# Using Linear Programming to Optimize Control Panel Design from an Ergonomics Perspective

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Linear programming (LP) for optimization of control panel layouts has been incorporating ergonomic constraints into models to reduce reaching distances required for control panel use since the 1960's. These algorithms have used a panel's frequency of use, distance from user, and transition distance as basic model variables. A new variation of the LP model for control panel design is proposed that modifies the layout from single point semidry to dual point semidry in terms of design using anthropometrics. The proposed model was applied to the design of a twelve-panel board of six-inch square panels. The model was able to take into account design factors such as control sequence, alignment, and clustering, as well as direct hand access. The resulting control panel solution minimized the reach and movement distances required by an operator. Results suggest that LP optimization can be used to construct "ergonomically designed" control panels that limit MSDs incidence and severity.

## INTRODUCTION

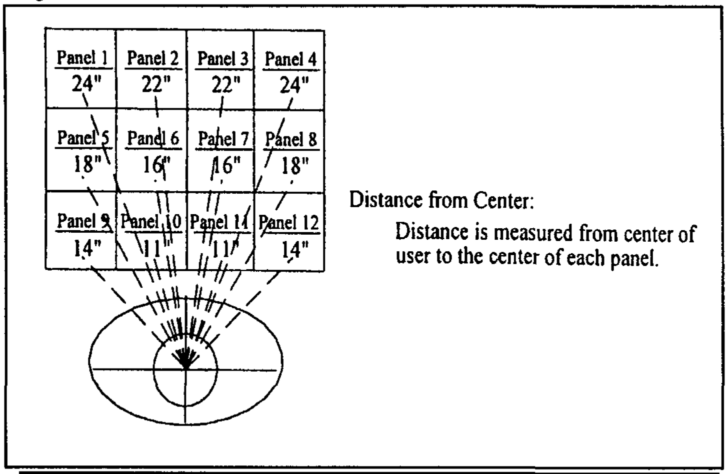
Workplace injuries from mechanical stress are one of the leading causes of illness and absenteeism in industry. Musculoskeletal disorders (MSDs) are a direct result of these stresses on the body due to repetitive actions, awkward postures, and cumulative task loading or exertion. Many MSDs such as carpal tunnel syndrome and tendonitis are caused or complicated as a result of poorly designed workstations. The result is decreased output with increased overhead in the form of employee absenteeism, employee turnover, training, workman's compensation claims, and medical treatment.

Linear programs written in the last twenty years for the optimization of control panels have been primarily based on Freund (1967). Freund, who applied a distance minimization function to a cockpit layout, used an instrument's dimensions, frequency of use, and distance from origin or each other as design constraints. Later work modified the distance variable by applying basic ergonomic principles to more robust models (Bonney & Williams, 1977) (Sargent et al, 1997). They limited the total distance moved by centering the origin on the user. The effect was reduced repetitive motion and distance traveled in sequenced task, effectively increasing efficiency. However, these models still lacked the ability to conform to the biomechanics of human movement. This paper will attempt to look at changing control panel layout by introducing a dual point design based about the axis of rotation, extension, and flexion of the user. Anthropometric data from an anthropometric survey of U. S. Army personnel (Gordon, 1989) will be used. Biomechanical and ergonomic criteria will be employed based on information from the Rapid Upper Limb Assessment technique (McAtamney et al, 1993), an ergonomic risk factor checklist for the upper extremity (Keyserling et al, 1993), and joint postural angles (Aaras et al, 1988).

## METHODOLOGY

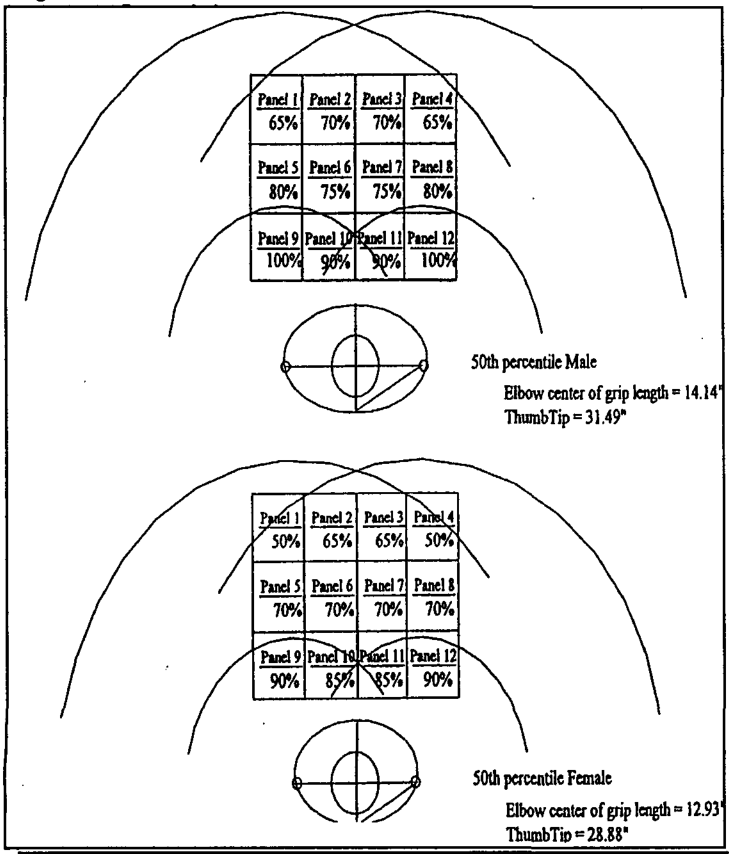
*Procedure.* Upon analysis of previous LP models, the ergonomic modification made by each technique was effective in minimizing distances traveled but still had problems with postural changes dealing with biomechanics of human motion. The panel layouts were designed with a single arc range from the center using distances from an operator's origin, figure 1. The layout shown is a 12-panel control with 6-inch square positions. The number within each square represents the sequencing of the positions. The operator is situated 2 inches from the control panel, centered. The control panel is on a horizontal plane with no angular tilt.

Figure 1.




In figure 2, you can see a biomechanical model taking into account a human's arm and hand movements about their axis of rotation, extension, and flexion of the shoulders and elbows. Reach arcs are displayed for a 50$^{th}$ percentile male and female. Data was taken from 1988 military anthropometric tables (Gordon, 1989). It is important to note that military anthropometric data is not representative of the general population.

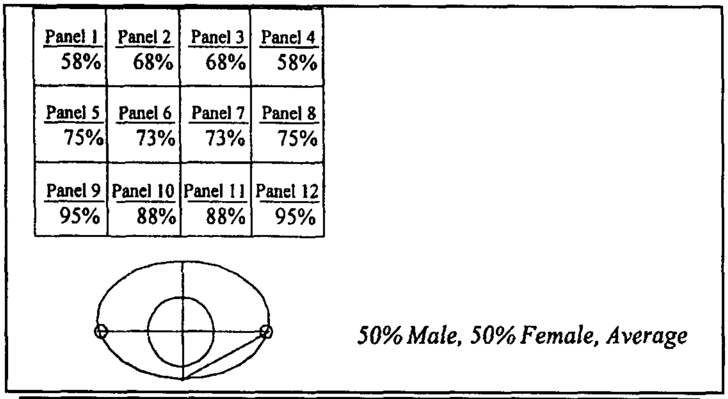
Figure 2.




In order to compare figures 1 and 2, a linear programming minimization model has to be explained. A minimization model looks for the smallest cost values for sequencing in order to become optimal. Since the cost is a relative index of an instrument's frequency of use multiplied by the distance from origin (user), the model will isolate the high frequency values with the small distances. This would normally be a good thing; however, in the current model, figure 1, the smallest distances are panels 10 and 11. If you look at panels 10 and 11 in the biomechanical model, figure 2, you will see that both panels are in optimal positions for multi-hand use, but they are not optimal for single hand use. The optimal positions for single hand use are panel 9 for the left hand and panel 12 for the right hand. This is shown by the effective use percentage derived from the reach arcs within each position.

The arcs represented in the model are products of Elbow-Center(Grip Length) and Thumbtip Reach. The overall model was formed using the following anthropometric data: Biacromial Breadth, Chest Depth, Elbow-Center(Grip Length), Sleeve Length, Spine-Scye, and Thumbtip Reach (Gordon, 1989). A biomechanics perspective of the Elbow-Center arc shows that it requires nominal shoulder movement with rotational elbow and wrist movement. Using Rapid Upper Limb Assessment (RULA) as a base guideline (McAtamney, 1993), the arch area was evaluated to be the most effective in limiting movement while performing a task, 100% effective use. Applying the same criteria to the Thumb Reach arc, it was found to be 70% effective with anything falling outside of this range being rated no higher that 30% effective. The effectiveness of an area was based on its direct accessibility. The positions were then evaluated based on these arc areas to determine their individual effectiveness for both 50$^{th}$ percentile males and females. An average was taken with the results in figure 3. It is important to note that in an actual workstation layout you would use data relative to the specific problem and user population. Combinations of data are not uncommon depending on your user population dynamics, such as gender and/or ethnicity.

Figure 3.




This data then allows for the modification of the distance value. The adjusted distance value, ΔB, will then be representative of the loss of effective travel distance for both multi-hand use (the original distance), and single hand use (the effective use percentage). ΔB is calculated by multiplying the original distance by the percentage of effective loss for each position. The percentage of effective loss is used here because the overall problem is to minimize the ineffective travel distance in the model. This changes the model by now making it a minimization of lost effective ergonomic workspace relative to an instrument's frequency of use. The resulting ΔB's in table 1 re-align the grid positions representative of biomechanical restraints.

Table 1.

| Position | Male/Female Averages | Minimize Function (loss) | Distance Moved | Adjusted Distance (DB) |
|---|---|---|---|---|
| 1 | 58% | 43% | 24 | 10.2 |
| 2 | 68% | 33% | 22 | 7.8 |
| 3 | 68% | 33% | 22 | 7.8 |
| 4 | 58%` | 43% | 24 | 10.2 |
| 5 | 75% | 25% | 18 | 6.0 |
| 6 | 73% | 28% | 16 | 6.6 |
| 7 | 73% | 28% | 16 | 6.6 |
| 8 | 75% | 25% | 18 | 6.0 |
| 9 | 95% | 5% | 14 | 1.2 |
| 10 | 88% | 13% | 11 | 3 |
| 11 | 88% | 13% | 11 | 3 |
| 12 | 95% | 5% | 14 | 1.2 |

The console in this model was used to operate a remote unit in a radioactive containment facility. The remote unit is powered by battery and has hydraulic controls with an extending mechanical arm fitted with a hydraulic clamp. The console panel has the following list of instruments and switches.

Table 2.

| Item | Symbol | Frequency of Use | Description |
|---|---|---|---|
| Keyboard | K | 4.0 | Direction Control Keypad |
| Joystick | J | 3.0 | Mechanical Arm Control |
| Outer Door | OD | 2.0 | Exterior Containment (Open) |
| Interior Door | ID | 1.5 | Primary Containment (Open) |
| Cameras | C | 5.0 | Keypad Camera Selection |
| Monitor (I) | RM | 1.0 | Radiation Monitor |
| Monitor (II) | TM | 1.0 | Thermal Monitor |
| Switch (I) | TI | 1.5 | Remote Unit Main Power |
| Switch (II) | TII | 1.5 | Remote Unit Hydraulic Pump |
| Switch (III) | TIII | 2.5 | Hydraulic Clamp (Open) |
| Main Shutdown | ES | 0.1 | Emergency Shutdown/Seal-Off |
| Main Override | EO | 0.1 | Emergency Shutdown Override |

The instruments listed here are of varying size and shape. This will not impact the current layout or linear model being used due to set and equal grid sizes. However, it is important to note that this will not always be the case. The cost coefficients for the model were calculated by multiplying the frequency ratio of instruments times the adjusted distance value, ΔB, with the results listed in table 3.

Table 3.

| | | Postion | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| | Frequency | Distance Variable, ΔB | | | | | | | | | | | |
| Instrument | Ratio | 10.2 | 7.8 | 7.8 | 10.2 | 6 | 6.6 | 6.6 | 6 | 1.2 | 3 | 3 | 1.2 |
| K | 4.0 | 40.8 | 31.2 | 31.2 | 40.8 | 24.0 | 26.4 | 26.4 | 24.0 | 4.8 | 12.0 | 12.0 | 4.8 |
| J | 3.0 | 30.6 | 23.4 | 23.4 | 30.6 | 18.0 | 19.8 | 19.8 | 18.0 | 3.6 | 9.0 | 9.0 | 3.6 |
| OD | 2.0 | 20.4 | 15.6 | 15.6 | 20.4 | 12.0 | 13.2 | 13.2 | 12.0 | 2.4 | 6.0 | 6.0 | 2.4 |
| ID | 1.5 | 15.3 | 11.7 | 11.7 | 15.3 | 9.0 | 9.9 | 9.9 | 9.0 | 1.8 | 4.5 | 4.5 | 1.8 |
| TI | 1.5 | 15.3 | 11.7 | 11.7 | 15.3 | 9.0 | 9.9 | 9.9 | 9.0 | 1.8 | 4.5 | 4.5 | 1.8 |
| TII | 1.5 | 15.3 | 11.7 | 11.7 | 15.3 | 9.0 | 9.9 | 9.9 | 9.0 | 1.8 | 4.5 | 4.5 | 1.8 |
| TIII | 2.5 | 25.5 | 19.5 | 19.5 | 25.5 | 15.0 | 16.5 | 16.5 | 15.0 | 3.0 | 7.5 | 7.5 | 3.0 |
| C | 5.0 | 51.0 | 39.0 | 39.0 | 51.0 | 30.0 | 33.0 | 33.0 | 30.0 | 6.0 | 15.0 | 15.0 | 6.0 |
| ES | 0.1 | 1.0 | 0.8 | 0.8 | 1.0 | 0.6 | 0.7 | 0.7 | 0.6 | 0.1 | 0.3 | 0.3 | 0.1 |
| EO | 0.1 | 1.0 | 0.8 | 0.8 | 1.0 | 0.6 | 0.7 | 0.7 | 0.6 | 0.1 | 0.3 | 0.3 | 0.1 |
| TM | 1.0 | 10.2 | 7.8 | 7.8 | 10.2 | 6.0 | 6.6 | 6.6 | 6.0 | 1.2 | 3.0 | 3.0 | 1.2 |
| RM | 1.0 | 10.2 | 7.8 | 7.8 | 10.2 | 6.0 | 6.6 | 6.6 | 6.0 | 1.2 | 3.0 | 3.0 | 1.2 |

The constraints established for this problem deal with several issues, especially human factors. Sequenced controls need to be arranged in order of use to prevent awkward movements. Clustered controls are another concern. These are controls, which are operated together but in different sequences and carry the same type of concerns. Alignment controls, such as one needing to be on the left side of the console or maybe aligned down the right edge are another consideration. The most difficult are controls that need right hand access, left hand access or both. These are unique to this problem. Left hand access will be limited to positions 1,2,5,6,7,9,10,11 due to angle and reach access for someone sitting in an erect stationary posture. The right hand access will be limited to 3,4,6,7,8,10,11,12. Dual hand access will be the mutual positions within the two sets. The linear program model will then be coded for Lingo 7.

*Analysis.* The objective function for the linear programming model is based on the console layout of 3 rows and 4 columns. This gives 12 possible locations. There are 12 components/instruments listed within the problems giving 479,001,600 possible control panel configurations, 12!. Panel locations times number of components yields 144 decision variables, $X_{ij}$, each with a corresponding cost variable, $C_{ij}$. These binary decision variables, $X_{ij}$, determine placement of an instrument to a panel and are defined as:

$$X_{ij} = 1 \text{ ;when the component i is placed in position j where } i= 1,2,\ldots,12 \ \& \ j= 1,2,\ldots,12$$
$$= 0 \text{ ;when no placement has occurred}$$

The cost variable, $C_{ij}$, can be thought of as an assessment, penalty, or fee for placing control i in position j and is defined as:

$$C_{ij} = \text{the frequency of component's use, i, multiplied by the distance value of } \Delta\beta, \text{j.}$$

The objective function's goal within the context of the console problem will be to minimize the cost; therefore, limiting the amount of distance traveled outside of ergonomically effective workarea. The objective function is defined as:

$$\text{Minimize } \sum_{I=1}^{12}\sum_{j=1}^{12} C_{ij} * X_{ij}$$

There are two basic constraints for a console problem model. One is that each position may only contain one component/instrument.

$$\sum_{i=1}^{12} X_{ij} = 1 \quad \text{where } j= 1,2,\ldots,12$$

The second is that each component/instrument may only occupy one position.

$$\sum_{j=1}^{12} X_{ij} = 1 \quad \text{where } i= 1,2,\ldots,12$$

*Constraints.* The specific constraints for this console problem are as follows:

*Control Alignments:* Controls that must be aligned specifically to the right or left hand side of the control panel. Controls are: 12 key numeric entry, directional control keypad, joystick, and emergency shutdown push button.

*Sequenced Controls*: Controls that must be assessed in a given sequence. Controls are: remote unit activation and the remote unit hydraulic pump switch.

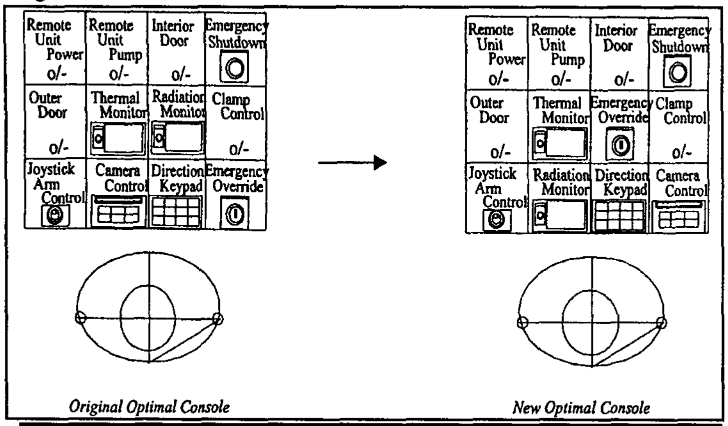
*Hand Access Controls*: Controls that must be aligned specifically for right or left hand use or so that simultaneous use of may occur. Controls are: 6-way camera control, hydraulic clamp, remote unit activation, and radiation and thermal readouts and acknowledgement switches.

*Cluster Controls*: Controls that are accessed in varying sequences that require maximum proximity to each other. Clustered controls are: the 6-way camera control, 12 key numeric entry, directional control keypad, and Joystick; the emergency override, thermal monitor, and radiation monitor.

## RESULTS

The resulting design change is shown in figure 4:

Figure 4.




Comparison of the new solution to the original solution is as follows: The new layout produced by the linear model is an improvement with loss reducing from 106.7 to 98.6. It has placed the camera controls in the optimal right hand position with the joystick controls in the optimal left hand position. The directional keypad has been placed in an optimal dual hand position with the thermal and radiation monitors placed in the user's direct line of sight. The emergency override has been positioned directly to the left of the thermal monitor. The remote unit activation switches have been placed side by side in sequence from left to right with left hand access in mind. And for the majority right-handed population, the emergency shutdown button has been placed in the far right hand corner for quick and easy access, but as not to interfere with daily routines.

## DISCUSSION

The overall effect of this layout seems to be positive. The linear model was able to minimize the loss function in terms of distance; therefore, maximizing the use of ergonomically effective space by providing a fluid transition between components. The overall effect appears to provide a more ergonomically friendly environment to its user while keeping job productivity at the forefront. The next step would be to test the solution against current models for efficiency and user preferences. The ergonomic impact on this is more difficult to evaluate because it is measured over time. But from a biomechanics standpoint, this model should limit a user's exposure to repetitive and/or awkward postural movement; therefore, decreasing job injuries attributed to MSDs, reducing incidence and severity. However, limitations when looking at actual workplaces are: not all consoles will have zero angular tilt, the size and shape of components can influence model outcomes, not all data/facts maybe known, and some panels may allow for multiple components per position or more positions than components.

## CONCLUSION

The reconfiguring of the control panel about the axis of rotation of the shoulders has shown an improvement of better than 7% by reducing ineffective movement from 106.7 to 98.6. However, these numbers are theoretical and the evaluation of the application of the applied anthropometrics through linear programming to design control panel layout should be additionally evaluated with time study and user preference model to determine the actual overall effect of the process.

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