86	88	80	88
Sleep												90	92	64	88	92	83	88	92	92	92	92	92	92	92	92	92
Private Recreation													86	80	85	86	88	92	92	92	92	88	92	92	88	90	92
Small-grp Recreation														90	88	86	88	90	92	92	92	92	92	92	92	90	92
Changing Clothes															65	96	93	96	83	96	92	96	96	96	92	96	96
Clothing Maint.																96	96	96	96	96	96	92	96	96	96	92	96
Meetings & Teleconf																	64	86	92	92	92	89	96	88	90	90	89
Planning & Sched.																		80	82	70	75	75	75	77	73	74	74
Subsys Monitoring																			79	82	83	95	71	82	79	83	83
Pre/Post-EVA																				50	92	96	92	100	96	100	100
IVA Support of EVA																					99	92	88	92	88	92	92
Prox Operations																						96	88	88	83	100	100
Gen. Housekeeping																							83	81	88	92	92
ORU Maintenance																								88	86	88	88
Logistics, Resupply																									88	88	88
Payload Support																										88	86
Life Sciences Exp.																											98
Mtl. Proc. Exper.																											

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Table 15. Matrix of Combined Zoning Data

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		39	37	66	89	104	77	103	104	71	119	120	93	87	67	82	64	66	60	59	69	57	60	32	74	76	77
Eating			43	74	101	111	82	108	109	87	124	125	100	90	72	81	73	87	81	81	86	66	78	51	90	91	94
Meal Clean-up				64	97	103	76	101	103	83	123	123	95	85	65	84	80	79	72	73	79	30	67	47	84	86	87
Exercise					84	95	67	92	94	75	117	93	70	76	65	83	86	93	85	86	93	61	75	65	78	79	80
Medical Care						97	78	93	93	85	96	100	89	80	84	106	95	105	102	101	103	96	99	89	86	83	88
Full-body Cleaning							57	60	62	111	91	87	96	72	94	119	117	127	121	121	127	100	112	103	109	106	108
Hand/Face Cleaning								79	88	80	100	101	76	69	67	88	87	96	91	91	95	73	83	76	78	76	77
Personal Hygiene									58	106	85	80	92	61	92	114	113	122	116	117	121	99	108	101	105	102	103
Urination/Defecation										107	81	80	93	72	94	114	114	123	117	118	122	100	110	102	105	103	104
Training											113	109	84	87	71	84	78	90	87	84	89	82	84	70	78	75	80
Sleep												85	101	80	107	128	123	132	131	130	130	122	131	122	114	111	118
Private Recreation													78	81	108	116	119	129	133	117	120	122	131	122	117	114	120
Small-grp Recreation														73	82	100	104	106	109	100	105	93	105	94	95	92	97
Changing Clothes															60	93	93	101	97	98	101	83	90	85	85	82	83
Clothing Maint.																77	77	86	80	81	85	63	73	65	77	75	76
Meetings & Teleconf																	87	109	103	102	108	87	102	84	101	100	105
Planning & Sched.																		88	83	66	78	83	87	67	83	84	89
Subsys Monitoring																			82	57	69	81	87	72	96	97	103
Pre/Post-EVA																				76	85	73	79	65	91	93	97
IVA Support of EVA																					41	74	79	64	90	91	95
Prox Operations																						81	87	72	95	96	102
Gen. Housekeeping																							63	57	83	85	85
ORU Maintenance																								60	87	89	92
Logistics, Resupply																									73	75	76
Payload Support																										77	82
Life Sciences Exp.																											79
Mtl. Proc. Exper.																											

The strongest clustering revealed by the cluster analysis of the combined circulation data (Figure 20) is the cluster composed of Meal Preparation, Eating, and Meal Clean-up, indicating the very close association between these functions. This cluster is also reflected in the lower right-hand portion of the MDS plot (Figure 22). In general, the remaining crew support functions fell in the top and right portions of the MDS plot while the Station and mission operations fell in the bottom and left. Near the center of the plot are three hygiene-related functions (Urination/Defecation, Hand/Face Cleansing, and Personal Hygiene) that appear to act as a "bridge" between the on-duty and off-duty functions. This is understandable, since those functions need to be performed throughout the day, both on-duty and off-duty.

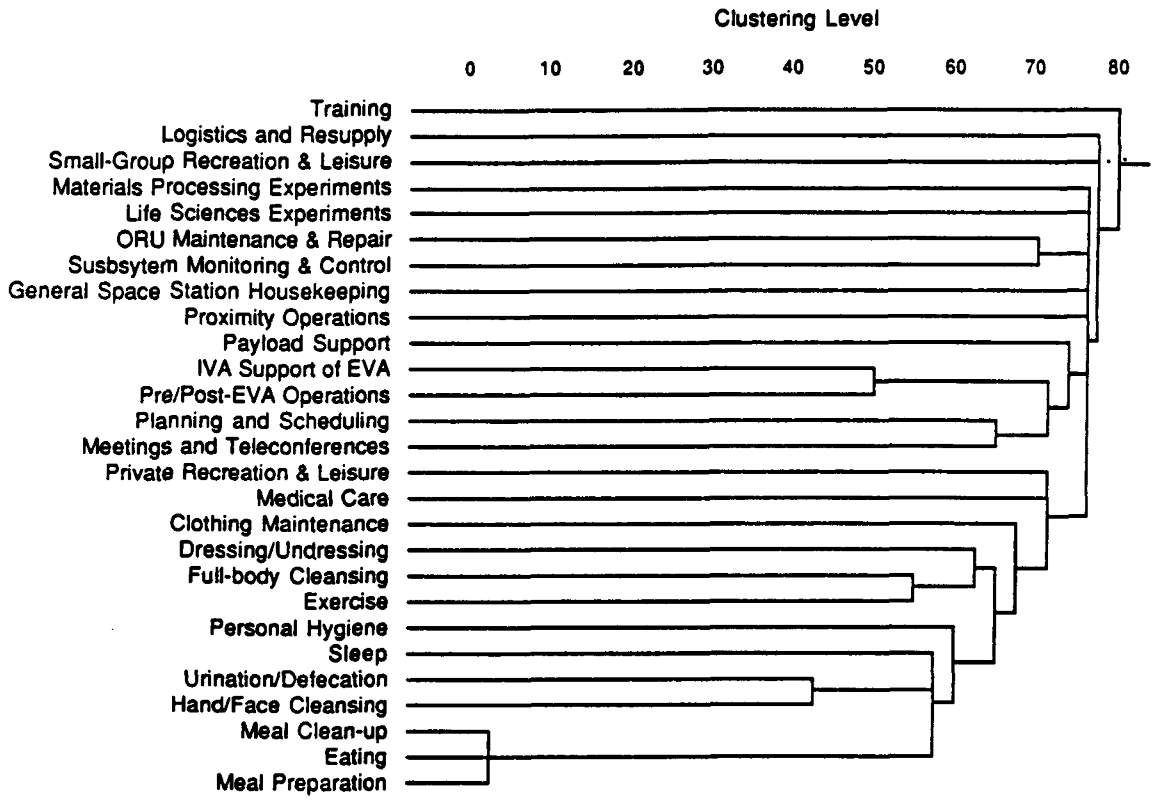

Figure 20. Hierarchical Cluster Analysis of Combined Circulation Data

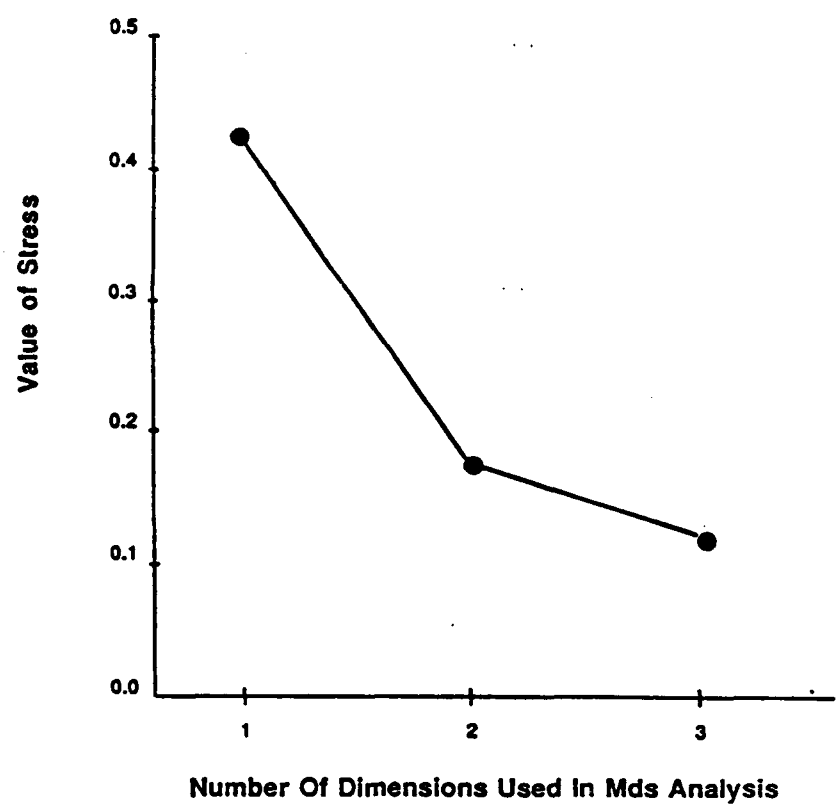

Figure 21. Stress for 1-, 2-, and 3-Dimensional MDS Configurations for Combined Circulation Data

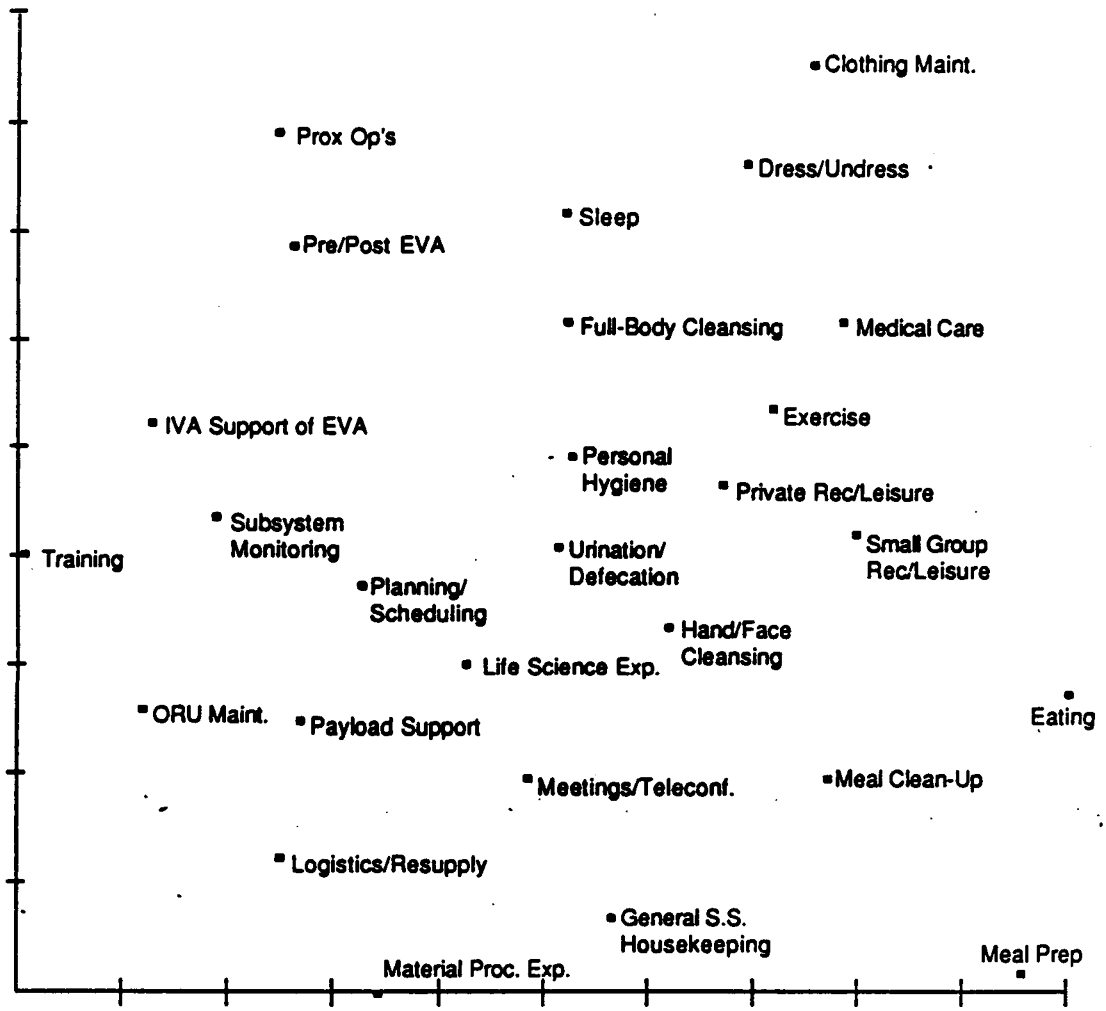

Figure 22. Two-Dimensional MDS Configuration for Combined Circulation Data

The strongest clustering revealed by the zoning analysis (Figure 23) is similar to the one revealed by the circulation analysis, except that the three mealtime functions have been joined by Logistics/Resupply and General Space Station Housekeeping. Another cluster indicated by Figure 23 is one composed of IVA Support of EVA Operations and Proximity Operations. Both of these clusters appear in the right-hand portion of the MDS configuration shown in Figure 25. In general, the remaining crew support functions fell in the left-hand portion of the MDS plot while the remaining Station operations and mission operations fell in the right-hand portion.

A comparison of the circulation MDS plot (Figure 22) and the zoning MDS plot (Figure 25) reveals that the decisions one might make about Space Station

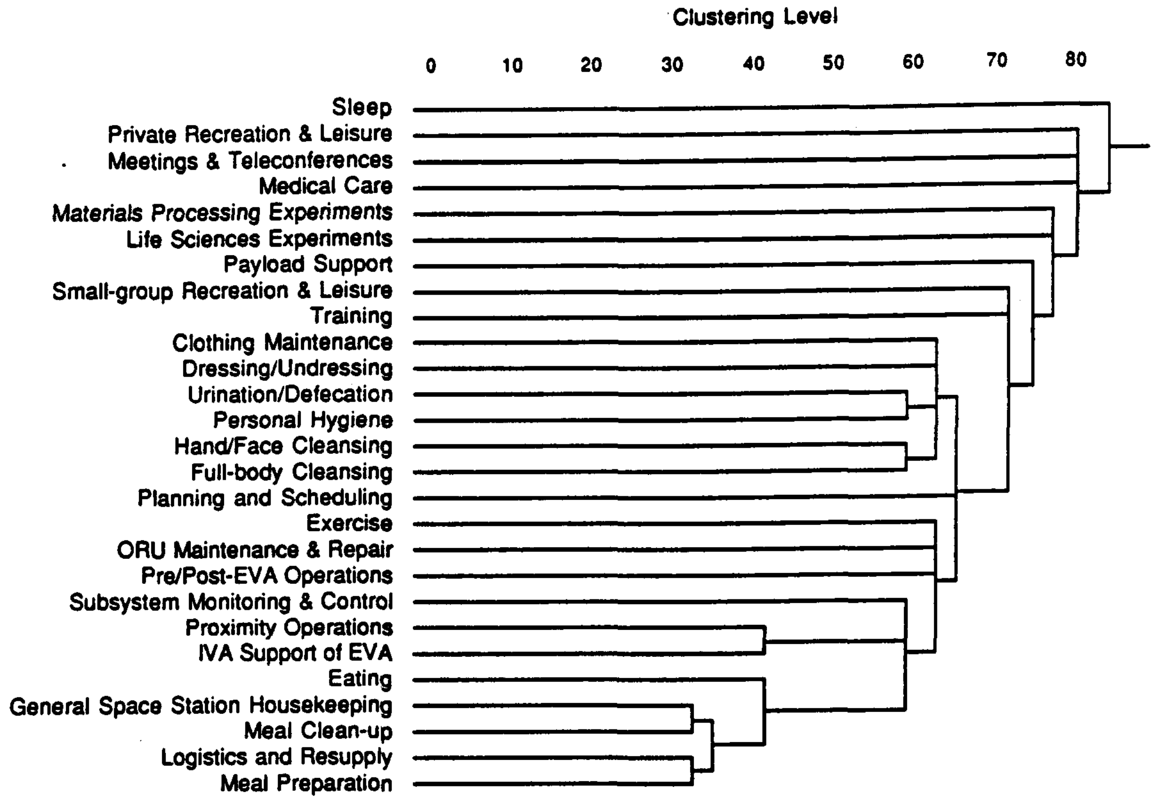

Figure 23. Hierarchical Cluster Analysis of Combined Zoning Data

layout would indeed differ depending upon which criterion is being considered. For example, the circulation plot (Figure 22) shows that Sleep, Proximity Operations, and Pre/Post-EVA Operations fell in the same general area (the top), indicating that those functions should be performed in proximity to each other in order to optimize circulation. The zoning plot (Figure 25), on the other hand, shows that while Proximity Operations and Pre/Post-EVA Operations fell near each other (the far right), Sleep fell at the extreme opposite end of the plot. This sort of apparent inconsistency implies that sleep should be performed in one Space Station module while Proximity Operations and Pre/Post-EVA Operations should be performed in another connecting module or node. In this manner, it is possible to establish different "zones" for the functions but still maintain a relatively low distance between them.

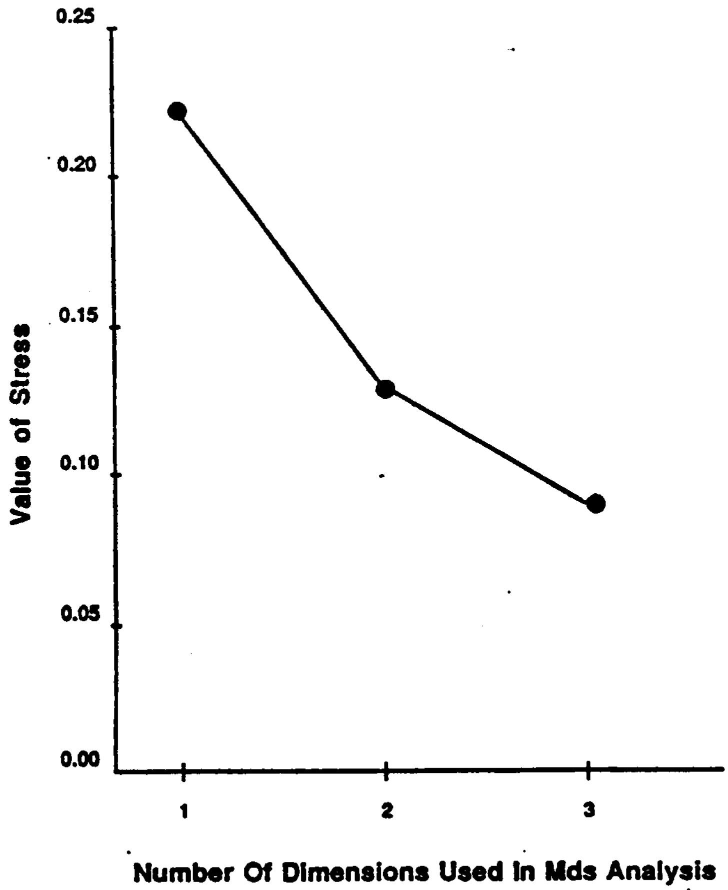

Figure 24. Stress for 1-, 2-, and 3-Dimensional MDS Configurations for Combined Zoning Data

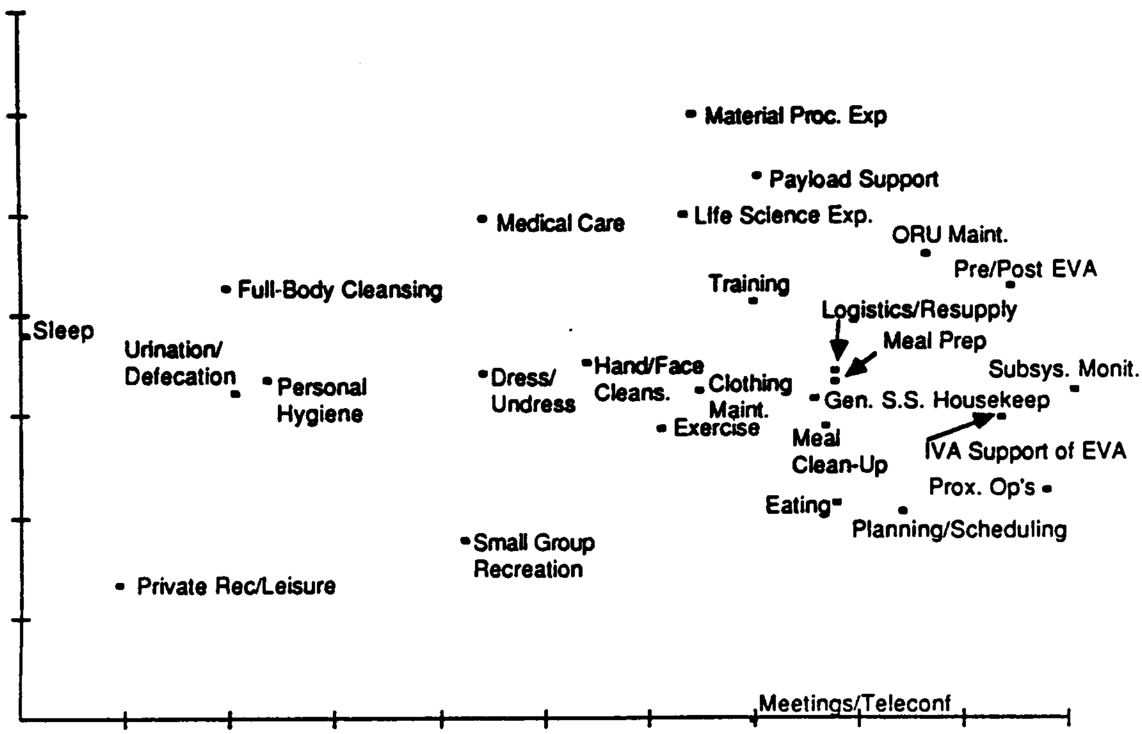

Figure 25. Two-Dimensional MDS Configuration for Combined Zoning Data

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In order to get an overall picture of the functional relationships, it is possible to combine all five of the matrices into one overall matrix (Table 16). As before, the matrices were rescaled to a common scale before they were added together. The result of the cluster analysis of Table 16 is shown in Figure 26. The values of stress are plotted in Figure 27. Since the "elbow" falls at two dimensions, the two-dimensional MDS configuration is shown in Figure 28.

As would be expected from the circulation and zoning analyses, the strongest clustering revealed by Figure 26 is the cluster composed of the three mealtime functions. This cluster is also reflected in the upper right-hand portion of the MDS plot (Figure 28). Interpretation of the MDS configuration is facilitated by an attempt to identify orthogonal dimensions in the plot that can be assigned meaning. Two dimensions that appear to accurately describe the configuration are shown in Figure 29. The horizontal axis has been labeled "Private-Public" and the vertical axis "Group-Individual".

Table 16. Matrix of Combined Data

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		39	91	161	179	204	134	191	192	171	219	220	190	181	167	180	152	164	160	159	169	142	160	123	174	174	174
Eating			45	166	192	211	145	183	183	187	220	216	182	190	172	177	169	187	181	181	186	166	178	151	190	191	194
Meal Clean-up				150	192	190	146	186	185	181	210	209	175	179	164	183	168	171	168	164	170	119	157	139	171	176	177
Exercise					166	149	132	170	167	175	204	176	152	153	153	168	174	183	177	177	185	153	166	156	169	167	172
Medical Care						184	148	180	179	173	183	187	177	171	176	198	186	196	190	192	191	184	190	181	178	171	180
Full-body Cleaning							124	124	140	206	173	169	180	134	181	203	205	219	196	208	218	188	200	194	201	190	195
Hand/Face Cleaning								148	129	179	177	187	161	151	158	176	173	180	170	181	187	160	170	167	166	155	160
Personal Hygiene									118	206	148	161	174	136	176	197	195	205	196	200	205	182	196	184	188	189	191
Urination/Defecation										204	138	149	170	145	181	193	194	205	193	201	203	184	189	182	184	184	182
Training											208	202	179	182	167	180	157	174	170	168	177	177	163	156	166	155	168
Sleep												176	193	145	195	220	207	219	222	221	221	214	223	213	206	202	209
Private Recreation													163	161	193	203	207	221	225	208	212	209	224	213	205	204	212
Small-grp Recreation														163	170	186	191	196	201	191	196	185	196	186	187	182	168
Changing Clothes															126	189	186	197	181	193	192	179	186	180	176	178	179
Clothing Maint.																173	172	182	176	176	181	155	169	161	173	166	172
Meetings & Teleconf																	152	195	194	194	199	176	198	171	191	190	195
Planning & Sched.																		167	165	136	153	158	162	144	156	158	163
Subsys Monitoring																			161	139	152	175	158	154	175	180	186
Pre/Post-EVA																				126	177	169	171	165	187	193	197
IVA Support of EVA																					140	165	166	155	177	183	187
Prox Operations																						177	174	159	178	196	202
Gen. Housekeeping																							146	138	170	176	177
ORU Maintenance																								148	173	176	179
Logistics, Resupply																									161	162	163
Payload Support																										165	169
Life Sciences Exp.																											177
Mtl. Proc. Exper.																											

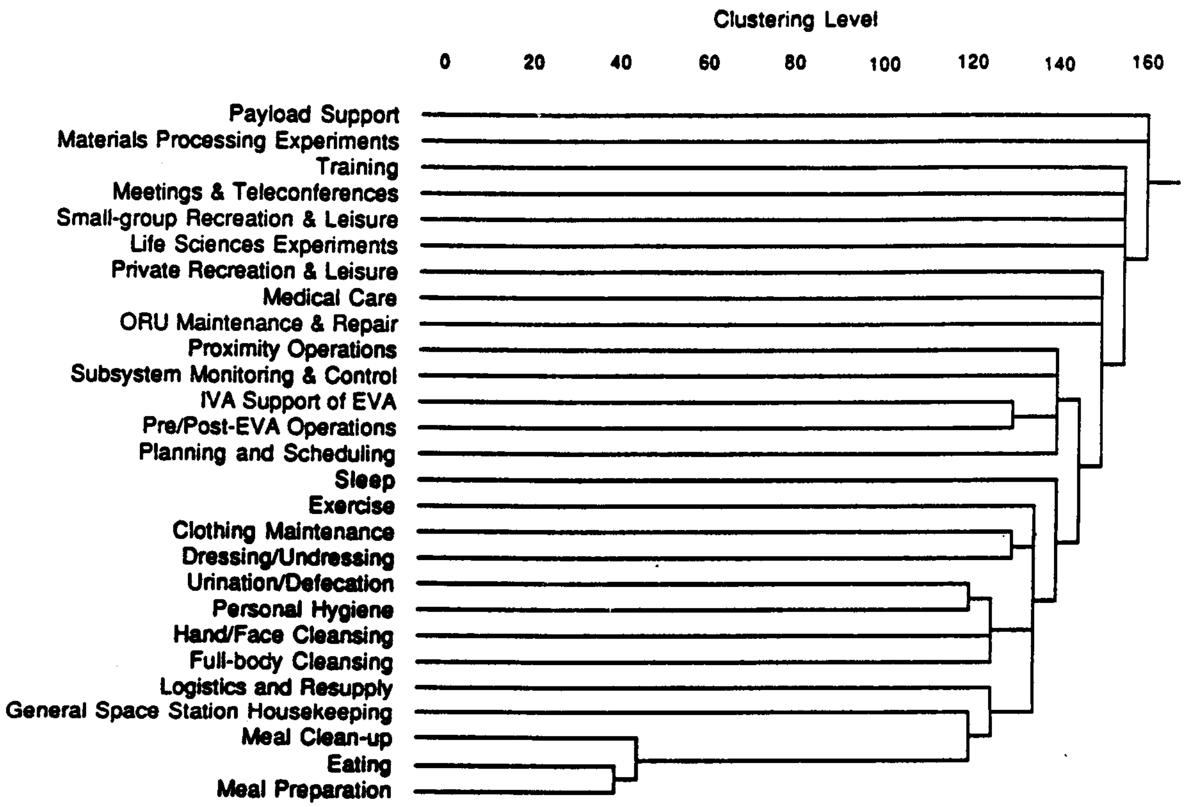

Figure 26. Hierarchical Cluster Analysis of Combined Data

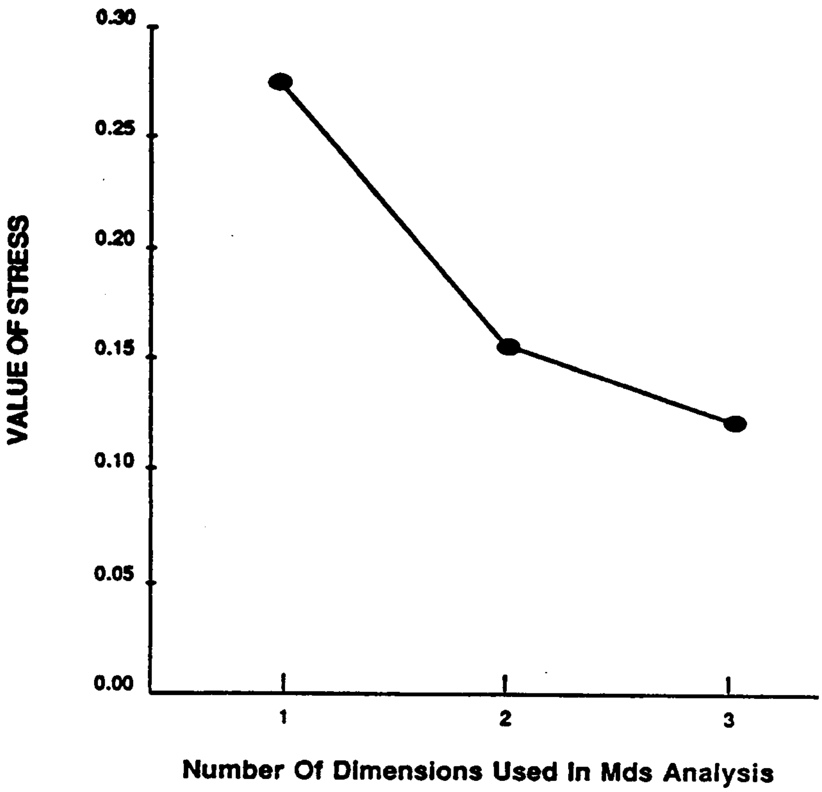

Figure 27. Stress for 1-, 2-, and 3-Dimensional MDS Configurations for Combined Data

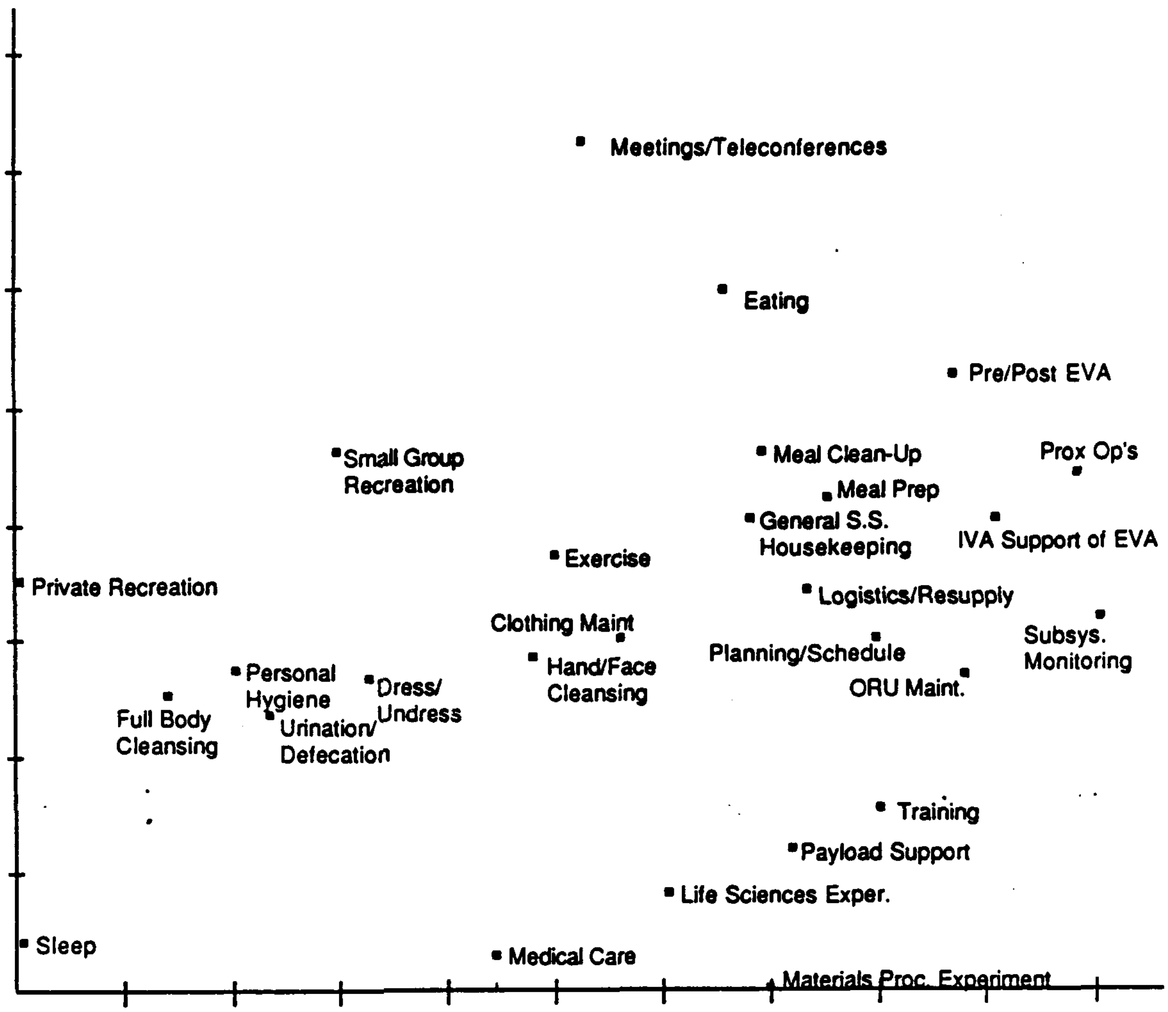

Figure 28. Two-Dimensional MDS Configuration for Combined Data

The "Private-Public" axis is the primary dimension of the MDS configuration. In fact, this dimension is essentially the one that a one-dimensional configuration reveals. The functions at the most extreme "Private" end are Private Recreation and Sleep, while at the extreme "Public" end are Subsystem Monitoring and Proximity Operations. From the standpoint of personal privacy, a crew member performing such Station operations as Subsystem Monitoring or Proximity Operations would have little concern about how much exposure to the rest of the crew he has. However, this study did not address other issues, such as Station security, that might indicate a need for privacy with some of these Station operations.

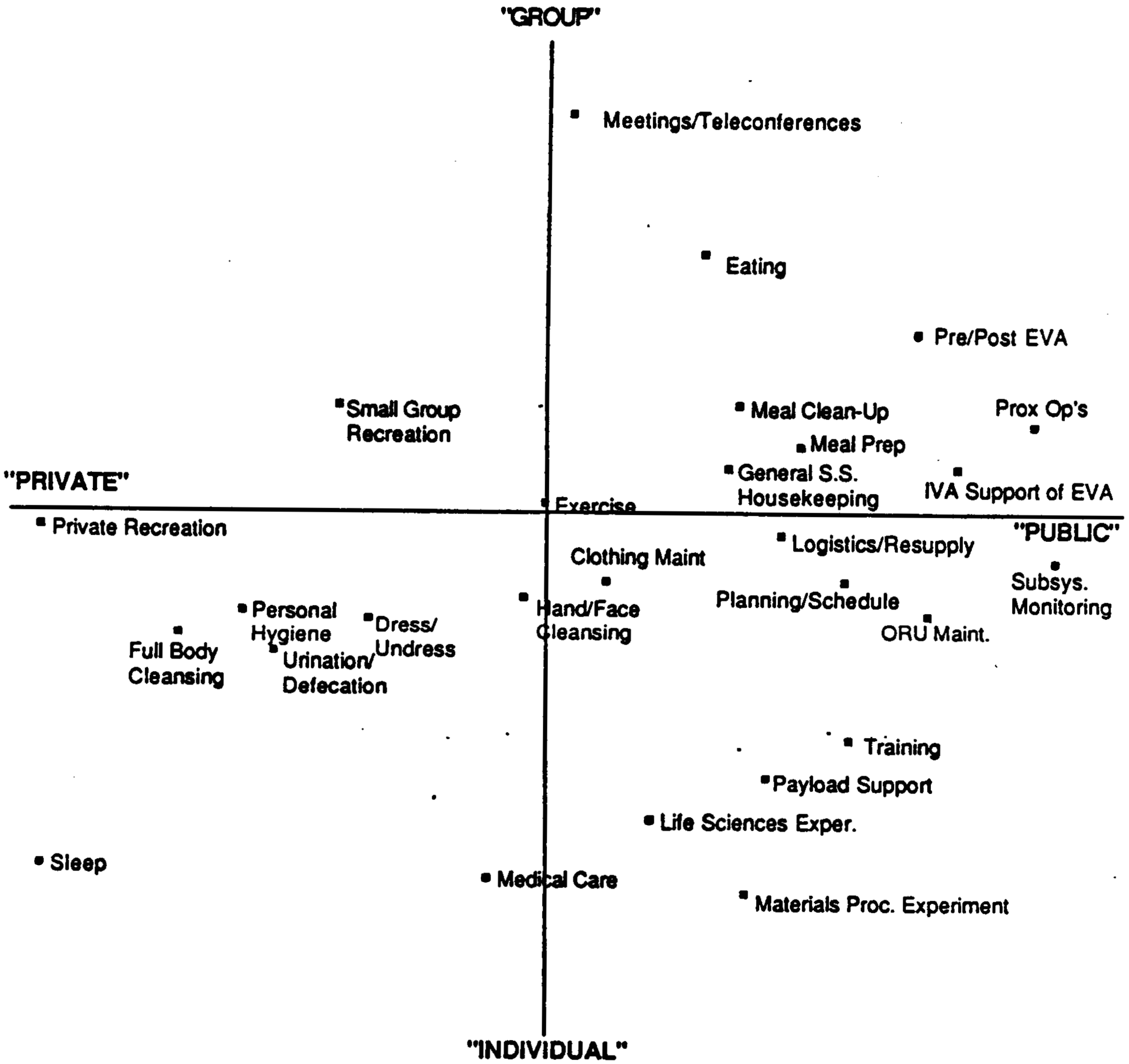

Figure 29. Two-Dimensional MDS Configuration for Combined Data with Dimensions Added

The "Group-Individual" axis is the secondary dimension of the MDS configuration. The functions at the extreme "Group" end are Meetings and Teleconferences, and, to a lesser extent, Eating. Meetings and Teleconferences are clearly a group activity (for work-related reasons), as is Eating (for social reason). The functions at the extreme "Individual" end are Medical Care and the two functions associated with experiments. The assumption on the part of the raters appears to have been that Medical Care will involve primarily self-care and that on-board experiments will be run primarily by the individuals trained to perform them.

Looking at the MDS configuration in terms of the four quadrants formed by these two axes reveals some interesting groupings. Starting at the top-right, the first quadrant is composed of "Public Group" functions. This contains the functions associated with meals, meetings, and, interestingly, EVA and proximity operations. The assumption appears to have been that EVA and proximity operations may commonly require more than one person. Proceeding clockwise, the next quadrant is composed of "Public Individual" functions. This contains the mission operations (payload and experiment support) and the Station operations that can reasonably be performed by individuals (e.g., ORU Maintenance, Subsystem Monitoring). The bottom-left quadrant is composed of "Private Individual" functions. This includes all of the hygiene-related functions (e.g., Full-body Cleansing, Urination/Defecation), as well as Sleep, Private Recreation, and Medical Care. Finally, the top-left quadrant is composed of "Private Group" functions. More correctly, it is composed of one "Private Group" function: Small-group Recreation. It seems apparent that this is the only group function that can be viewed as requiring some degree of privacy as well. A final point worth noting about the MDS configuration relates to the Exercise function, which fell in the center of the plot. Apparently, Exercise is viewed as neither particularly public nor private and it may be performed either individually or in a group.

IMPLICATIONS FOR SPACE STATION LAYOUT

These findings have several implications for the design of an optimally habitable Space Station. In considering these implications, no particular number or configuration of Space Station modules is assumed. In fact, the results of this analysis can be applied to any number of modules (even one) and any configuration of modules.

The major implications of these findings for Space Station interior layout are as follows:

1. Private functions need to be separate from public functions.

   The primary dimension revealed by the MDS analysis of the combined data is a "Public-Private" dimension. This implies that the facilities supporting the functions at the extreme ends of this dimension should be as clearly separated from each other as the Space Station configuration will allow. At the "Private" end are the facilities for Sleep and Private Recreation. At the "Public" end are many of the facilities supporting Station operations (e.g., Subsystem Monitoring, IVA Support of EVA, Proximity Operations). One effect of this kind of separation of the facilities is that it allows the crew members to adopt a clear distinction, in their own minds, between on-duty ("public") periods and off-duty ("private") periods.

2. Facilities for meal preparation, eating, and meal clean-up should be close together.

   Almost all of the cluster analyses and MDS analyses revealed a close grouping of the three functions associated with meals. This is not particularly surprising, since it follows the traditional wisdom of locating kitchens and dining areas in close proximity with each other.

3. At least two kinds of meeting spaces are needed.

   In most of the MDS configurations, including the overall configuration (Figure 29), the two functions that involve group meetings -- "Meetings and Teleconferences" and "Small-group Recreation" -- did not fall close to each other. This implies that they should not be supported by the same facility. It appears that a relatively large meeting space is needed to accommodate the kind of meetings and teleconferences that may involve the entire crew (e.g., shift changes, crew changes, press conferences with the ground). For the most part, these meetings will be work-related. On the other hand, these findings indicate that another, probably smaller, meeting space needs to be provided for small-group recreation and leisure (e.g., playing cards, group viewing of television). Although these meetings will mainly be non-work-related, one can also envision situations where work-related meetings among small groups may be needed (e.g., discussions of particular experiments, disciplinary actions). In general, the facility for small-group meetings should allow for greater privacy than the facility for large-group meetings.

Another function that typically involves groups is Eating. The relative proximity of Eating and Meetings and Teleconferences in the overall MDS configuration (Figure 29) implies that they may be able to share a meeting space (e.g., a "wardroom"). However, this may need to change with larger crews since there could be timing conflicts between the two sets of activities.

4. The two functions associated with health maintenance need to be performed separately.

The two functions directly associated with maintaining the crew's health -- Medical Care and Exercise -- are relatively incompatible with each other and should not be co-located. This is indicated by the separation of those functions in the overall MDS configuration (Figure 29). Most of the MDS configurations show Exercise being more closely associated with the public Station operations and mealtime functions, and Medical Care being more closely associated with the private individual functions.

5. <u>Hygiene-related functions should be co-located.</u>

Most of the MDS configurations show a relatively close association among the following five functions associated with the crew's hygiene:

1. Full-body Cleansing
2. Personal Hygiene
3. Urination/Defecation
4. Dressing/Undressing
5. Hand/Face Cleansing

This suggests that facilities supporting these functions should be co-located. Obviously, this conforms to the traditional (ground-based) wisdom of designing bathrooms to support all of these functions. In general, these functions are more closely associated with the other private crew functions (Sleep and Private Recreation) than they are with the public Station operations. Assuming there will be more than one Space Station module, crew size and frequency of use will probably dictate that at least some of these facilities be duplicated and provided in more than one module. For example, the "circulation" MDS plot shows that the facilities for urination/defecation, hand/face cleansing and personal hygiene should be readily accessible from both the "private" off-duty areas and the "public" on-duty areas. Assuming that the on-duty and off-duty areas will be in two different modules, this circulation need implies that the hygiene facilities should be provided in both modules.

6. <u>Facilities for experiments and payload support should be separate from other facilities.</u>

In most of the MDS configurations, including the overall configuration shown in Figure 29, the functions associated with Payload Support, Life Sciences Experiments, and Materials Processing

Experiments are more closely associated with each other than they are with any other functions. This implies that the facilities supporting these experiments and payload functions should be separate from both the facilities supporting day-to-day Station operations and the private crew support facilities.

7. Facilities for on-board training probably need to be provided in more than one place.

"Training" is perhaps the one function whose position relative to the other functions changed the most from one MDS configuration to another. For example, the noise interference analysis (Figure 16) grouped Training with the quiet crew support functions (Sleep, Medical Care). On the other hand, the sequential dependencies analysis (Figure 9) grouped it with the Station operations (e.g., ORU Maintenance, IVA support of EVA), while the overall analysis (Figure 29) shows it more associated with the misssion operations (Payload Support, Life Sciences and Materials Processing Experiments). This suggests that more than one facility should be provided for training. Depending upon the circumstances, it may be most appropriate for training to be done in proximity with the Station operations, mission operations, or even crew support functions.

USE OF THE MODEL AS AN EVALUATION TOOL

In addition to providing information useful in designing the Space Station interior layout, this model can also be used as a tool for evaluating any given Space Station configuration. In essence, it is possible to take a particular configuration, determine which crew functions will be performed where, measure the distances between them, and calculate the correlation between these distances and the "optimum" distances derived from this study.

As an illustration of this process, consider the Space Station layout illustrated in Figure 30. This figure, which is from MDAC's Phase B Space

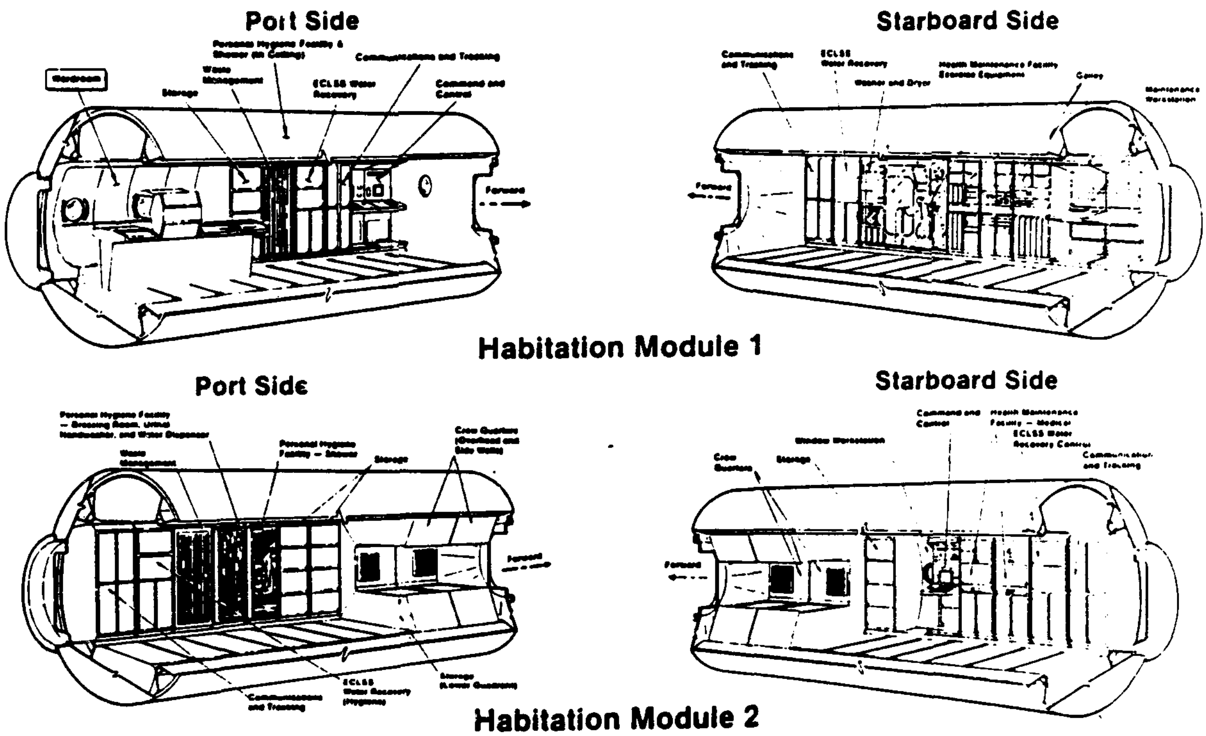

Figure 30.. Candidate Space Station Layout

Station Definition work, shows only the two "Hab" modules of a four-module configuration. The other two modules are "Lab" modules -- one for life sciences experiments and the other for materials processing experiments. The four modules are assumed to be arranged in a "Figure-8" configuration with Hab 1 above Hab 2 and the Life Sciences Lab above the Materials Processing Lab. The steps in evaluating the layout are as follows:

1. Determine what crew functions will be performed in what areas. This is shown in Table 17, which contains a list of the areas illustrated in Figure 30 and shows the crew functions likely to be performed in each area. Notice that some functions are duplicated (e.g., Urination/Defecation).

2. Measure the distances between all pairs of crew functions, as indicated by the configuration (Figure 30) and the mapping of crew functions to the configuration (Table 17). In those cases where a function is duplicated, the distance chosen should be the smallest

one (e.g., the distance from Meal Preparation to Hand/Face Cleansing was taken to be the distance from the Galley to the Hab 1 Personal Hygiene Facility). Further, all distances should be "city block" distances reflecting distances along the most likely paths of crew movement. The resulting distances are shown in Table 18. The units used in these distance measurements are totally arbitrary since they are simply going to be correlated with another set of distances. For the measurements shown in Table 18, the units used were based upon the expected width of a standard Space Station rack; the distances shown are actually the number of half-racks. The distances between areas were measured, approximately, from center to center.

3. Calculate the correlation between the distances in the hypothetical configuration (Table 18) and the "optimum" distances derived from the FRA model (Table 16). For this particular configuration, the correlation (r) is .30. Although this correlation is rather low, it is highly significant ($p < .001$). In general, it is not likely that the correlation will be very high for any configuration due to the fact that it is a comparison between city-block distances and Euclidean distances, and due to the variety of other considerations that must enter into the determination of a physical layout (e.g., volume, restrictions on module size and shape).

To illustrate the fact that this correlation coefficient is sensitive to the "goodness" of the layout, the above steps were repeated using a slightly different layout. The only change was to swap the "Maintenance Workstation" and "Medical Facility" with each other. The resulting distances are shown in Table 19. This configuration runs counter to the FRA model, which indicated that ORU Maintenance should be grouped with the other "Public" functions, not the "Private" functions. The resulting correlation, r = .22, although not drastically lower, reflects the poorer layout.

TABLE 17. CREW FUNCTIONS TO BE PERFORMED IN EACH AREA OF THE SAMPLE CONFIGUATION

Wardroom
- Eating
- Meetings and Teleconferences
- Small-group Recreation and Leisure
- Planning and Scheduling

Galley
- Meal preparation
- Meal clean-up
- Logistics and resupply
- General Space Station housekeeping

Hab 1 Shower
- Full-body cleansing

Exercise Area
- Exercise

Hab 1 PHF
- Hand/face cleansing
- Personal hygiene
- Dressing/undressing

Hab 1 Toilet
- Urination/defecation

Washer/Dryer
- Clothing maintenance

Maintenance Workstation
- ORU maintenance

Primary Command and Control Workstation
- Planning and scheduling
- Subsystem monitoring
- Payload support
- Logistics and resupply
- IVA support of EVA
- Proximity operations

Crew Quarters
- Sleep
- Private recreation and leisure
- Dressing/undressing

HMF-Medical
- Medical care

TABLE 17. CREW FUNCTIONS TO BE PERFORMED IN EACH AREA OF THE SAMPLE CONFIGUATION (Continued)

Secondary (Hab 2) Command and Control Workstation	
	Training
Hab 2 Shower	
	Full-body cleansing
Hab 2 PHF	
	Hand/face cleansing
	Personal hygiene
	Dressing/undressing
Hab 2 Toilet	
	Urination/Defecation
Airlock	
	Pre/post-EVA
Life Sciences Lab	
	Life sciences experiments
Materials Processing Lab	
	Materials processing experiments

Table 18. Matrix of Distances for Sample Configuration

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		6	0	11	36	6	3	3	7	39	33	33	6	33	7	6	6	8	15	8	8	0	10	8	8	29	37
Eating			6	6	32	8	6	6	12	34	29	29	0	29	6	0	0	10	11	10	10	6	8	10	10	25	33
Meal Clean-up				11	36	6	3	3	7	39	33	33	6	33	7	6	6	8	15	8	8	0	10	8	8	29	37
Exercise					26	13	11	11	18	29	37	37	6	37	6	6	6	16	5	16	16	11	5	16	16	19	27
Medical Care						6	5	5	5	3	11	11	32	11	29	32	32	34	24	34	34	36	26	34	34	31	23
Full-body Cleaning							2	2	5	5	8	8	8	8	11	8	8	4	23	4	4	6	13	4	4	32	26
Hand/Face Cleaning								0	7	5	10	10	6	10	9	6	6	6	21	6	6	3	11	6	6	30	24
Personal Hygiene									7	5	10	10	6	10	9	6	6	6	21	6	6	3	11	6	6	30	24
Urination/Defecation										6	12	12	12	12	14	12	12	5	22	5	5	7	17	5	5	36	22
Training											8	8	34	8	32	34	34	31	12	31	31	39	29	31	31	32	25
Sleep												0	29	0	36	33	33	23	20	23	23	29	37	23	23	40	34
Private Recreation													29	0	36	33	33	23	20	23	23	29	37	23	23	40	34
Small-grp Recreation														29	6	0	0	10	11	10	10	6	8	10	10	25	33
Changing Clothes															36	33	33	23	20	23	23	29	37	23	23	40	34
Clothing Maint.																6	6	14	8	14	14	7	3	14	14	21	30
Meetings & Teleconf																	0	10	11	10	10	6	8	10	10	25	33
Planning & Sched.																		10	11	10	10	6	8	10	10	25	33
Subsys Monitoring																			21	0	0	8	18	0	0	35	43
Pre/Post-EVA																				21	1	5	0	15	21	17	28
IVA Support of EVA																					0	8	18	0	0	35	43
Prox Operations																						8	18	0	0	35	43
Gen. Housekeeping																							10	8	8	29	37
ORU Maintenance																								18	18	19	27
Logistics, Resupply																									0	29	37
Payload Support																										35	43
Life Sciences Exp.																											35
Mtl. Proc. Exper.																											

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Table 19. Matrix of Distances for Modified (Worse) Configuration

	Meal Preparation	Eating	Meal Clean-up	Exercise	Medical Care	Full-body Cleaning	Hand/Face Cleaning	Personal Hygiene	Urination/Defecation	Training	Sleep	Private Recreation	Small-grp Recreation	Changing Clothes	Clothing Maint.	Meetings & Teleconf.	Planning & Scheduling	Subsystem Monitoring	Pre/Post-EVA Ops	IVA Support of EVA	Prox. Operations	Gen. Housekeeping	ORU Maintenance	Logistics & Resupply	Payload Support	Life Sciences Exper.	Mtl. Proc. Exper.
Meal Preparation		6	0	11	10	6	3	3	7	39	33	33	6	33	7	6	6	8	15	8	8	0	36	8	8	29	37
Eating			6	6	8	8	6	6	12	34	29	29	0	29	6	0	0	10	11	10	10	6	32	10	10	25	33
Meal Clean-up				11	10	6	3	3	7	39	33	33	6	33	7	6	6	8	15	8	8	0	36	8	8	29	37
Exercise					5	13	11	11	18	29	37	37	6	37	6	6	6	16	5	16	16	11	26	16	16	19	27
Medical Care						13	11	11	17	29	37	37	8	37	3	8	8	18	0	18	18	10	26	18	18	19	27
Full-body Cleaning							2	2	5	5	8	8	8	8	11	8	8	4	23	4	4	6	6	4	4	32	36
Hand/Face Cleaning								0	7	5	10	10	6	10	9	6	6	6	21	6	6	3	5	6	6	30	24
Personal Hygiene									7	5	10	10	6	10	9	6	6	6	21	6	6	3	5	6	6	30	24
Urination/Defecation										6	12	12	12	12	14	12	12	5	22	5	5	7	5	5	5	36	22
Training											8	8	34	8	32	34	34	31	12	31	31	39	3	31	31	32	25
Sleep												0	29	0	36	33	33	23	20	23	23	29	11	23	23	40	34
Private Recreation													29	0	36	33	33	23	20	23	23	29	11	23	23	40	34
Small-grp Recreation														29	6	0	0	10	11	10	10	6	32	10	10	25	33
Changing Clothes															36	33	33	23	20	23	23	29	11	23	23	40	34
Clothing Maint.																6	6	14	8	14	14	7	29	14	14	21	30
Meetings & Teleconf																	0	10	11	10	10	6	32	10	10	25	33
Planning & Sched.																		10	11	10	10	6	32	10	10	25	33
Subsys Monitoring																			21	0	0	8	34	0	0	35	43
Pre/Post-EVA																				21	21	15	24	15	21	17	28
IVA Support of EVA																					0	8	34	0	0	35	43
Prox Operations																						8	34	0	0	35	43
Gen. Housekeeping																							36	8	8	29	37
ORU Maintenance																								34	34	31	23
Logistics, Resupply																									0	29	37
Payload Support																										35	43
Life Sciences Exp.																											35
Mtl. Proc. Exper.																											

CONCLUSIONS

A detailed method for assessing relationships between Space Station crew functions has been developed and applied. Hierarchical clustering and multidimensional scaling have been successfully used to help visualize these relationships. One of the key results is the distinction between "Private" and "Public" crew functions and the implications that has for Space Station layout. Finally, a technique for evaluating the "goodness" of any Space Station layout has been developed and applied.

While the results of this particular application of the FRA methodology should be useful to Space Station designers, the more important benefits will probably be gained through an iterative application of this methodology. As the design of the Space Station evolves, it will be possible to define the crew functions in greater detail and more accurately assess their relationships using the techniques described here. These analyses can then be repeated to gain a better understanding of the Space Station as a functional system and to more accurately project a physical system.

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APPENDIX A

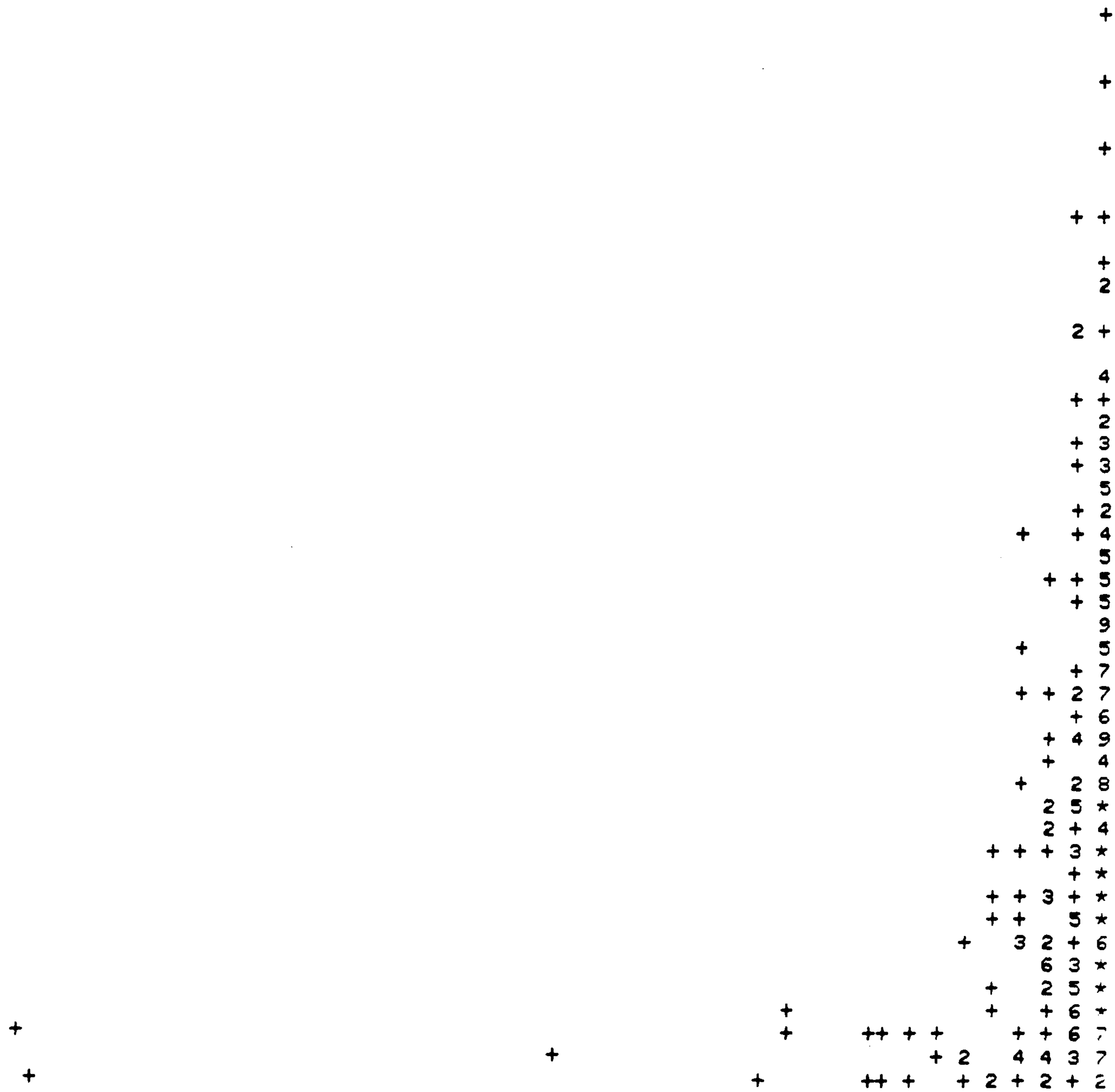
Plots of original matrix distances (x-axis) versus MDS configuration distances (y-axis)

Note: On each plot, single data points are represented by "+" signs. Plot points representing 2-9 actual data points are indicated by the appropriate digit. Plot points corresponding to more than 9 data points are represented by an asterisk ("*").

PLOT 17-FEB-1986 18:46

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? FREQ1.DAT
Name of file containing MDS configuration? FREQ_1D.MDS

Correlation Coefficient = .24329

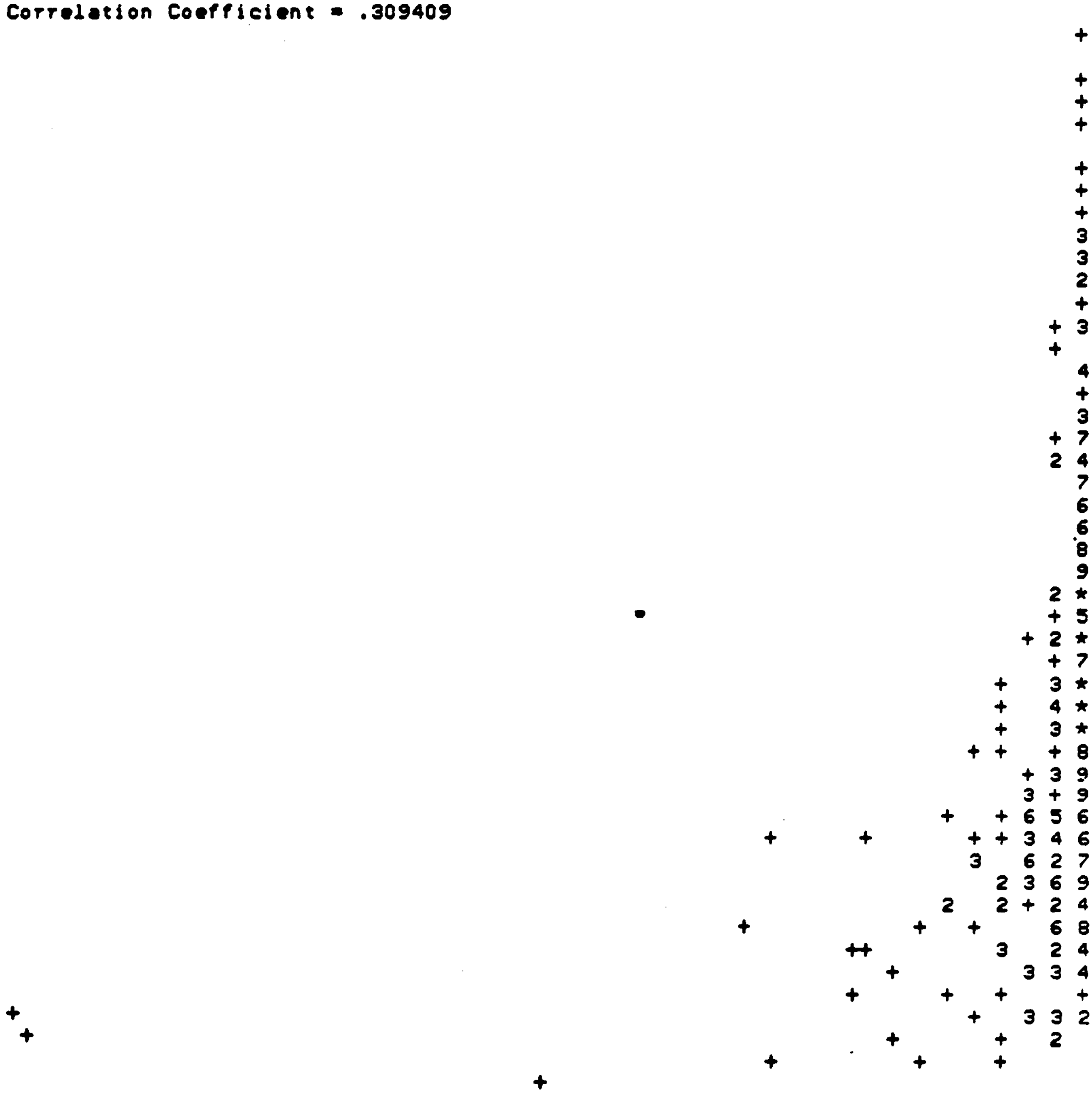


TRANSITION FREQUENCY - ONE-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:47

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? FREQ1.DAT
Name of file containing MDS configuration? FREQ_2D.MDS

Correlation Coefficient = .309409

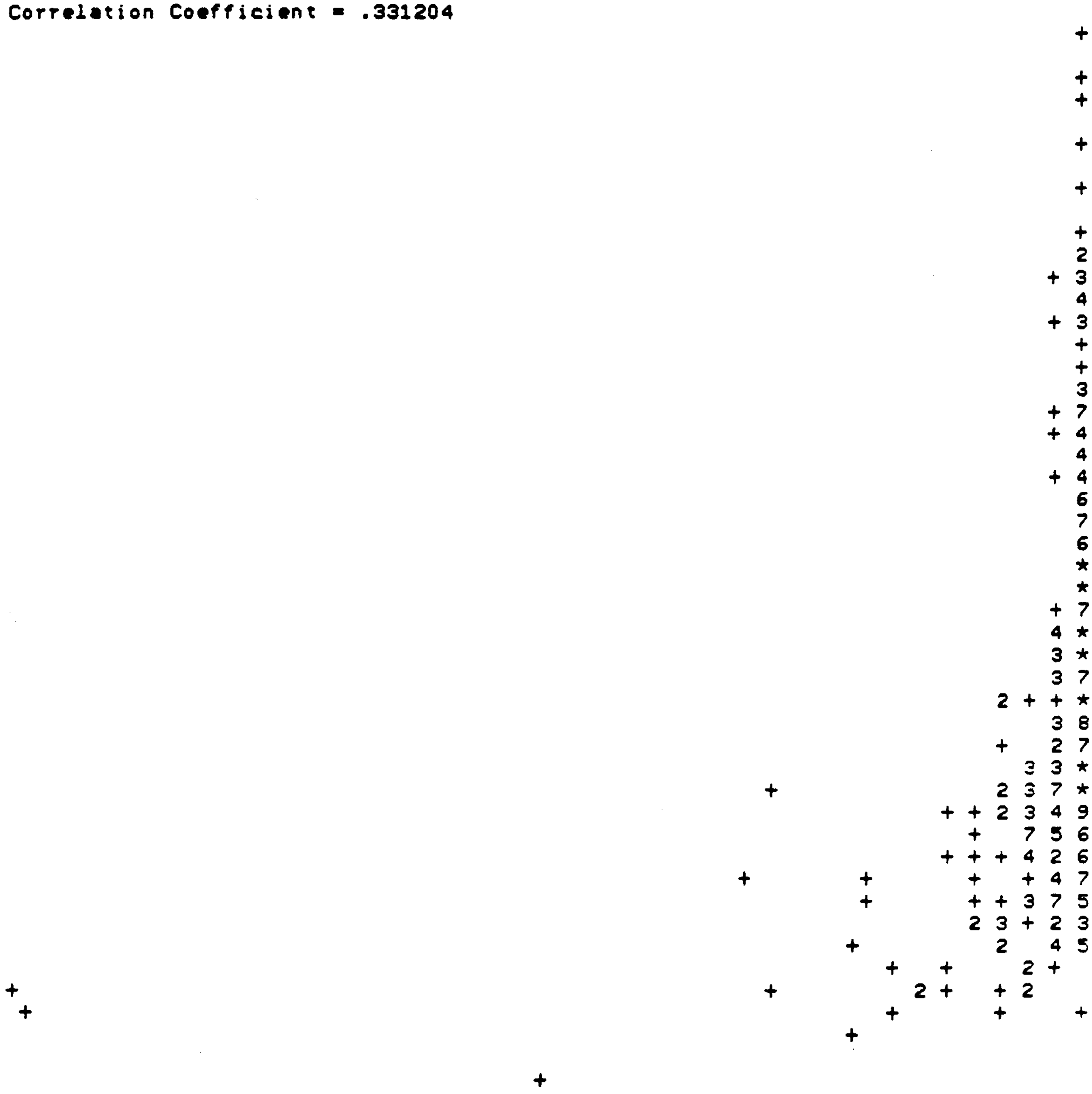


TRANSITION FREQUENCY - TWO-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:48

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? FREQ1.DAT
Name of file containing MDS configuration? FREQ_3D.MDS

Correlation Coefficient = .331204

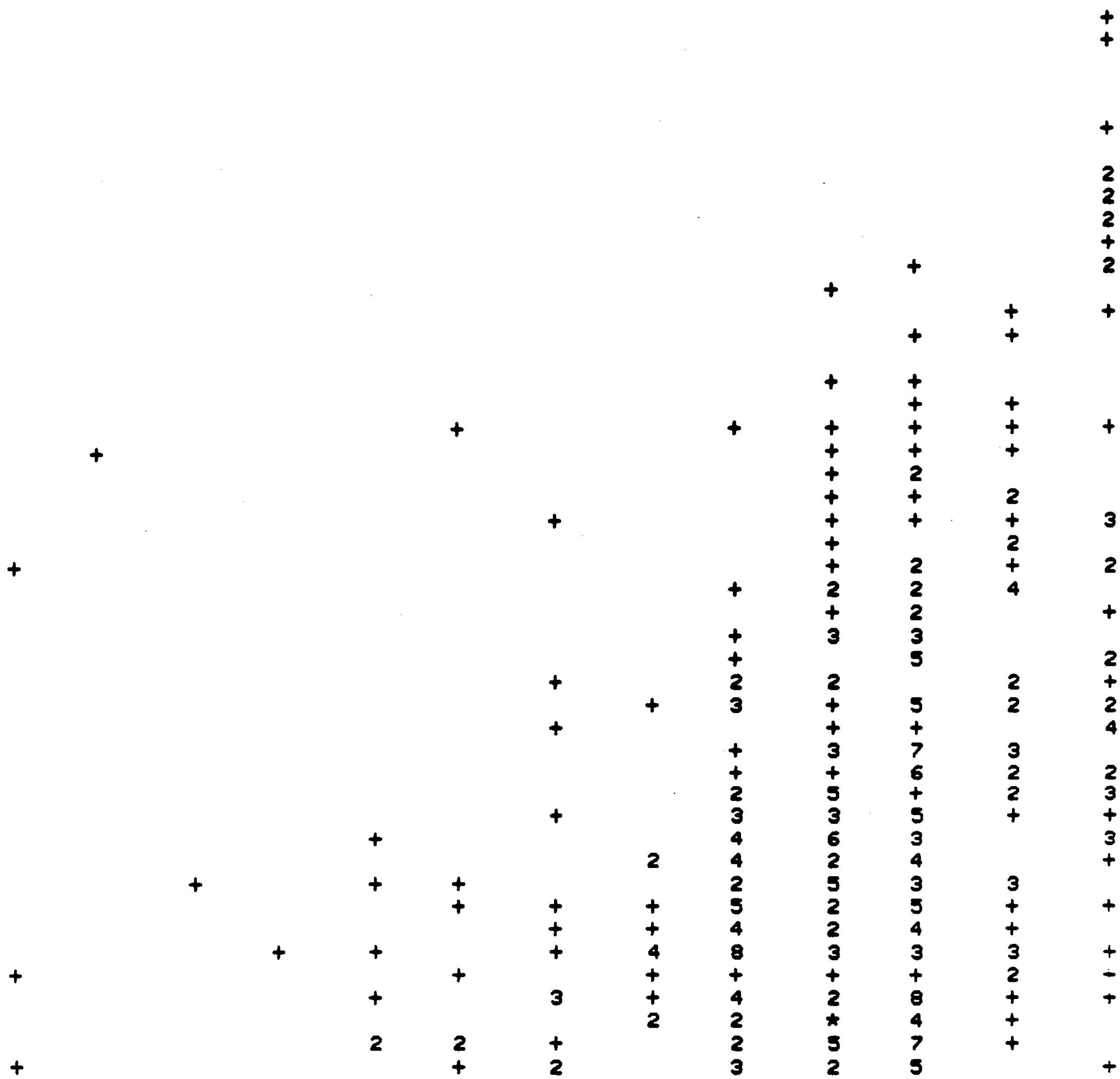


TRANSITION FREQUENCY - THREE-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:27

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? seq.dat
Name of file containing MDS configuration? seq_1d.mds

Correlation Coefficient = .344352

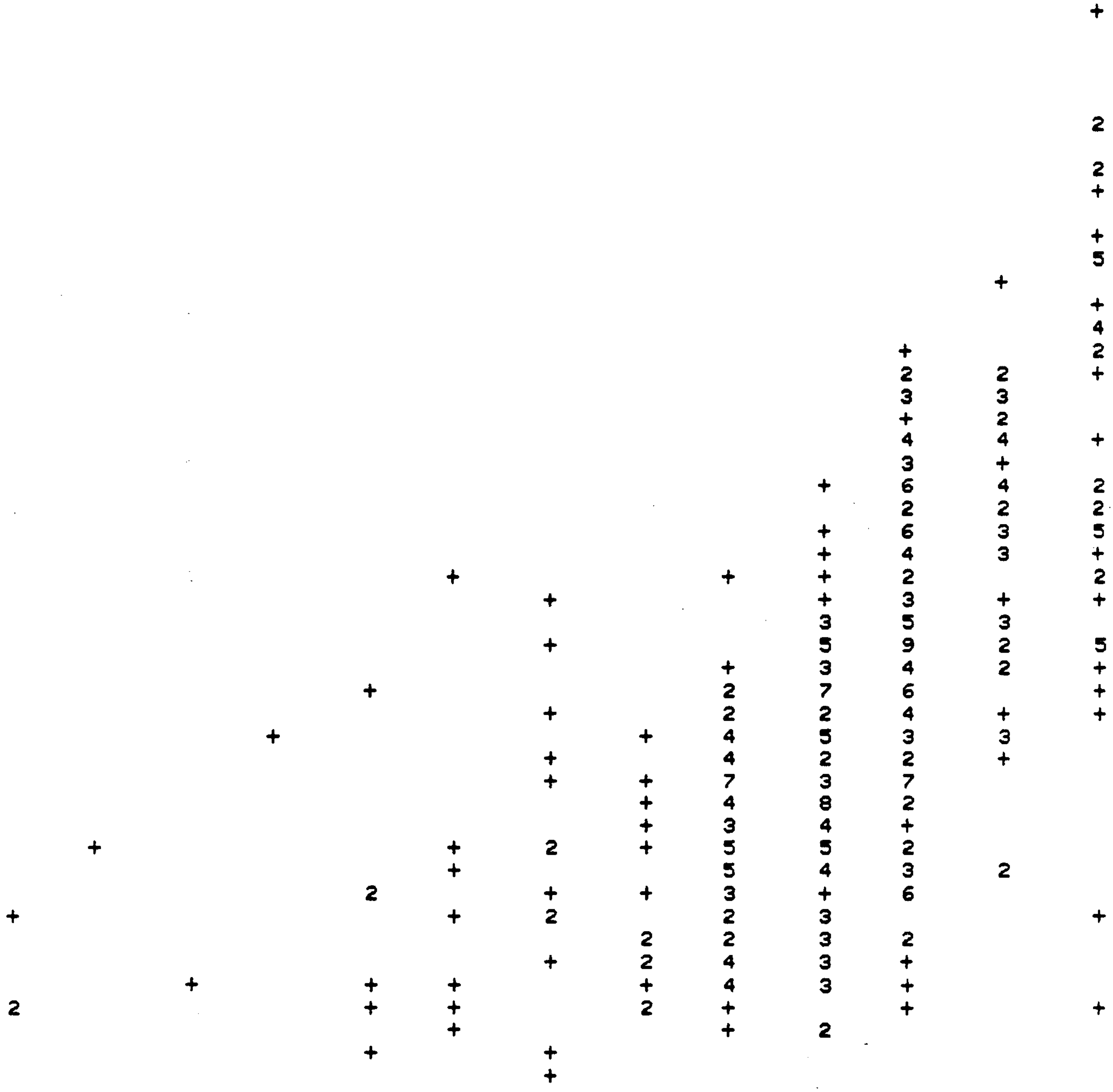


SEQUENTIAL DEPENDENCIES - ONE-DIMENSIONAL CONFIGURATION

PLOT   17-FEB-1986 18:33

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? SEQ.DAT
Name of file containing MDS configuration? SEQ_2D.MDS

Correlation Coefficient = .617724

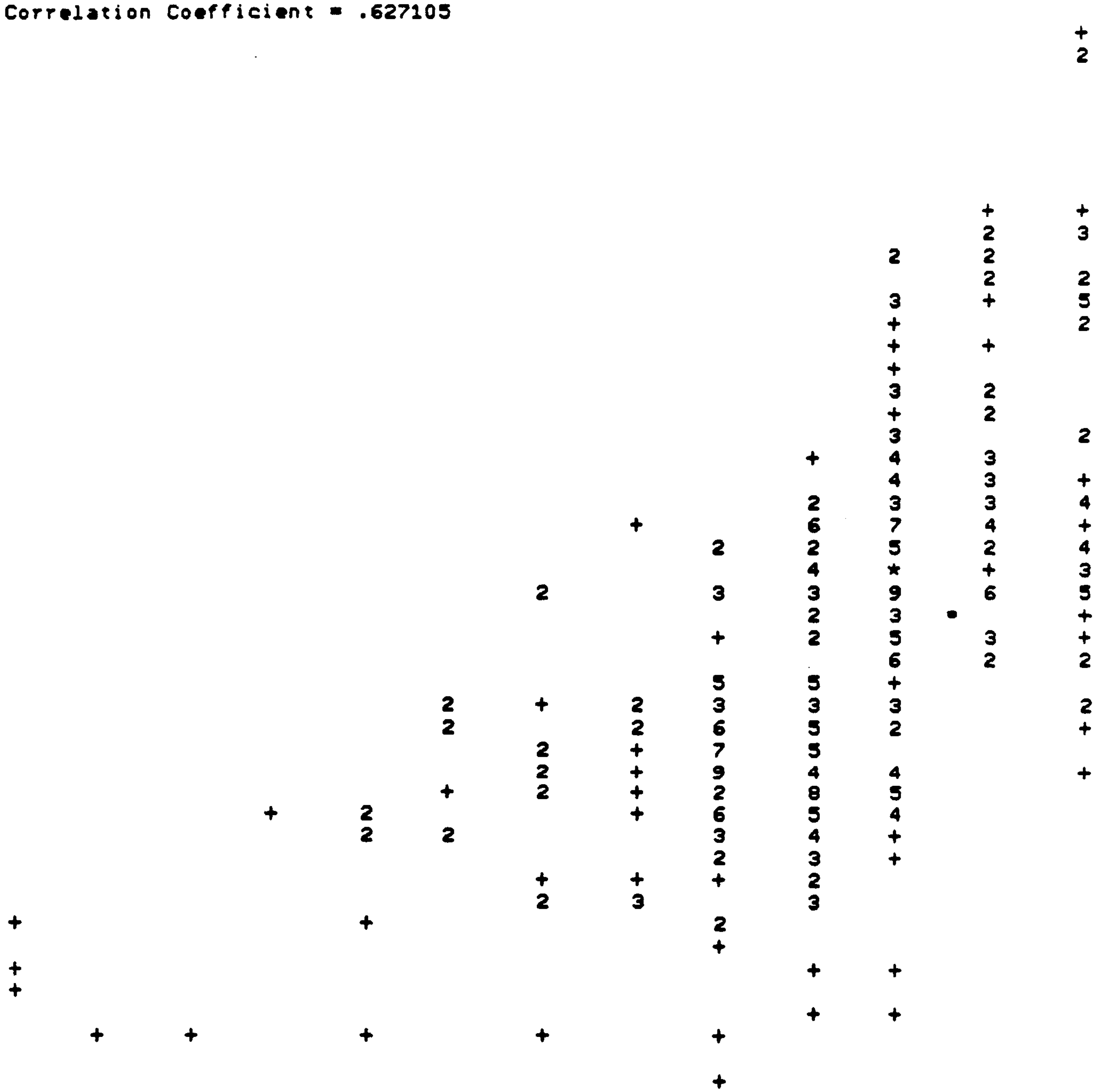


SEQUENTIAL DEPENDENCIES - TWO-DIMENSIONAL CONFIGURATION

```
PLOT    17-FEB-1986 18:29

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? SEQ.DAT
Name of file containing MDS configuration? SEQ_3D.MDS

Correlation Coefficient = .627105
```



SEQUENTIAL DEPENDENCIES - THREE-DIMENSIONAL CONFIGURATION

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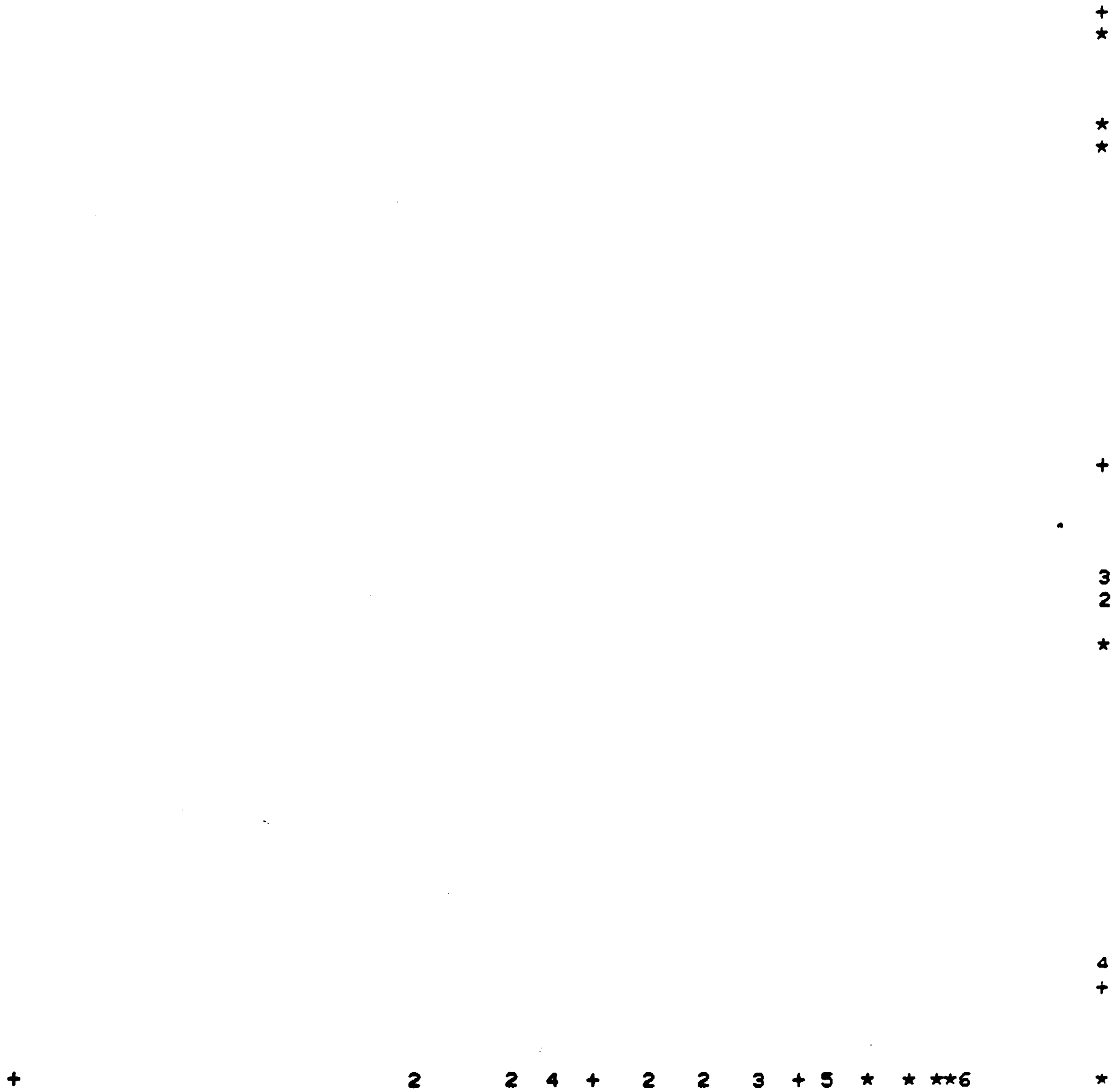
PLOT   17-FEB-1986 18:43

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? SHARED1.DAT
Name of file containing MDS configuration? SHARED_1D.MDS

Correlation Coefficient = .442265

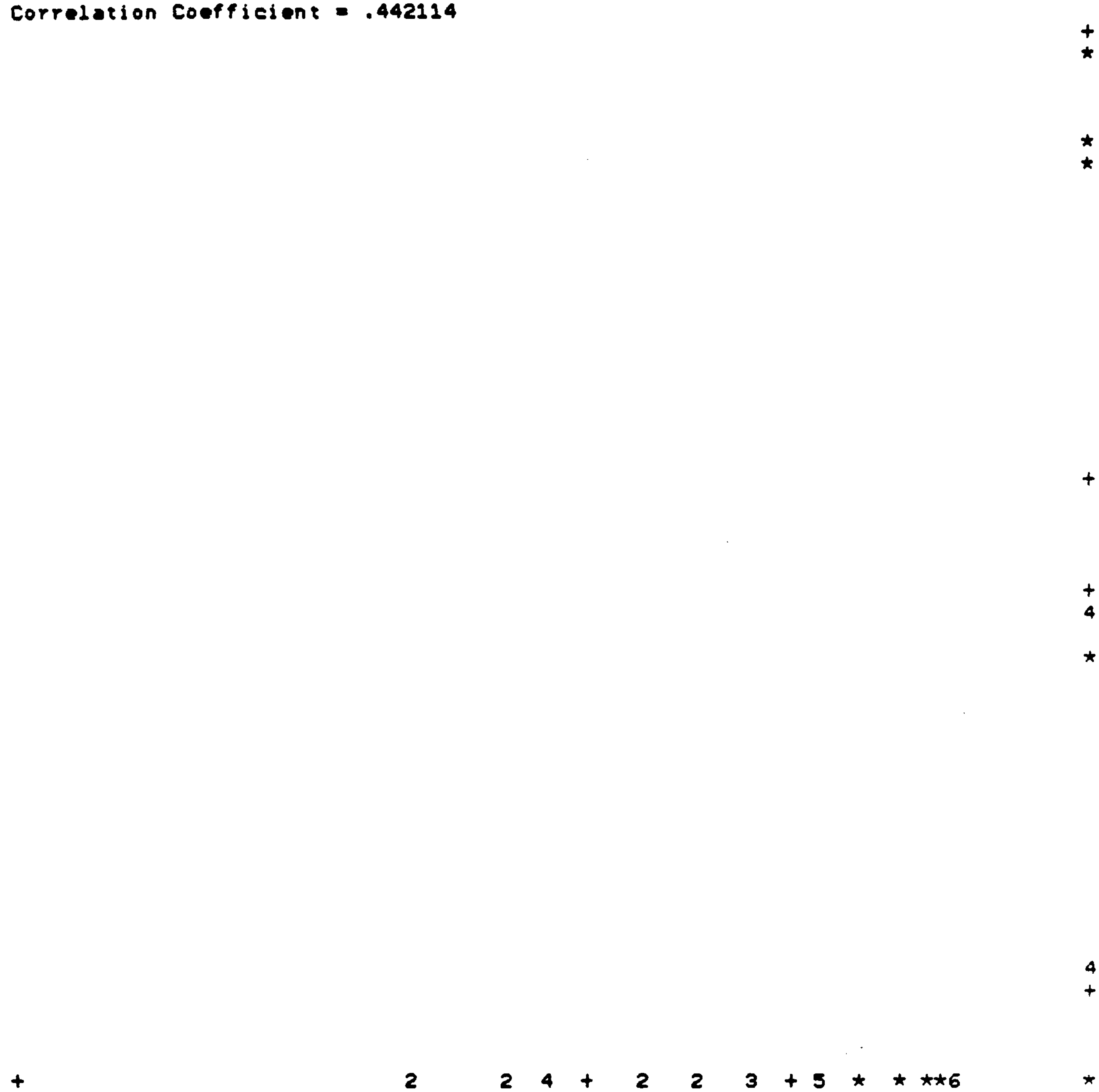


SHARED EQUIPMENT - ONE-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:45

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? SHARED1.DAT
Name of file containing MDS configuration? SHARED_2D.MDS

Correlation Coefficient = .442114

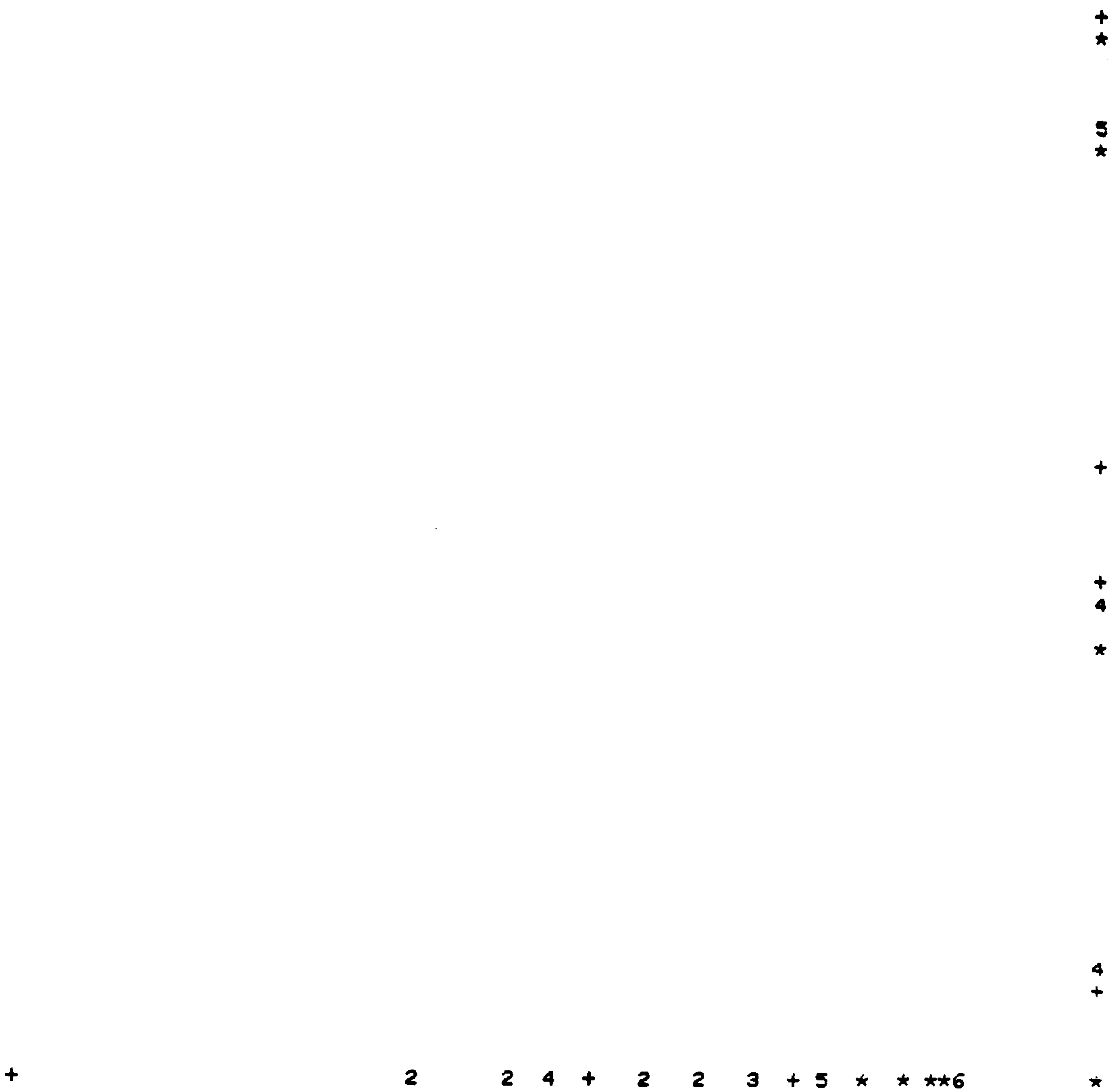


SHARED EQUIPMENT - TWO-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:45

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? SHARED1.DAT
Name of file containing MDS configuration? SHARED_3D.MDS

Correlation Coefficient = .44219

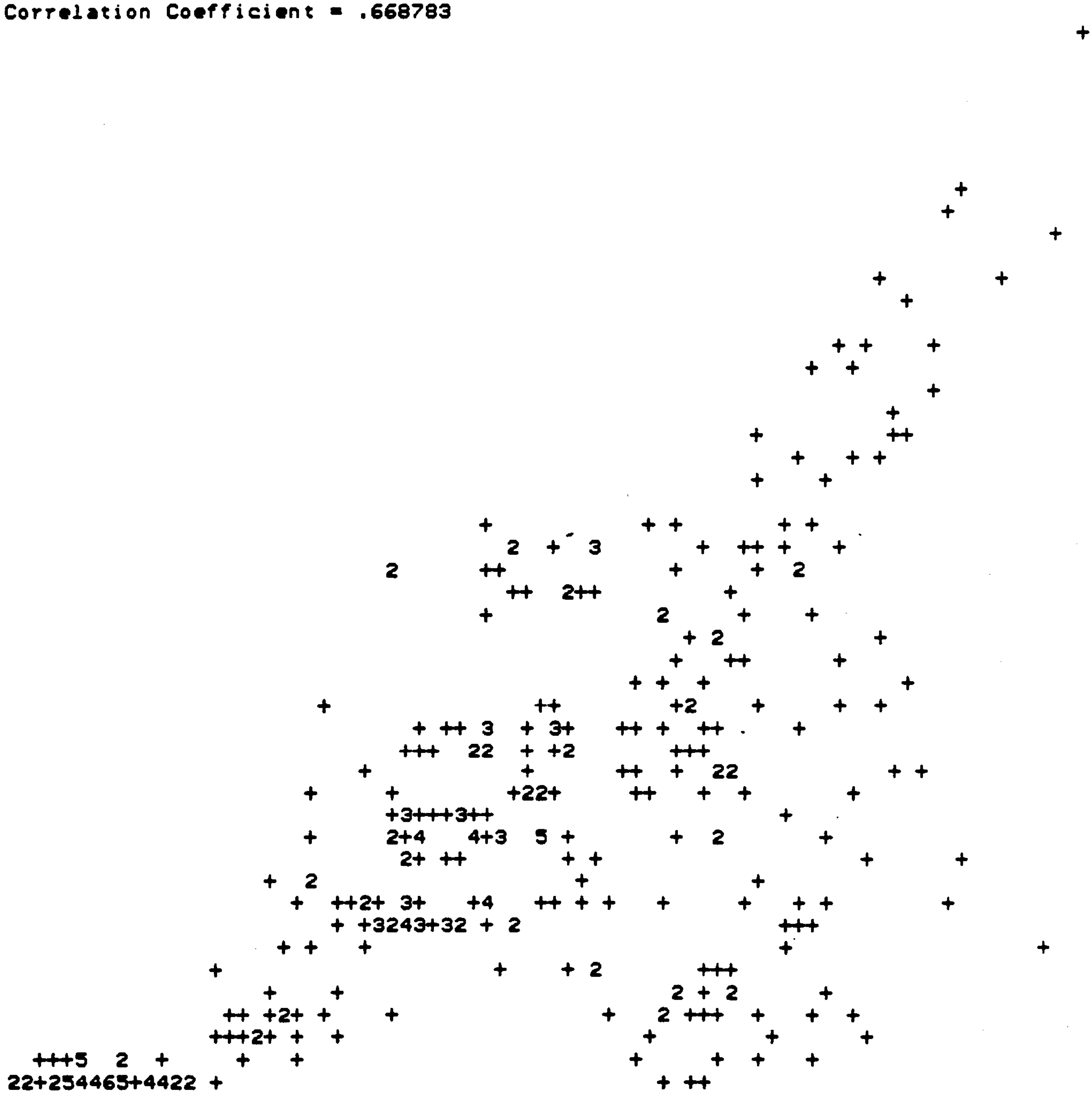


SHARED EQUIPMENT - THREE-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:35

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? NOISE.DAT
Name of file containing MDS configuration? NOISE_1D.MDS

Correlation Coefficient = .668783

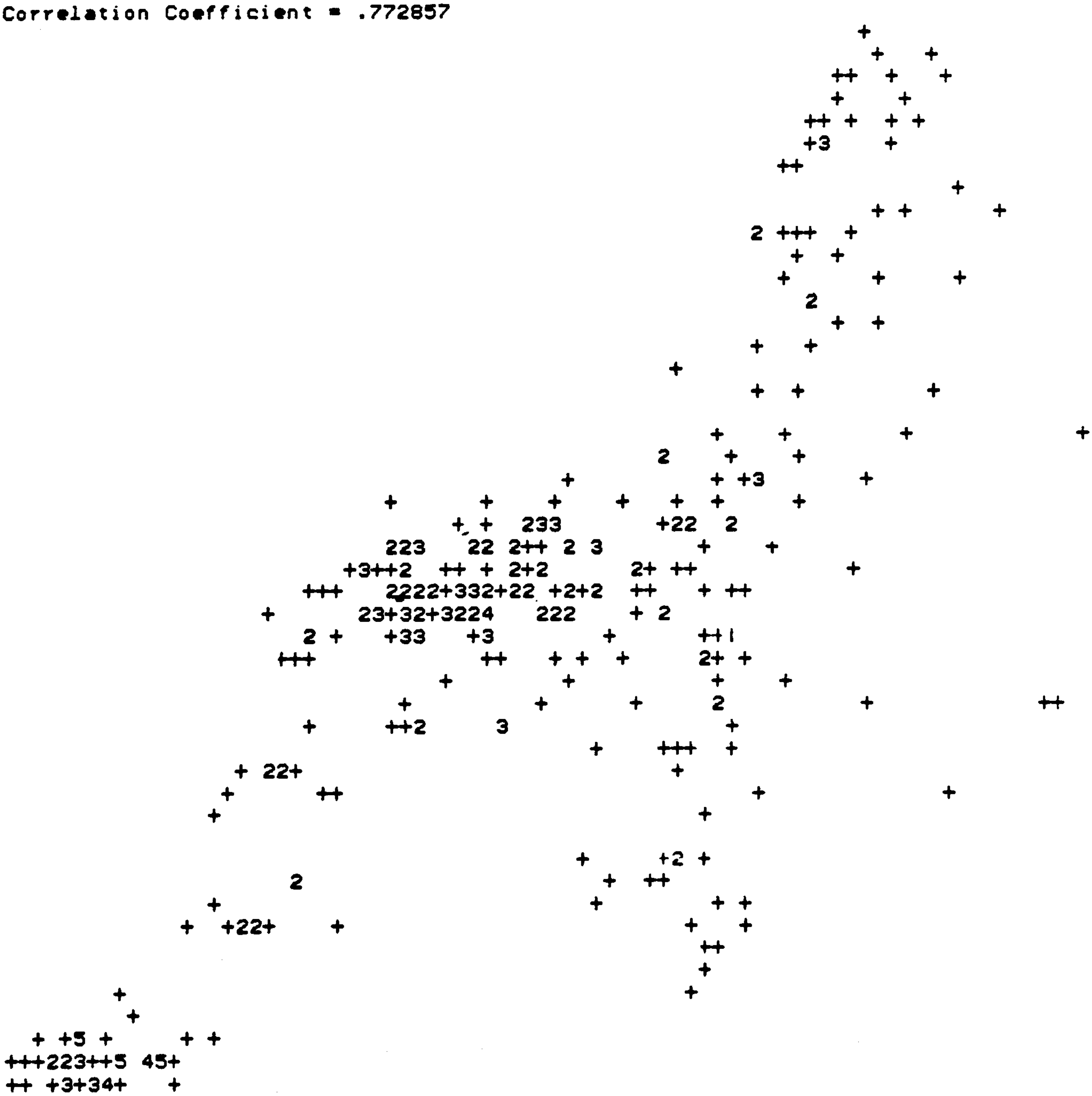


NOISE INTERFERENCE - ONE-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:38

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? NOISE.DAT
Name of file containing MDS configuration? NOISE_2D.MDS

Correlation Coefficient = .772857

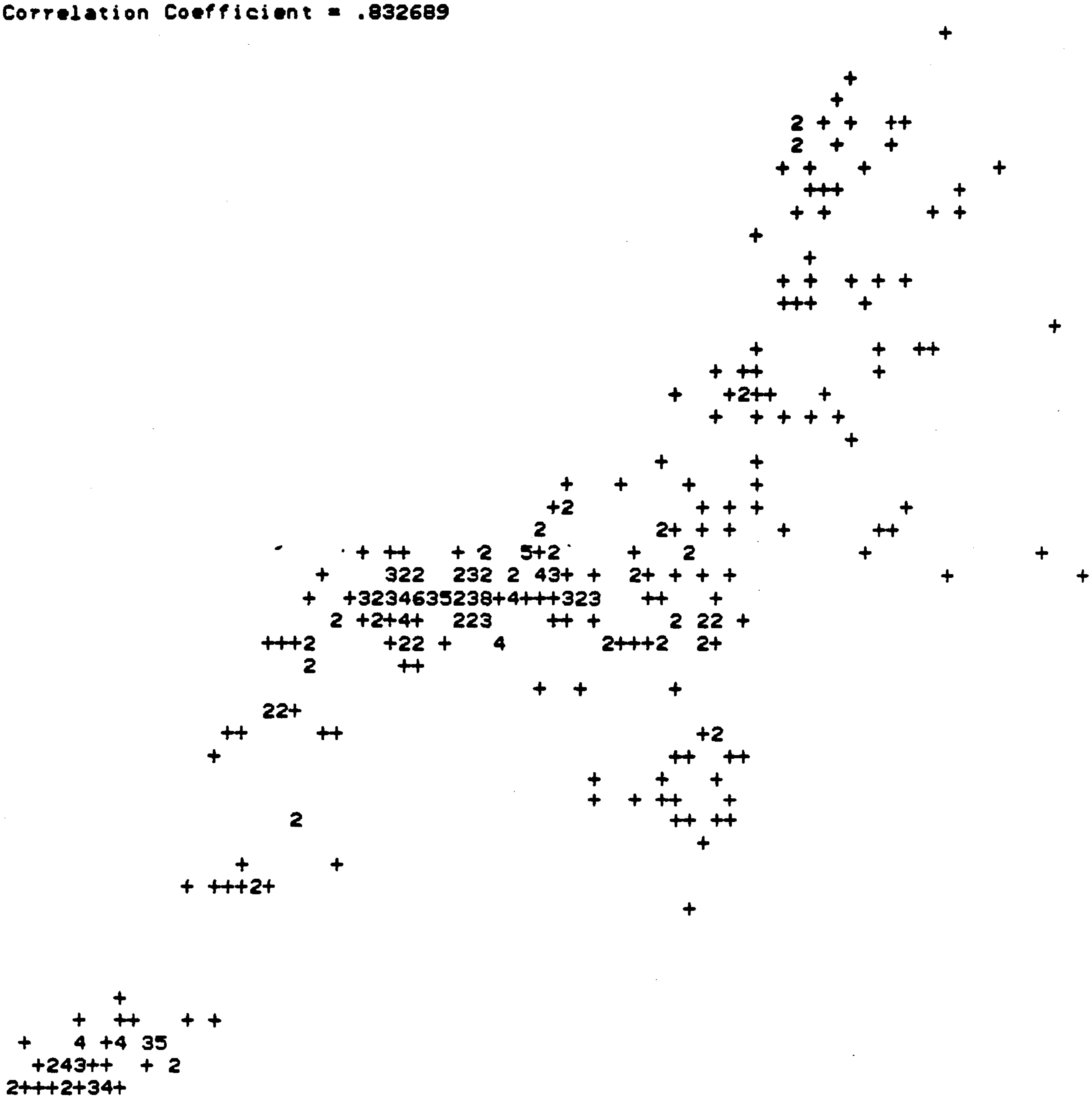


NOISE INTERFERENCE - TWO-DIMENSIONAL CONFIGURATION

```
PLOT    17-FEB-1986 18:39

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? NOISE.DAT
Name of file containing MDS configuration? NOISE_3D.MDS

Correlation Coefficient = .832689
```

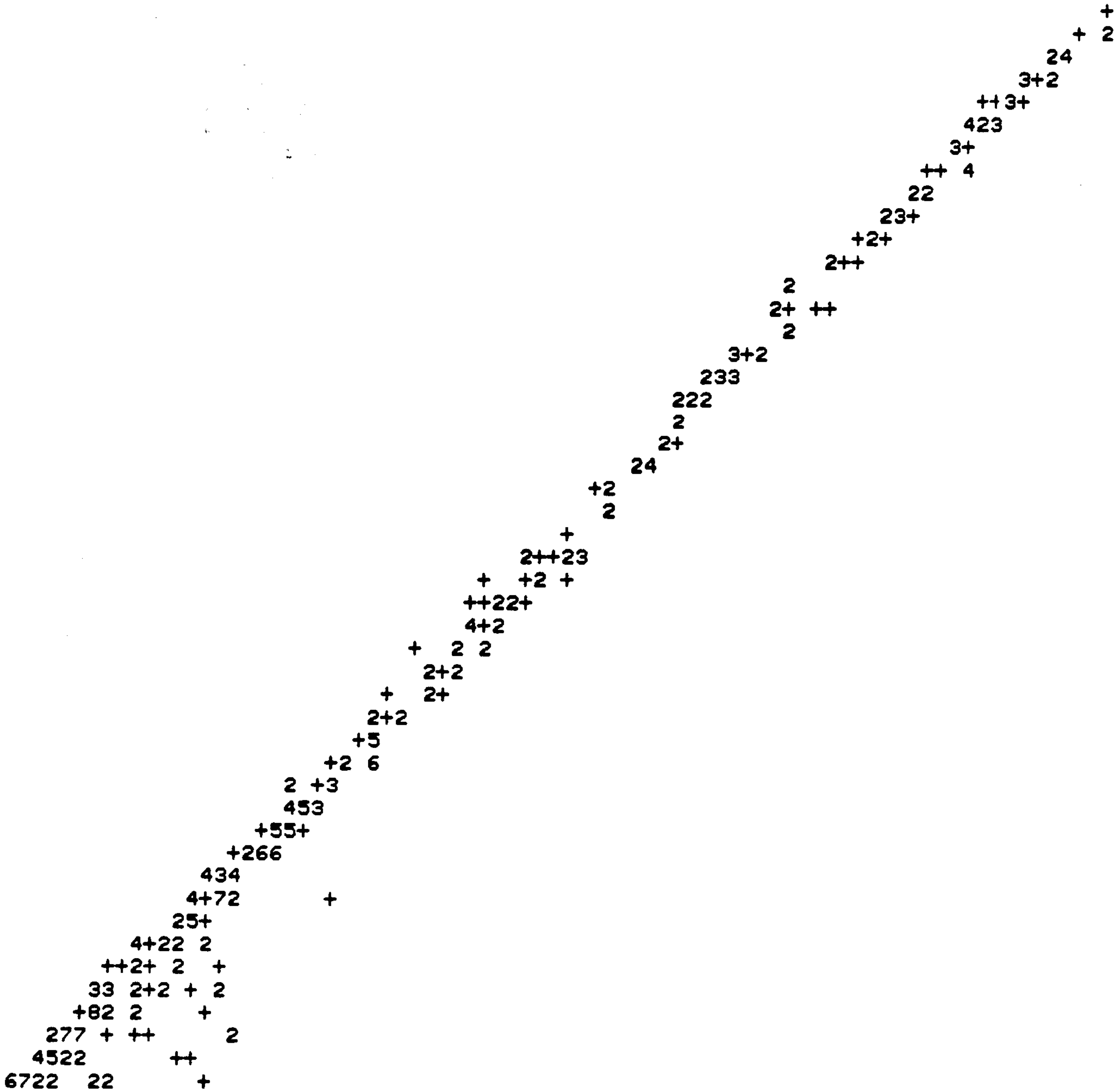


NOISE INTERFERENCE - THREE-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:40

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? PRIVACY.DAT
Name of file containing MDS configuration? PRIVACY_1D.MDS

Correlation Coefficient = .996392

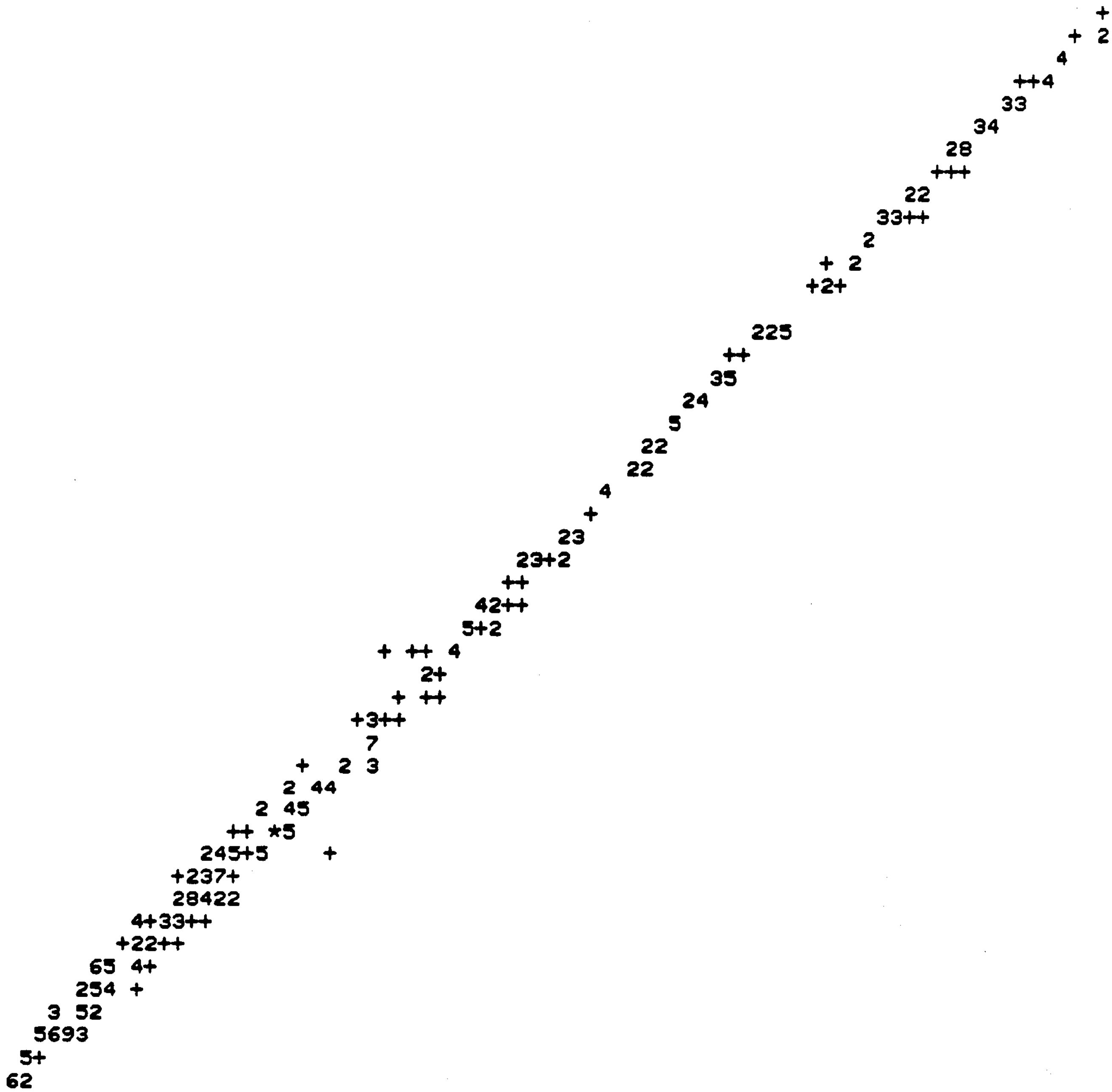


PRIVACY - ONE-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:42

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? PRIVACY.DAT
Name of file containing MDS configuration? PRIVACY_2D.MDS

Correlation Coefficient = .99895



PRIVACY - TWO-DIMENSIONAL CONFIGURATION

PLOT 17-FEB-1986 18:42

```
Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? PRIVACY.DAT
Name of file containing MDS configuration? PRIVACY_3D.MDS

Correlation Coefficient = .999044
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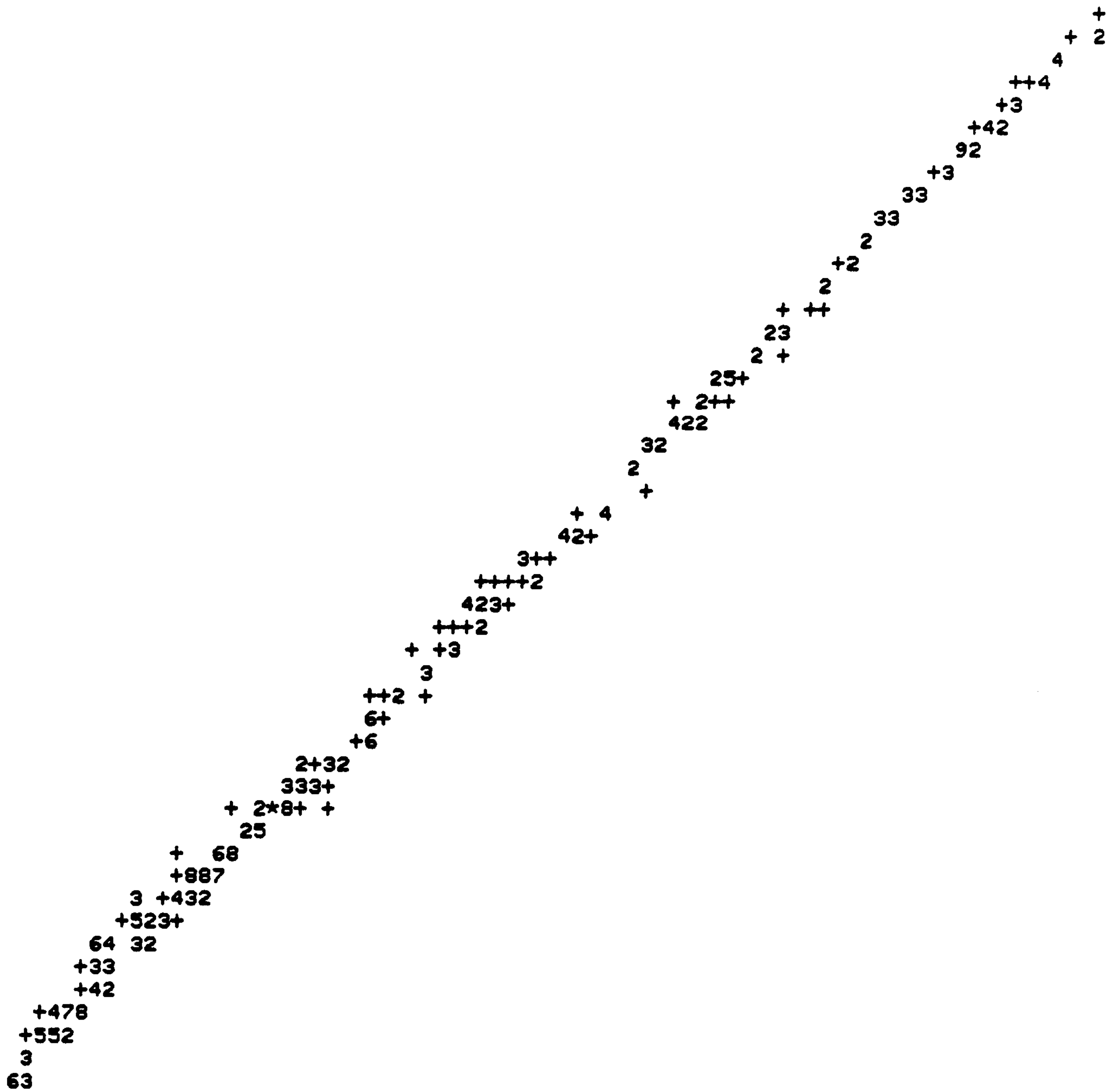

PRIVACY - THREE-DIMENSIONAL CONFIGURATION

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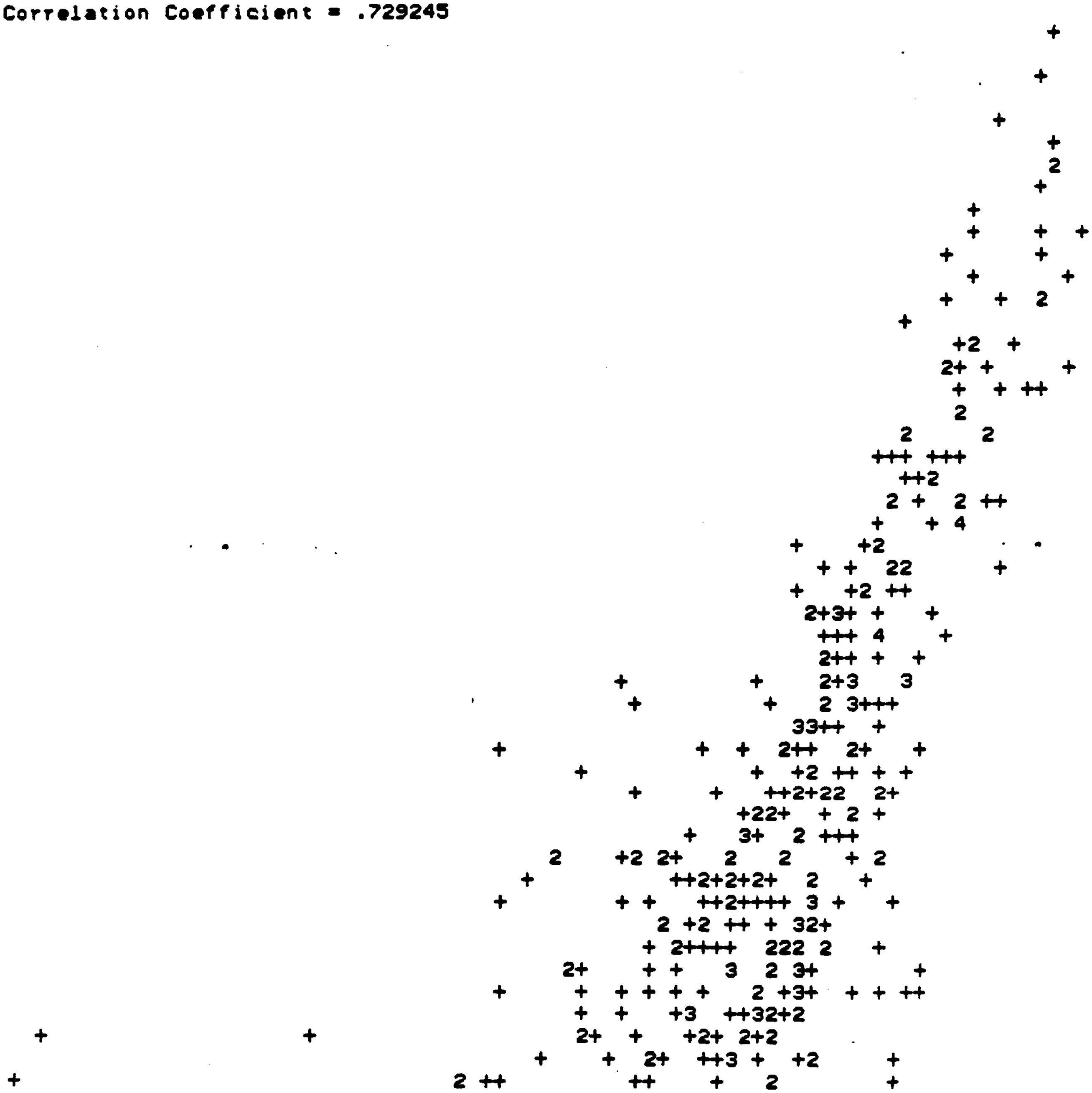
PLOT 17-FEB-1986 19:31

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? COMBINED.DAT
Name of file containing MDS configuration? COMBINED_1D.MDS

Correlation Coefficient = .729245



COMBINED DATA - ONE-DIMENSIONAL CONFIGURATION

```
PLOT    17-FEB-1986 19:32

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? COMBINED.DAT
Name of file containing MDS configuration? COMBINED_2D.MDS

Correlation Coefficient = .82155
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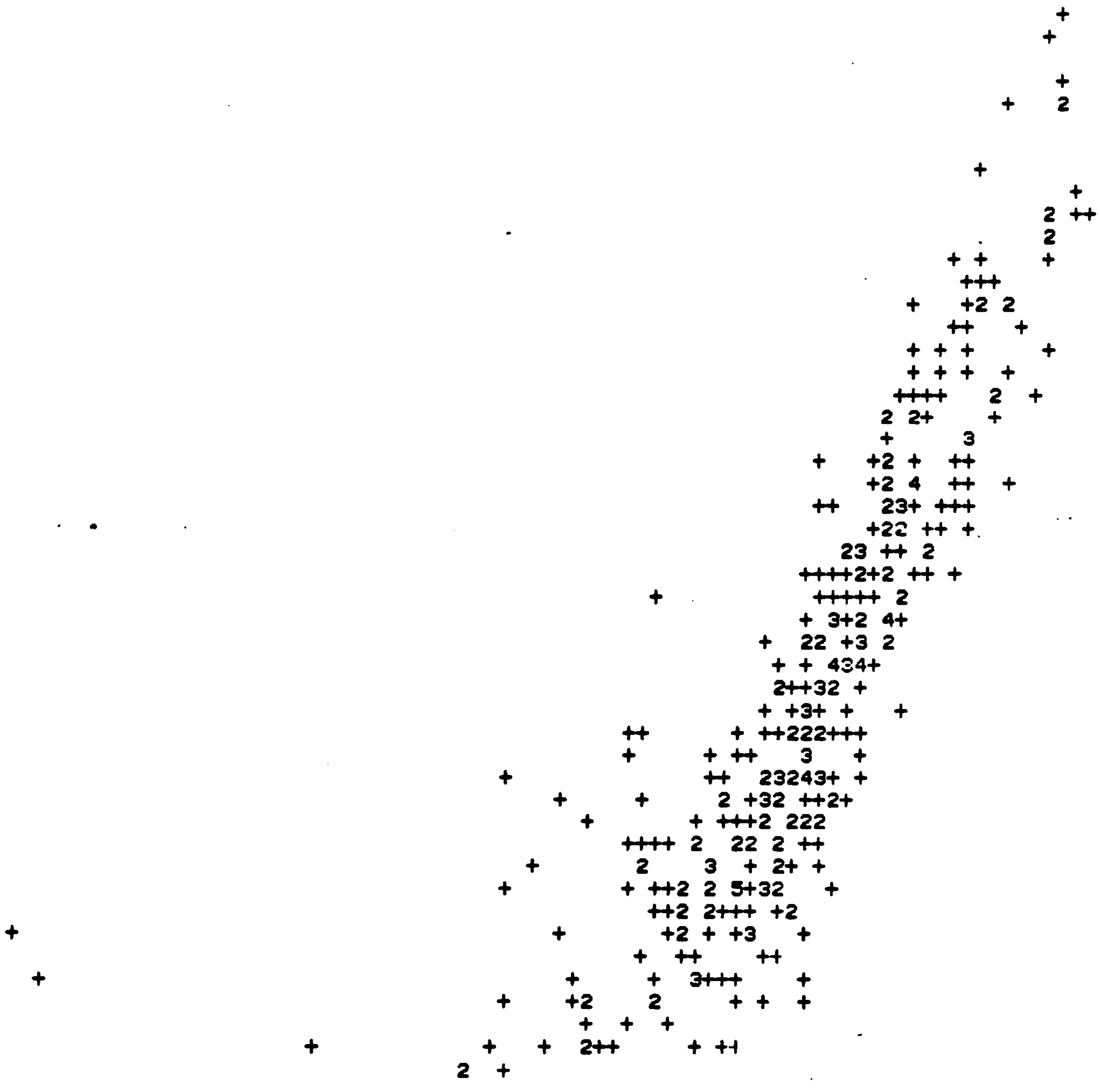
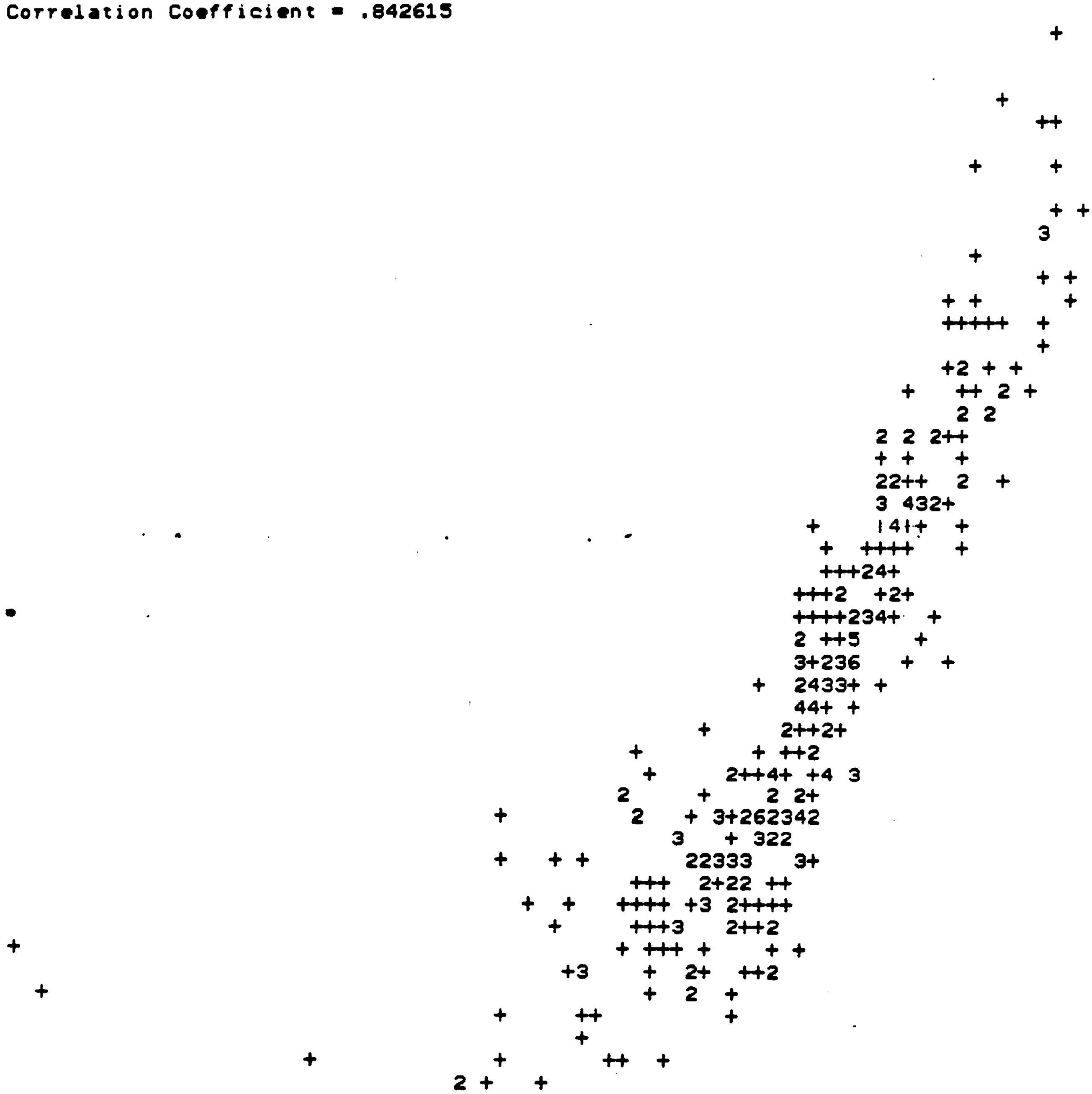


COMBINED DATA - TWO-DIMENSIONAL CONFIGURATION

PLOT   17-FEB-1986 19:36

Name of file containing names of items to be clustered? fn_names.lst
Name of file containing similarity data? COMBINED.DAT
Name of file containing MDS configuration? COMBINED_3D.MDS

Correlation Coefficient = .842615



COMBINED DATA - THREE-DIMENSIONAL CONFIGURATION

APPENDIX B

Sample Sequences of Crew Functions

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TIMELINE.1
(STATION SPECIALIST)
Sleep
Urination/Defecation
Full-body Cleansing
Personal Hygiene (shaving)
Dressing/Undressing
Meal Preparation (breakfast)
Eating
Meal Clean-up
Planning and Scheduling (shift change)
Logistics and Resupply
Urination/Defecation
Subsystem Monitoring and Control
Hand/face Cleansing
Meal Preparation (lunch)
Eating
Meal Clean-up
ORU Maintenance and Repair
Subsystem Monitoring and Control
Urination/Defecation
Hand/face Cleansing
General Space Station Housekeeping
Meal Preparation (dinner)
Eating
Meal Clean-up
Exercise
Urination/Defecation
Hand/face Cleansing
Small-group Recreation and Leisure
Private Recreation and Leisure
Personal Hygiene
Urination/Defecation
Dressing/Undressing
Sleep

TIMELINE.2
(STATION SPECIALIST)
Sleep
Urination/Defecation
Full-body Cleansing
Personal Hygiene
Dressing/Undressing
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Planning and Scheduling (SHIFT PLANNING)
IVA support of EVA Operations
Proximity Operations
Urination/Defecation
Hand/face Cleansing
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Exercise
Subsystem Monitoring and Control
Planning and Scheduling
Meetings and Teleconferences
General Space Station Housekeeping
Meal Preparation (DINNER)
Eating
Meal Clean-up
Small-group Recreation and Leisure
Personal Hygiene
Urination/Defecation
Dressing/Undressing
Sleep

TIMELINE.3
(MISSION SPECIALIST)
Sleep
Urination/Defecation
Full-body Cleansing
Personal Hygiene
Dressing/Undressing
Exercise
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Planning and Scheduling (DAILY CREW ACTIVITIES)
Training
Logistics and Resupply
Urination/Defecation
Hand/face Cleansing
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Life Sciences Experiments
Meal Preparation (DINNER)
Eating
Meal Clean-up
Personal Hygiene
Urination/Defecation
Dressing/Undressing
Sleep

TIMELINE.4
(OFF-DUTY DAY)
Sleep
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Hand/face Cleansing
Sleep
Urination/Defecation
Dressing/Undressing
Exercise
Full-body Cleansing
Personal Hygiene
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Clothing Maintenance
Private Recreation and Leisure
Training
Urination/Defecation
Hand/face Cleansing
Meal Preparation (DINNER)
Eating
Meal Clean-up
Personal Hygiene
Dressing/Undressing
Sleep

TIMELINE.5
(MISSION SPECIALIST)
Sleep
Urination/Defecation
Full-body Cleansing
Personal Hygiene
Dressing/Undressing
Planning and Scheduling (SHIFT)
Subsystem Monitoring and Control
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Payload Support
Urination/Defecation
Hand/face Cleansing
Materials Processing Experiments
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Exercise
Payload Support
Planning and Scheduling (REPLANNING/SHIFT HANDOVER)
Personal Hygiene
Urination/Defecation
Meal Preparation
Eating
Meal Clean-up
Dressing/Undressing
Sleep

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TIMELINE.6
(STATION SPECIALIST)
Sleep
Dressing/Undressing
Urination/Defecation
Hand/face Cleansing
Personal Hygiene
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Training
Planning and Scheduling
Meal Preparation (LUNCH)
Eating
Urination/Defecation
Pre/Post-EVA Operations
Urination/Defecation
ORU Maintenance and Repair
Hand/face Cleansing
Medical Care
Meal Preparation (DINNER)
Eating
Meal Clean-up
Exercise
Full-body Cleansing
Private Recreation and Leisure
Dressing/Undressing
Sleep

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TIMELINE.7
(MISSION SPECIALIST)
Sleep
Urination/Defecation
Exercise
Medical Care
Dressing/Undressing
Hand/face Cleansing
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Planning and Scheduling
Life Sciences Experiments
Materials Processing Experiments
Urination/Defecation
Hand/face Cleansing
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Payload Support
Urination/Defecation
Life Sciences Experiments
Materials Processing Experiments
Meetings and Teleconferences
Urination/Defecation
Hand/face Cleansing
Small-group Recreation and Leisure
Meal Preparation (DINNER)
Eating
Meal Clean-up
Small-group Recreation and Leisure
Private Recreation and Leisure
Urination/Defecation
Personal Hygiene
Dressing/Undressing
Sleep

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TIMELINE.8
(STATION SPEC)
Sleep
Dressing/Undressing
Urination/Defecation
Personal Hygiene
Exercise
Hand/face Cleansing
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Meetings and Teleconferences
Planning and Scheduling
Urination/Defecation
Hand/face Cleansing
Subsystem Monitoring and Control
Logistics and Resupply
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Proximity Operations
Urination/Defecation
Logistics and Resupply
General Space Station Housekeeping
Subsystem Monitoring and Control
Urination/Defecation
Hand/face Cleansing
Training
Small-group Recreation and Leisure
Meal Preparation (DINNER)
Eating
Meal Clean-up
Small-group Recreation and Leisure
Urination/Defecation
Private Recreation and Leisure
Dressing/Undressing
Full-body Cleansing
Personal Hygiene
Sleep

TIMELINE.9
(STATION SPEC)
Sleep
Personal Hygiene
Urination/Defecation
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Planning and Scheduling
Pre/Post-EVA Operations
Urination/Defecation
Hand/face Cleansing
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Payload Support
ORU Maintenance and Repair
Medical Care
Urination/Defecation
Hand/face Cleansing
IVA support of EVA Operations
Subsystem Monitoring and Control
Meetings and Teleconferences
Meal Preparation (DINNER)
Eating
Meal Clean-up
Urination/Defecation
Small-group Recreation and Leisure
Eating
Private Recreation and Leisure
Urination/Defecation
Personal Hygiene
Sleep

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TIMELINE.10
(STATION SPEC)
Sleep
Urination/Defecation
Sleep
Full-body Cleansing
Personal Hygiene
Dressing/Undressing
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Planning and Scheduling
Subsystem Monitoring and Control
ORU Maintenance and Repair
Urination/Defecation
ORU Maintenance and Repair
Subsystem Monitoring and Control
Hand/face Cleansing
Meal Preparation (LUNCH)
Eating
Meal Clean-up
General Space Station Housekeeping
Logistics and Resupply
Planning and Scheduling
Training
Urination/Defecation.
Subsystem Monitoring and Control
Small-group Recreation and Leisure
Meetings and Teleconferences
Meal Preparation (DINNER)
Eating
Meal Clean-up
Small-group Recreation and Leisure
Exercise
Urination/Defecation
Hand/face Cleansing
Private Recreation and Leisure
Urination/Defecation
Personal Hygiene
Sleep

TIMELINE.11
(MISSION SPEC)
Sleep
Urination/Defecation
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Exercise
Full-body Cleansing
Dressing/Undressing
Planning and Scheduling
Payload Support
Urination/Defecation
Hand/face Cleansing
Life Sciences Experiments
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Training
Life Sciences Experiments
Meetings and Teleconferences
Urination/Defecation
Hand/face Cleansing
Life Sciences Experiments
Small-group Recreation and Leisure
Meal Preparation (DINNER)
Eating
Meal Clean-up
Life Sciences Experiments
Private Recreation and Leisure
Urination/Defecation
Personal Hygiene
Sleep

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TIMELINE.12
(MISSION SPEC)
Sleep
Personal Hygiene
Urination/Defecation
Dressing/Undressing
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Planning and Scheduling
Materials Processing Experiments
Payload Support
Urination/Defecation
Hand/face Cleansing
Planning and Scheduling
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Materials Processing Experiments
Urination/Defecation
Materials Processing Experiments
Meetings and Teleconferences
Exercise
Hand/face Cleansing
Meal Preparation (DINNER)
Eating
Meal Clean-up
Medical Care
Urination/Defecation
Private Recreation and Leisure
Small-group Recreation and Leisure
Dressing/Undressing
Full-body Cleansing
Personal Hygiene
Private Recreation and Leisure
Urination/Defecation
Sleep

TIMELINE.13
(MISSION SPEC)
Sleep
Hand/face Cleansing
Urination/Defecation
Dressing/Undressing
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Payload Support
Meetings and Teleconferences
Urination/Defecation
Materials Processing Experiments
Meal Preparation (LUNCH)
Eating
Meal Clean-up
General Space Station Housekeeping
Meetings and Teleconferences
Urination/Defecation
Hand/face Cleansing
Life Sciences Experiments
Training
Life Sciences Experiments
Urination/Defecation
Planning and Scheduling
Meal Preparation (DINNER)
Eating
Meal Clean-up
Small-group Recreation and Leisure
Private Recreation and Leisure
Exercise
Urination/Defecation
Private Recreation and Leisure
Sleep

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TIMELINE.14
(OFF-DUTY)
Sleep
Urination/Defecation
Personal Hygiene
Meal Preparation (BREAKFAST)
Eating
Meal Clean-up
Private Recreation and Leisure
Meetings and Teleconferences
Exercise
Urination/Defecation
Hand/face Cleansing
Meal Preparation (LUNCH)
Eating
Meal Clean-up
Dressing/Undressing
Clothing Maintenance
Private Recreation and Leisure
Training
Urination/Defecation
Hand/face Cleansing
Meal Preparation (DINNER)
Eating
Meal Clean-up
Small-group Recreation and Leisure
Private Recreation and Leisure
Dressing/Undressing
Full-body Cleansing
Personal Hygiene
Urination/Defecation
Sleep

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16. Abstract

The purpose of this study was to develop a systems engineering process to assist Space Station designers in understanding the underlying operational system of the facility so that it can be physically arranged and configured to support crew productivity. The study analyzed the operational system proposed for the Space Station in terms of mission functions, crew activities, and functional relationships in order to develop a quantitative model for evaluation of interior layouts, configuration, and traffic analysis for any Station configuration. Development of the model involved identification of crew functions, required support equipment, criteria for assessing functional relationships, and tools for analyzing functional relationship matrices, as well as analyses of crew transition frequency, sequential dependencies, support equipment requirements, potential for noise interference, need for privacy, and overall compatability of functions. The model can be used for analyzing crew functions for the Initial Operating Capability of the Station and for detecting relationships among those functions. Note: This process (FRA) was used during Phase B design studies to test optional layouts of the Space Station habitat module. The process is now being automated as a computer model for use in layout testing of the Space Station laboratory modules during Phase C.

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