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Designing Space Habitats for Human Productivity

Marc M. Cohen
Space Human Factors Branch
NASA-Ames Research Center
Mail Stop 239-15
Moffett Field, CA 94025-1000

Architecture and Planning Research Laboratory
2000 Bonisteel Blvd.
University of Michigan
Ann Arbor, MI 48109

Abstract

This summary paper addresses each of the key words in its title; Designing, Space Habitats and Productivity; from the perspective of a research architect engaged in inquiry into the fundamental aspects of design method and process and their application to spacecraft design. This approach looks at definitions of productivity and the respective concepts of designing for productivity in relation to the specific economic, industrial and sociotechnical context in which they evolved.

INTRODUCTION

When I was invited to present a "summary paper" for this session on Human Productivity in Space, my initial concern was with the difficulty in defining or measuring productivity outside of a narrow band width of well–defined tasks that are controllable under laboratory conditions. Certainly all of the other speakers in this session are presenting well–focused analyses of highly specific issues of productivity in crew training, exercise, work station design and on–orbit operations. I will take a broader approach to defining productivity in living and working environments and their implications for design.

I will address the three research domains suggested by the title, but in a different order; a more apt title might be ***Designing Human Productivity into Space Habitats.*** This difference in emphasis is significant. I believe that design applies not just to a physical setting, but to shaping all the human and machine activities that will occur in that setting. Therefore, designing is a primary approach to human productivity and all other human activities. All of the other speakers in this session address design as a means to achieve productivity withing their definitions of it. In this presentation, I will examine the concept of designing in relation to different and evolving definitions of productivity. The context of the space habitat is secondary to the fundamental relationship of designing and productivity.

I will begin with the understanding of design that has evolved through research in a number of fields; architectural research, cognitive science and design management. In addition to architectural theory and the environmental psychology research literature, I will draw upon my own experience of working on the Space Station Program at NASA–Ames Research Center from 1983 to 1988.

Social values underlie all of the decisions made in the design process for space habitats or any other environment. These social values constitute the hidden or deep structure of design. The social values of the architect include his concept of why he designs the environment, how he designs it, and who it serves. The social values of productivity include the assessment measures of human performance, who does the assessing, and for what purpose. The social values embodied in the habitable environment determine how well it enhances peoples lives.

Design process embodies the social, political, and economic values of the designers and their clients. The distinction between systematic methods and participatory methods reflect a difference between hierarchical and democratic values.

DESIGN AND DESIGNING

Designing refers to the process of translating intentions or requirements into a physical form that embodies and supports the operational and organizational aspects of an human endeavor. Designing is one of the most fundamental human activities; making tools, shaping the environment, conditioning human activities as a social art (1). Daniel Whitney argues that "design is a strategic activity, whether by intention or default. It influences flexibility . . ." in all areas of productive activity and may be responsible for the future viability of any product, program or project (2). Designing spans the dimensions of process, production, performance and aesthetic form and integrates them together within a larger social and economic value system. Designing involves analysis, matching, selection, evaluation and integration functions in all problem solving domains.

The deep structure of design for work environments involves the organizational, physical, social and technical setting for productivity. As the definition of productivity evolves so must the design approach. Hy Kornbluh observes that a changing, high technology economy creates the demand for more workplace flexibility for workers "designed to take advantage of workers' mental abilities and learned skills as well as group-based, collective competencies." Kornbluh predicts that this demand will cause a shift in management perspective from *control of people* to *control of outcomes.* (3).

DESIGN VALUES - Fundamental to the design / implementation continuum (7) is the value system that defines the role of people in the working and living environment. I believe that in the previous NASA spacecraft SpaceLab and the Space Station Laboratory Module, the design value system is *the people serving the machines*, *not the machines serving the people*. This situation reflects the designers' values, based on their understanding of worklife, habitability and productivity.

Research in design process through protocol analysis methods indicates that designers tend to create "rules, types and worlds" in which they conceptualize their tasks and refine their decision-making (8). System engineering offers a perfect example of a complete and too-often closed "world" of rationality with its own internal rules and its own types of legitimate design products. I have worked in both the traditional/hierarchical and innovative productivity "design worlds" and I attempt to illustrate their value systems in Figures 1 and 2. Figure 1 shows my interpretation of the traditional "Design World 1" (DW1) approach to space laboratory workplace design, in which the human services the machine in an environment designed principally to support the machine - with appropriate structural, thermal, electrical power and ventilation systems. DW1 reflects the most reductionist system engineering approach to productivity. Figure 2 shows the "Design World 2" (DW2) ensemble that I envision for future long duration space missions. In this model, machine and environment or habitat equally support the human activity, reflecting the "New Value," participatory approach to designing-in productivity.

These two models of design worlds have further implications. DW1 encompasses the traditional view of human-machine interaction, with a goal of reducing or eliminating error between human and machine. However, William Rouse states that if designers structure all tasks to avoid human error, they will inhibit human innovation as well, which can often be an unintentional effect of institutionalizing systematic methods as a means of error avoidance. Participatory design process involves taking conceptual and organizational risks and thus can facilitate group and individual innovation separately from the institutionalization of production processes.

As an alternative, Rouse suggests a strategy that combines both error reduction and error tolerance to allow the freedom to innovate (9). The key to reducing error is to predict human performance as affected by selection, training, equipment design, job design and aiding or various combinations of these interventions (10). Walter Kroner proposes an approach parallel and complementary to Rouse's, questioning the causal nature of prediction:

> The need to predict creates the need to control. Effective control means removing the uncertainty of human actions; automation with centralized control system; legislating behavior, style, or manner; and, dictating standards for health, well-being and comfort. . . . Individuals would violently object, in fact revolt, at an attempt to legislate diet, clothing, and hygiene for example. Yet, we seem to be moving toward such a life-style in order to predict performance and productivity. (11)

Understanding the differences between DW1 and DW2 is fundamental to the concept of designing productivity into an environment. In the traditional DW1 work environment of people serving machines, control of people (Kornbluh, above) and the need to predict their performance as a means of control (Kroner, above), become paramount. In the working and living environment of DW2, there is a balance between reduction and tolerance of errors (Rouse, above) to support the control of outcomes (Kornbluh, above). ***For a large and complex project like a space habitat, design management becomes the critical path; filtering the values by which designers work.***

DESIGN MANAGEMENT - Design management values change as the definition of productivity changes. People in NASA speak quite unselfconsciously about "following the system." But how does the definition of productivity inform "the system," and conversely how does the system force a particular notion of productivity? For example, in the "systematic method" approach, design managers consider it both possible and necessary to know all the design requirements for a project at the beginning of the design synthesis (12), inhibiting design research-in-action.

NASA Systems Engineering - The traditional NASA system engineering approach structures the design process into disciplines and domains, each with set of procedures laid out step by step in management manuals: requirements definition, work breakdown structure, schedule, budget, and design reviews. Presumably, a work package manager need only consult the project manual and question only specific design decisions, not the design process itself.   This situation exists in connection with many large and complex programs and is not unique to NASA or the aerospace industry.   Herbert Simon observed a similar circumstance in computer science:

> . . . we as designers, or as designers of design processes, have had to be explicit as never before about what is involved in creating a design and what takes place while the creation is going on. (13)

Participatory Design Research - An alternative to the systematic methods of DW1 is the participatory design research of DW2, which treats design as a research method to discover, make explicit and refine design criteria and requirements. Instead of inhibiting user participation and innovation by imposing from the outset, complex schedules and work breakdown structures, "inquiry by design" encourages it (14). If the scientists, scientific users and future crew members can participate effectively in space habitat design, the design process will produce a significantly different result than the present methods.

The experimental design of models, mock-ups, prototypes and other renderings is an essential component of the design research process. Since the measure and definition of productivity can change and evolve, it is essential to evaluate how a habitat or work environment design performs in terms of differing definitions of productivity.

Designing productivity into a living and working environment requires self-examination about both the design process and the definition of productivity. This definition embodies the social and economic values about the measure of human performance, that the designers bring to the design process. I will explore autonomy, democracy and teamwork as the touchstones of productivity in living and working to design into future space habitats.

HUMAN PRODUCTIVITY

Human Productivity was the buzz-word of the 1980s, but now, space human factors researchers are developing a grasp of this dimension of living and working in space. The key points of human productivity include sustained human performance, consistent accuracy and quality of the work output, sustained motivation and morale. On an exploration mission, perhaps the most important measures of productivity are more elusive: creativity, improvisation and serendipity. Designing for these human attributes requires a different process than the traditional approaches that emphasize equipment packaging and functionality.

The defintions of productivity are rooted in an economic and sociotechnical matrix. In the economic realm, the criteria derives from a measure of return on investment based on worker output. In the sociotechnical realm, the criteria derives from the quality of work life (QWL), occupational health and safety. In the sociotechnical view, the design of the products

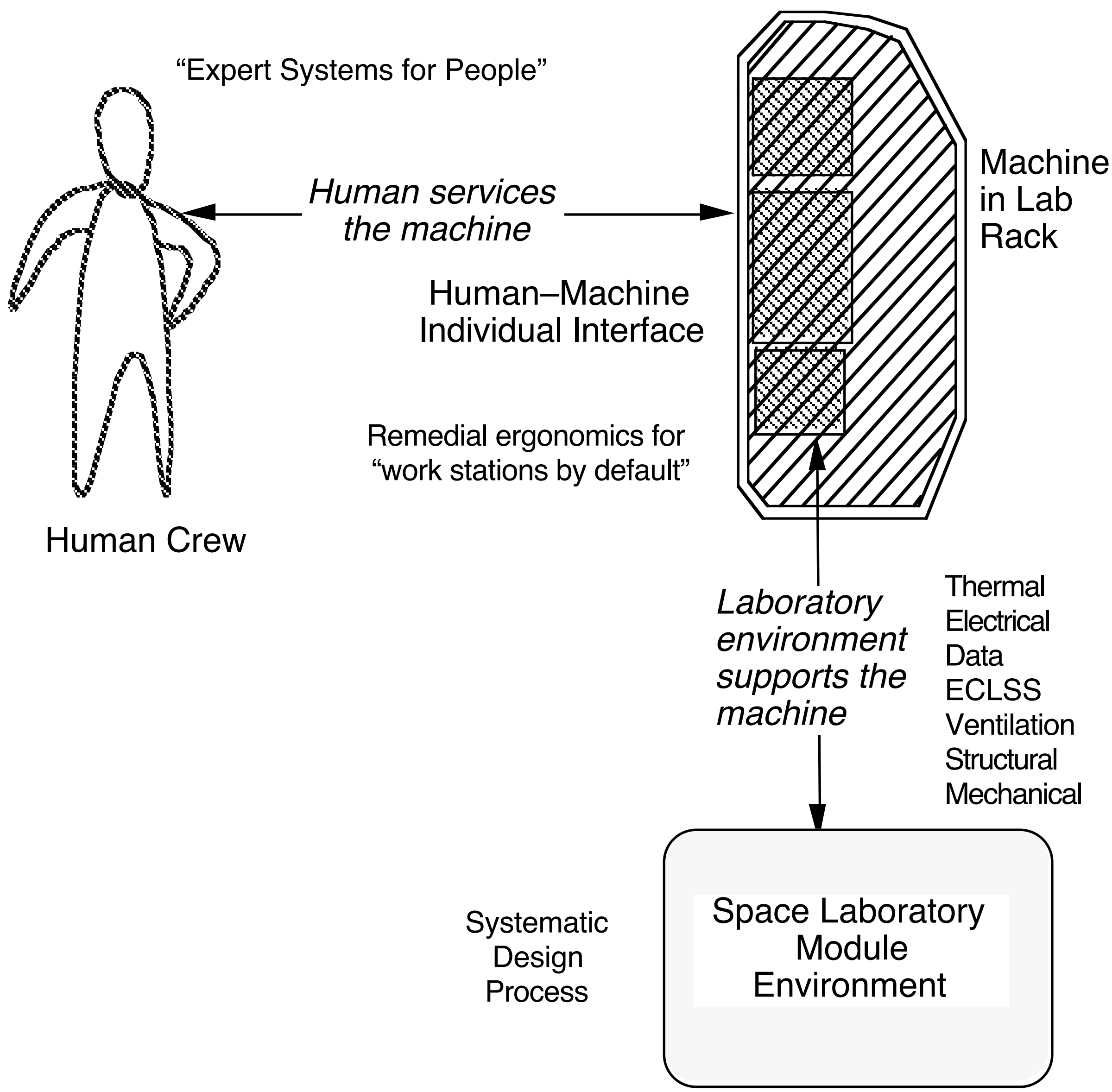

Figure 1. Traditional productivity measures: "Design World 1" design values as manifested in SpaceLab and Space Station Laboratory module design. Equipment packagingis the foremost design consideration as an ordering system for the entire habitat.

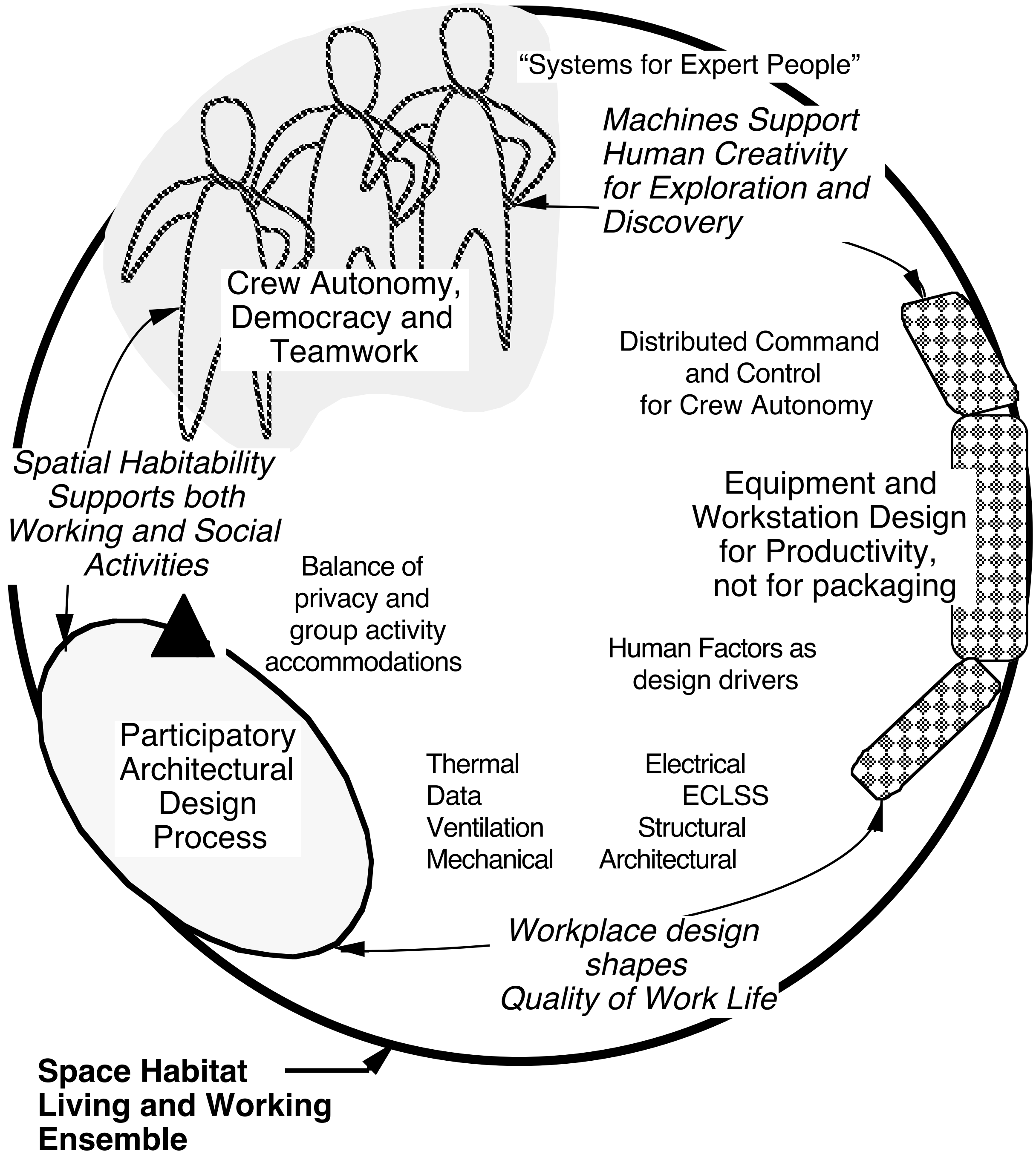

Figure 2. New Value productivity measures: Design World 2 design values for future long–duration Space Missions. Equipment design responds to multiple task, operational environment worklife — packaging is customizable to meet autonomy and teamwork needs. Both the machines and the space habitat environment support and enrich living and working in space.

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at workers produce, the design of their productive work, and the design of the workplace are linked. The measure of productivity constitutes a major part of this linkage.

MEASURES OF PRODUCTIVITY - The definition of a task as discrete or multiple, simple or complex is the key to most measures of productivity. These distinctions reflect value assumptions about human labor, performance and creativity on the job.

Taylorism - The ergonomics of Frederick Taylor embodied the earliest quantitative approach to measuring productivity (other than counting piecework or profits). Taylor proposed a system in which traditional craft work groups would be broken down to achieve greater individual efficiency, with each individual assigned to a highly specialized and repetitive task. Taylor broke each task and each motion down into its minimum parts to achieve the maximum repetitions in the work day (15). Taylor's methods achieved increases in worker output that his contemporaries considered remarkable and helped to make American industry a model for the rest of the world. These measures of human productivity are outdated and even counter-productive for today's technologies but still haunt American industry. Although many people still associate ergonomics with Taylorism, perhaps because of the productivity crisis in much of American manufacturing industry, the discipline of ergonomics evolved far beyond its origin to encompass a broad domain of human factors.

Industrial Workplace Analogue - The "Taylorization" of American industry contributed to the development of automobile assembly lines, exemplified by Henry Ford's River Rouge plant. River Rouge and other assembly plants share certain architectural characteristics: large, long buildings with undifferentiated bays, in which production engineers laid out the assembly line. The Model-T assembly line produced identical products in huge quantities, initially available in only one color - black. In the interest of "efficiency" the assembly line work life suppressed the worker's individuality, just like the products they produced. There was little or no "sense of place" in these wide-open plants. The individual's "work station" - often just a place to stand - was as impersonal and arbitrary his job.

I suggest that the present layout of the Space Station, particularly the USL Laboratory Module, is analogous to this early phase of industrial ergonomics. The "rack functional units," correspond to the bays of an assembly plant, undifferentiated except by the equipment placed in them. Utility runs determine equipment location more strongly than any other factor. There is no overarching social or functional logic for the crew, and little operational relationship between the racks. As in the auto assembly plant, the crew member situates himself or herself in front of a task station - a rack - and performs tasks largely in isolation from the tasks to either side. Even the Element Control Work Station (on which I worked with MSFC Man/Systems Integration Branch) which will monitor and control experimental equipment activities in the Lab Module, shows little interaction by proximity or design with the other task stations in the Lab Module.

Ergonomics and Human Factors - Ergonomics and human factors are part of the same productivity continuum: the real distinction involves the understanding of complexity and interaction in the work environment. They view the work environment as comprising not just discrete, separate actions, but a complex multiplicity of activities. In the United States this evolution occurred largely within the military, aviation industry and nuclear power industry. In Germany and Sweden, the industrial unions led much of the ergonomics movement in association with organizational changes in the workplace. The Japanese automakers developed ergonomics to a very high level, to make the assembler's job easier and more efficient. Their concept translates as "just in time - respect for workers," although American workers at the NUMMI plant in Fremont, CA, that runs on the Japanese management system, feel that it is mostly a means of speed-up on the assembly line (16).

Each of these work situations incorporates a corresponding measure of human performance. In the Space Station Laboratory Module, ergonomics play a predominately remedial role; to "human factor" retroactively the hardware packaging racks that became work stations by default.

<u>Task Assessment Approaches</u> - Task assessment approaches evolved with the understanding of the complexity of the work and operational environment. Connors et al present a thorough overview of several approaches to assessing human performance. They describe the limited advantages of discrete-task assessment (like Tayloristic ergonomics) that tests single measures such as arm steadiness, eye-hand coordination, reach or dexterity. But they emphasize the disadvantages of these approaches in terms of validity and transferability to the operational environment of spaceflight. Instead of the discrete- task approach, Connors et al prefer the multiple-task battery which offers a more "synthetic-work" aspect, at least for the selection and preliminary training of astronauts. However, they recognize that both task- assessment approaches fall short of meaningful measures of human performance when conducted outside of the operational environment. Instead, they advocate partial and full-scale simulation of space missions (17). However even in full-scale simulation "it is often difficult to isolate individual work units or to identify the particular environmental stressors of interest" (18). These criticisms of productivity measures apply to all operational environments because of the complex, fluid and dynamic nature of the working environment itself.

<u>Human Factors Approaches</u> - As task assessment productivity measures became less satisfactory, a new approach to human factors evolved. According to Martin Krampen, this new approach is less production-oriented to the "peripheral input and output of the human operator" and focuses more upon the perceptual and cognitive dynamics of people in the operational environment. This focus provides a basis for current "man--machine relationship models, based on psychological field theory rather than on stimulus--response theory" (19). The significance of this advance in human factors of human-machine relationships is that it may show the way towards "psychological field theory" of habitation and its relationship to productivity.

At present, most of the arguments for habitability support systems in space habitats rest on a basis that would have been familiar to Marx and Engels: that the nature of labor is to "reproduce itself" to return to work the next day. So long as such input/output models of productivity dominate habitability values, it will be difficult to design space environments that address the broader social, cultural and spiritual aspects of living in a space habitat. The Soviet architect Moisei Ginzburg first observed this contradiction in the 1920s, that productivity measurements in the workplace are different than in the home, more feasible to quantify, and perhaps not transferable at all (20). When home and workplace combine as on a space station or in a lunar base, the living environment may create new confounds for evaluating the workplace and vice versa.

In permanent lunar and planetary bases, with larger crews with tours of duty measured in years, these broader quality of life issues will make the experience worthwhile. For permanent bases on other planets, the industrial workplace analogue becomes particularly significant because the base will need to incorporate many life sustaining production functions.

<u>Job Stress and Lack of Autonomy</u> - In the auto industry, the cost to the workers from lack of autonomy is high job stress, "de-skilling" that restricts skilled craftsmen to limited tasks, and stress-related occupational illness such as heart disease (21). The alienation of the workers from the management grows from that lack of autonomy and participation. Today, the auto industry in the USA is undertaking a number of experiments in new approaches to participatory decisionmaking in the workplace.

The cost to the company from lack of autonomy is an enormous management hierarchy, comprised of foremen, first line supervisors, second line supervisors, etc. These large overheads of management people and offices reduce the overall organizational efficiency. While the automakers were profitable, these costs seemed acceptable, but as the companies lost profits to foreign competition, the companies and union began collaborating on QWL, teamwork and participation to improve productivity and competitiveness.

While the work situation of highly trained and motivated space crews differs from the large manufacturing industries with repetitive operations, the stressors may be similar. Harasek and Theorell correlate the lack of autonomy or "decision latitude" with high stress, and occupational illness (22). Conversely, increased decision latitude correlates with improved productivity and reduced absenteeism.

The key to implementing worker autonomy to enhance productivity lies in addressing the social context of work (23), particularly group activities and teamwork. A substantial body of organizational research from many industries shows the positive effects of work groups upon productivity (24), particularly in high technology industries in which the human-computer relationship often seems to take precedence over the work group (25). In both industrial and space settings, this social context involves teamwork and autonomy

<u>Serendipity and Creativity</u> - One of the most provocative statements in the space crew literature came in an anonymous interview with a pre-shuttle astronaut conducted by Bill Douglas, the Mercury 7s' flight surgeon:

> Let's ease off on the work load. Let’s let the astronomers have some time to just sit there and look through telescopes. What’s wrong with that? That’s where all the great astronomers got all their great ideas anyway (26).

This interviewee suggested a "routine- enough" approach to work load, to allow time off in case of sickness and to encourage the type of serendipity that may lead to great discoveries. Ultimately, the performance of space missions will be judged by what they discover or accomplish. If the crew is scheduled down to the last minute of every day, as on Skylab and SpaceLab, they may not have time to make the observations that lead to important discoveries. Tight scheduling militates against opportunities for creativity.

In this respect, NASA space crews resemble assembly workers; despite the variety of their tasks, they are rarely in control of scheduling or task decision-making. The crew of Skylab IV even staged a "slow-down" or "strike" over the furious pace of computer driven task scheduling (27). Karasek and Theorell point out that most attempts at reducing work-related stress for both executives and workers are "individual-oriented:" diet, exercise, meditation, recreation, etc. While these measures have their place in space as well as on the ground, they fall far short of the design values that would lead to workplace changes in human productivity.

New Value scale of Productivity - As an alternative to traditional output-oriented measures of productivity, Karasek and Theorell propose a New Value for measuring productivity. This scale focuses on the people in the work environment rather than the products they produce. New Value measures include:

1. *Unlike economic value, New Value is not "zero-sum."* . . . Education, learning, skill-enhancement, enrich the work experience.
2. *New Value creates desirable new needs, rather than satisfying biological needs.* . . . The needs for new learning, stimulation, higher quality.
3. *New Value is process-oriented, not product oriented.* . . . Feedback processes from the user to the worker, not parts-added but a system-oriented approach to desirable combinations of components.
4. *New Value reflects long-term, rather than short-term, value.* . . . Growth of capabilities and skills. Not planned obsolescence but planned reliability and quality.
5. *New Value resides in the person, not in the object.* . . . . Producing New Value involves adding value to a person or to an organization. [original emphasis](28)

New Value measure of productivity signifies an approach to viewing work life as sustaining and enhancing the overall quality of life, rather than being the primary source of chronic stress. It also suggests an "unpriced value" system on personal and professional development that would encourage they type of serendipity and personal development needed for future space missions.

SPACE HABITATS AND HABITABILITY

Space Habitats are the environments in which people live and work in space, both in space vehicles and planetary bases. However, systems engineers define the habitat too narrowly, as in the case of the Space Station Freedom, with its "habitability module" and "laboratory module." This nomenclature suggests, unfortunately, that only the living quarters need to be "habitable." Actually, the entire "shirt sleeve environment" comprise a total habitable domain, all of which demands the designers' attention.

HABITABILTY - Through Yvonne Clearwater's initiative, the Space Human Factors Office at NASA-Ames defined habitability as:

> A measure of the degree to which an environment promotes the productivity, well-being, and situationally desirable behavior of its occupants.

"Well-being and situationally desirable behavior" come close to the traditional domain of architects. Relevant and effective architectural design requires an understanding of these concepts. For a compendium of habitability concerns and functional relationships, see Tullis and Bied (29).

Habitability has significant spatial characteristics, which Wise et al. conceive as visual, kinesthetic and social logic (30). Two of the most important aspects of habitability are privacy (31) and group activities (32) accommodations. Research in the isolated and confined environment of Antarctica (33) as well investigations of personal space (34) both suggest that the best way to support these aspects of habitability is through architectural design of a spatially and socially flexible environment.

Habitability and Productivity - The linkage of habitability to productivity is important because traditional system engineering approaches view habitability as a cost to conduct business; the business of operating the engineering systems, rather than as a benefit of those engineering systems. Gillan et al draw an analogy between habitability as the quality of life and productivity as the quality of work, (35). A vital link exists between habitability and the astronaut's response. Sometimes a single negative comment will send a whole design group scurrying, while a single positive comment may cement a design decision into place. What record does NASA keep of these responses? How much weight should the other reviewers give to a remark from any individual who may attend just one meeting out of a whole series? Do these responses constitute an official position of the Astronaut Office?

On the basis of research in "parallel organizations" engaging in design participatory practices, Neal Herrick presents 34 hypotheses, of which the first 3 relate directly:

1. The fewer design features decided prior to the formation of a design committee, the greater will be the acceptance of the parallel organization.
2. The more the design committee meets representative criteria, the greater will be the acceptance of its work.
3. The more communication which occurs between the members of the planning committee and their constituents, the greater will be their acceptance of its work. (38)

Clearly, NASA needs further refinement in the ways that researchers, designers and crew members participate in the design process. But for very long range programs, the design research may occur before the prospective crews become astronauts. One hope is to accelerate the design-develop-build process for space vehicles (compared to the present space station, which under various rubrics has been in process for about 11 years) so that the crews can participate in their design.

Architectural Design for Teamwork - A step toward achieving the shift to New Value in productivity through teamwork is to design the working and living environments to support these teams. Sweden is probably most advanced in teamwork and worker democracy. Volvo's conventional assembly line plants were not adaptable to the new teamwork approaches. Volvo has built two assembly plants, at Kalmar and Uddevalle that emphasize identifiable and communal work places for each of the worker teams, with considerable success. Each team of 10 to 15 has its own work area. At Kalmar, the vehicles come to the work area on an automatically guided vehicle platform and the team performs a complex sub-assembly task. At Uddevalle, each team produces an entire vehicle in a garage-like environment, an ideal arrangement for producing vehicles with many options (39).

The work of a space crew team is more similar to the Uddevalle arrangement of teamwork for variability than to the assembly line's repetitive operations. Brady and Emurian's behavioral research on small groups in simulated isolation and confinement confirms the positive impact of cooperation upon productivity compared to "non-cooperative conditions," involving one or more "social isolates" (40).

Cooperation has become a key issue in industrial environmental design for teamwork, extending to the superstructure of labor relations. Neal Herrick found "the specific design characteristics of joint participative systems should be collectively bargained and enforced as part of the labor contract" (41). Envision a future generation of space crews that demands a larger role in designing their working and living conditions as a contractual part of their job descriptions. This joint participative system would cast aside the conventional design for hardware in favor of design for the crew team that will operate that equipment.

Although designing productive teamwork into the working environment is an immediate challenge for the measure of human performance, a more acute design challenge is to create a habitat that encourages cooperation and teamwork without infringing upon individual autonomy, personal space or privacy. While it is possible to circumscribe the working environment to the laboratory modules and nodes, the habitability needs of the crew apply to the total spatial envelope.

DESIGN FOR CREW AUTONOMY - Another parallel between assembly workers and space crews is the immense management hierarchies associated with each endeavor. Early in the Space Station Program, the Space Station Task Force hoped to achieve an order of magnitude increase in crew autonomy, thereby reducing both the "cast of thousands" on the ground at Mission Control and the program operating costs, freeing many NASA people for activities more productive than just maintaining the Space Station on orbit (42).

Distributed Command and Control - To change mission control from business as usual, the Space Station would require a change of design value. Instead of the "Captain Kirk on the bridge of the Starship Enterprise" model of command and control systems (the CCWSs currently are in the nodes), the "bridge" would be distributed in each of the modules. The station commander (if there is one) would be free to move about the station and perform other tasks, never more than 7 meters from from a CCWS. Obviously, this autonomy would require significant increases in automation and refinements in the human-machine interfaces. The interior architecture could facilitate this distributed system, perhaps with virtual imaging, by transcending the conventional rack-based notion of a work station to create a work environment suited to the CCWS tasks.

Participation in the Workplace - Worker autonomy and teamwork has also accompanied increased automation and robotics in auto assembly plants. Worker teams operate out of team stations that support a team of 5 to 15 workers. At the Buick-Oldsmobile-Cadillac Division plant in Hamtramack, MI, the team station may include a close circuit TV, office, telephone, refrigerator, picnic table and other amenities, enclosed in a portable office structure in high-noise areas (43); an autonomous space habitat may need comparable amenities in the working areas. But worker teams are not satisfied with just focusing on the production work and working conditions. Real participation means a voice in higher-level decisions (44). After the Challenger tragedy, the astronauts took a much more active role in making NASA policy. Eventually this role may extend to the whole design of long duration missions.

Long Duration Mission Autonomy - In addition to amenities in the work environment, space crews on long duration missions would also expect a voice in decision making, especially in the case of a Mars Base with a typical 20 minute interval between "communication monologues." This time lag would aggravate the kind of tension that occurs on SpaceLab:

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