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ANTHROPOMETRIC DESIGN OF WORKSTATIONS

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ABSTRACT

In this study, the use of AD was demonstrated for anthropometric design of workplaces. Two examples explore how the formulation of Functional Requirements and Design Parameters can help in conceptualizing design principles and selecting design parameters for a seated work place. To improve the ease of adjustability the *Independence Axiom* was used to formulate functional requirements with respect to adjustability, and select suitable design parameters. Two case studies were used to illustrate how the methodology can be used to improve design solutions. The results show that use of height adjustable chairs is not necessarily a good design solution. *The Information Axiom* was then used to calculate the information in adjustability features. This involved a redefinition of the concepts of system range and design range, which are used in AD, and resulted in a modified calculation of information contents. The two axioms fit well with the type of design methodology that has developed in ergonomics over the years. 1. It has been well recognized that formulations of functional requirements are essential to ergonomics design. AD now gives a robust methodology, which may drive design solutions. 2. In Ergonomics design, minimization of information has long been recognized as an important criteria; this is expressed through Fitts' law and Hick's law. The less the information the quicker it is to operate and the easier it is to learn.

Keywords: anthropometry, workstation design, Fitts' law, Hick's law

1 INTRODUCTION

The primary goal of Axiomatic Design is to establish a systematic foundation for design activity by two fundamental axioms and a set of implementation methods (Suh, 1990). The axioms are:

Axiom 1: *The Independence Axiom*: Maintain the independence of functional requirements.

Axiom 2: *The Information Axiom*: Minimize the information content in design.

The first axiom advocates that for a good design, the DPs should be chosen so that each FR is satisfied by only one DP. Thus the number of FRs and DPs is equal. The best design has a strict one-to-one relationship between FRs and DPs. This is called an uncoupled design. This mapping between FRs and DPs is represented by a design equation:

$$\{\boldsymbol{FR}\} = [\boldsymbol{A}]\,\{\boldsymbol{DP}\} \qquad (1)$$

where $\{\boldsymbol{FR}\}$ is a column vector that contains all the FRs of the design,

$\{\boldsymbol{DP}\}$ is a column vector that contains all the DPs of the design, and

$[\boldsymbol{A}]$ is the "design matrix" that defines the relationships between the design parameters and the functional requirements.

With an equal number (n) of FRs and DPs, $[\boldsymbol{A}]$ is a square matrix of size n x n, which measures the effect of DP_j on FR_i. If the DP influences the FR, this element is non-zero. Otherwise it is zero. The independence axiom is satisfied for an uncoupled design matrix $[\boldsymbol{A}]$ having all non-zero elements on its diagonal, indicating that the FRs are completely independent. However, complete uncoupling may not be easy to accomplish in a complex real world, where interactions of factors are common. Designs where FRs are satisfied by more than one DP are acceptable, as long as the design matrix $[\boldsymbol{A}]$ is a triangular, that is, the non-zero elements occur in a triangular pattern either about or below the diagonal. This is called a decoupled design. A decoupled design still satisfies the independence axiom, provided that the DPs are specified in a sequence such that each FR is ultimately controlled by one unique DP. Any other formation of the design matrix that cannot be transformed into triangular one represents a coupled design, indicating the dependence of the FRs. Therefore, the design is unacceptable, according to Axiomatic Design.

The Information Axiom provides a means of evaluating the quality of designs, thus facilitating a selection among available design alternatives. This is accomplished by comparing the information content of the several designs in terms of their respective probabilities of successfully satisfying the FRs. Information content is defined in terms of entropy, which is expressed as the logarithm of the inverse of the probability of success p:

$$I = \log_2 \frac{1}{p} \qquad (2)$$

In the simple case of uniform probability distribution, the above equation can be written as:

$$I = \log_2 (\text{System Range}/\text{Common Range}) \qquad (3)$$

where, System Range is the capability of the current system, given in terms of tolerances, Common Range refers to the amount of overlap between the Design Range and the system capability, and Design Range is the acceptable range associated with the DP specified by the designer, see Figure 1.

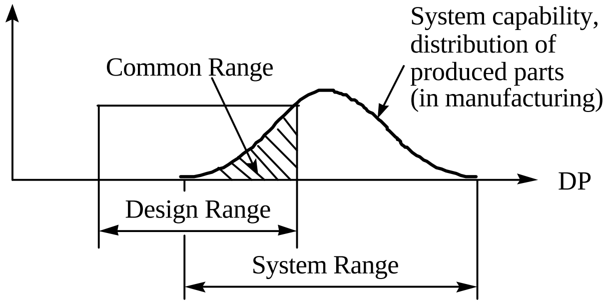

Figure 1: Definition of Design Range, System Range and Common Range for the Calculation of Information Content

By definition, the total information of a design for *n* FRs is given by the sum of the information content calculated for each FR, including any conditional probabilities: All alternative designs are compared by their total information content; and the design chosen is the one with the minimum amount of information. Below we provide two examples of axiomatic design for design of sitting workplaces.

2 ERGONOMICS DESIGN

In anthropometry human body dimensions are used to design artifacts. The general principle is that the artifact must fit the size of the human body (Helander, 1995). But operators or users vary in size. Percentiles of body measures are commonly used to represent variability - from 5th percentile small size to 95th percentile large size. Several different body measures are used for design purposes, such as stature, sitting eye height, sitting elbow height, forward reach, lower leg length, and so forth. These measures are listed in anthropometric tables for various populations – civilians, men/women, U.S. Air Force pilots, and so forth. It would be too expensive to design for dwarfs and giants, therefore the 5th to 95 th range is commonly used for design. There are many anthropometric design guidelines and they are commonly used for design of airplane cockpits, automobile compartments, chairs and workplace arrangements (Helander, 1995). Below we give examples of two design scenarios, the first one is a design of a driver's compartment and the second one is a design of a workstation for microscopes.

2.1 Design of adjustability in a driver's compartment

To design a driver's compartment reach distances are usually dimensioned for 5th percentile small user (large persons can overreach) and clearance dimensions for 95th percentiles large users (small persons can always fit). There is a choice between different types of adjustments. a. *Seat adjustments* that position the driver's seat in an advantageous position and b. C*ar adjustments* that make the interior design of the car adjust to the person. An example of the latter is a steering wheel that can be pulled out or pushed in.

For a design of a driver's compartment the top-level FR1 and FR2 and the corresponding DP1 and DP2 are given in Table 1. The top level FRs and DPs are then decomposed and their constraining influences are used to derive FRs and then suggest DPs and at a lower level of abstraction: Given the top goal FR 1 - to make it easy to manipulate controls, and given that we have decided to put controls within easy reach (DP 1), we may then proceed to formulate FR11 and FR12 at a lower level of abstraction and propose DP 11 and DP 12, see Table 1.

Similarly, given the constraining influence of DP2 Ergonomics Design, FR2 is expanded at a lower level of abstraction into FR21 – FR24. The selected design parameters DP11 through DP 24 are commonly found in vehicles.

Table 1. FRs and DPs for design of a driver's compartment. First Iteration.

FR1	Easy to Manipulate Controls	DP 1	Controls within Easy Reach
FR 2	Comfortable Sitting	DP2	Ergonomics Design
FR 11	Reach Dashboard Controls	DP 11	Dashboard Close
FR 12	Reach Pedals	DP 12	Forward/Backward Seat
FR 21	Clear Steering Wheel	DP 21	Push/Pull Steering Wheel
FR 22	Reach Floor (with feet)	DP 22	Up/Down Seat Height
FR 23	Clear Roof	DP 23	High Roof
FR 24	Comfortable Sitting	DP 24	Adjustable Backrest Angle

We may then derive the design equation as in equation (4).

$$\begin{bmatrix} FR_{11} \\ FR_{12} \\ FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{bmatrix} = \begin{bmatrix} A_{1111} & 0 & A_{1121} & A_{1122} & 0 & 0 \\ A_{1211} & A_{1212} & 0 & 0 & 0 & A_{1224} \\ A_{2111} & 0 & A_{2121} & 0 & 0 & A_{2124} \\ 0 & 0 & 0 & A_{2222} & 0 & 0 \\ 0 & 0 & 0 & A_{2322} & A_{2323} & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{2424} \end{bmatrix} \begin{bmatrix} DP_{11} \\ DP_{12} \\ DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{bmatrix} \qquad (4)$$

The design matrix in equation (6) indicates a coupled design, and it is therefore not a satisfactory solution. It is difficult for the driver to use the adjustability features. The driver can first set DP 22 and DP 24, which are independent. DP 23 is then feasible to adjust. However, DP 11, DP12 and DP 21 are coupled, which makes it difficult to make the adjustments so as to reach the floor, reach the dashboard and clear the steering wheel.

Second design iteration. For the second design iteration we used a car with DP12 Adjustable Length Pedals and DP23 Adjustable Roof. These are much more unconventional design solutions than what we used above: Adjustable Seat Forward/Backward and High Roof. The following solution is obtained see Table 2. The design equation is given in (5).

Table 2. FRs and DPs for design of a driver's compartment. Second iteration.

FR1	Easy to Manipulate Controls	DP 1	Controls within Easy Reach
FR 2	Comfortable Sitting	DP2	Ergonomics Design
FR 11	Reach Dashboard Controls	DP 11	Dashboard Close
FR 12	Reach Pedals	DP 12	Long/Short Pedals
FR 21	Clear Steering Wheel	DP 21	Push/Pull Steering Wheel
FR 22	Reach Floor (with feet)	DP 22	Up/Down Seat Height
FR 23	Clear Roof	DP 23	Up/Down Roof
FR 24	Comfortable Sitting	DP 24	Adjustable Backrest Angle

$$\begin{bmatrix} FR_{11} \\ FR_{12} \\ FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{bmatrix} = \begin{bmatrix} A_{1111} & 0 & A_{1121} & 0 & 0 & 0 \\ 0 & A_{1212} & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{2121} & 0 & 0 & A_{2124} \\ 0 & 0 & 0 & A_{2222} & 0 & 0 \\ 0 & 0 & 0 & A_{2322} & A_{2323} & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{2424} \end{bmatrix} \begin{bmatrix} DP_{11} \\ DP_{12} \\ DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{bmatrix} \qquad (5)$$

This is a de-coupled design, and therefore acceptable. For the operator it is however still difficult to learn the sequence of operation of the different adjustabilities. In this case DP12, DP22 and DP 24 must be dealt with first, followed by the other adjustments. Assume a driver will first adjust either the Backrest Angle (DP24) considering Comfort, Chair Height (DP22) to reach the floor, or Pedal Length DP12 to reach the pedals. Having finished these adjustments he can then set DP23 – the height of the roof, DP11- Move the Dashboard close, and set the Steering Wheel DP21 to accommodate his large stomach.

The design matrix may represent a simplified representation of some of the user requirements. FR 24 - Comfortable Sitting, is assumed to be accomplished by a single design parameter, DP 24 – Adjustable Backrest Angle. From a biomechanics perspective this is indeed the most important variable, since a large hip joint angle reduces the compressive force in the spine (Helander, 1995). We could also have considered additional design parameters, such as Adjustable Length Seat Pan. Fifth percentile users need a short Seat Pan to reach to the backrest with their back, whereas 95th percentile users need a long Seat Pan to support their thighs. An Adjustable Seat Pan would also affect some of the other FRs. Although this design solution was not explored here, it would be worthwhile to consider this and other design parameters.

Obviously the second design iteration with Long/Short Pedals produced a more satisfactory design than Forward/Backward Seat. The first design, although it is the conventional design found in all cars, creates unwanted couplings, which may be difficult to deal with for the user.

Third design iteration. Guided by the results of in Equations (4) and (5) we may suggest an uncoupled, albeit unconventional design: Dashboard controls on steering wheel (DP11), Adjustable length pedals (DP12), Push/pull steering wheel (DP21), Height adjustable floor (DP22), High Roof (DP23) and Adjustable backrest angle (DP24). Note that in case Car adjustments are used, and no Seat Adjustments. Obviously by carefully selecting car adjustments that do not impact other adjustabilities, it is possible to obtain an un-coupled design. In this case the order of adjustment does not matter, since the adjustabilites are independent. The problem with a height adjustable seat is that it affects many functional requirements. In the proposed design solution is in Table 3. The design equation is as in (6).

Table 3. FRs and DPs for design of a driver's compartment. Third iteration.

FR1	Easy to Manipulate Controls			DP 1	Controls within Easy Reach		
FR 2	Comfortable Sitting			DP2	Ergonomics Design		
	FR 11	Reach Dashboard Controls			DP 11	Controls on Steering Wheel	
	FR 12	Reach Pedals			DP 12	Long/Short Pedals	
	FR 21	Clear Steering Wheel			DP 21	Push/Pull Steering Wheel	
	FR 22	Reach Floor (with feet)			DP 22	Height Adjustable Floor	
	FR 23	Clear Roof			DP 23	Up/Down Roof	
	FR 24	Comfortable Sitting			DP 24	Adjustable Backrest Angle	

$$\begin{bmatrix} FR_{11} \\ FR_{12} \\ FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{bmatrix} = \begin{bmatrix} A_{1111} & 0 & 0 & 0 & 0 & 0 \\ 0 & A_{1212} & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{2121} & 0 & 0 & 0 \\ 0 & 0 & 0 & A_{2222} & 0 & 0 \\ 0 & 0 & 0 & 0 & A_{2323} & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{2424} \end{bmatrix} \begin{bmatrix} DP_{11} \\ DP_{12} \\ DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{bmatrix} \qquad (6)$$

To summarize, this exercise demonstrates the use of AD for anthropometric design. The design matrix provides a conceptualization of dependencies in design that we would otherwise not have been able to consider. Below we offer a second example of anthropometrics design – for microscope workstations.

2.2 Anthropometric design of microscope workstation.

A study was performed at IBM Corporation in San Jose with the purpose of developing guidelines for anthropometric design of microscope workplaces (Helander, Grossmith, and Prabhu [3]). Microscope work is generally taxing, since the operators have to assume a very static work posture – the eyes must constantly be positioned at the eyepiece and the hands on the focus controls. At IBM Corporation in San Jose, there were about 1000 microscope operators, most of whom were Asian females. They were much smaller than the regular USA population. As a result many of them could not accommodate to the oversize work place. The seat pan of the chair was too long so that they could not use the backrest. The seat was too high so that their feet could not reach the floor. The eyepieces were too high so that the operators had difficulties looking through them and seeing the magnified items.

To understand the underlying design problem an anthropometric survey was conducted. Fifteen different body measures were recorded for 400 operators and 5th percentile (5 % smallest), 50th percentile (average) and 95th percentile (5 percent largest) were calculated.

In our report we recommended a conventional design solution using a height adjustable chair, a height adjustable table and a height adjustable microscope (Helander, Grossmith, and Prabhu [3]). The amount of height adjustability was determined so as to fit a design range of 5th through 95th percentile operators. The use of height adjustable chairs is a conventional design recommendation and is without exception recommended in the literature [e.g. 4,5]. As we will see below the height adjustable chair is not necessary. It is possible to use Axiomatic Design to derive a better, albeit unconventional design solution

General analysis of the design. In the daily work situation, a microscope operator must make the necessary adjustments so that the workstation is comfortable. There are several possible adjustability design parameters in a microscope workstation that may affect operator comfort, see Figure 1 [6]. Hardware manufacturers can supply all these height adjustabilities, including the microscope itself:

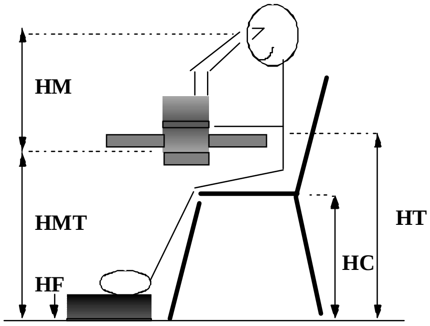

Figure 1: Design of a Microscope Workstation

- The height of the table (HT) where the operator is sitting.
- The height of a special microscope table (HMT), which is additional to the worktable
- The height of the microscope eyepieces (HM)
- The height of the operator’s chair (HC)
- The height of the foot rest (HF)

We can now specify the top-level FR and its corresponding DP:

FR = Provide a good work posture for operators at a microscope workstation

DP = Provide height adjustable workstation

A further analysis based on the decision of using ergonomic design in an adjustable workstation decomposed the top-level FR (good work posture for operators) into the following FRs:

FR_1 = Support for feet

FR_2 = Table top at sitting elbow height

FR_3 = Eyes at microscope height

These FRs are reasonable, and they are commonly recommended, since they avoid many potential biomechanics problems. The top-level DP was decomposed using the conventional solution that was proposed to IBM in our study [3].

DP_1 = Adjustable chair height

DP_2 = Adjustable table height

DP_3 = Adjustable microscope height

Analysis of independence of the design: The design equation is given in (7).

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \qquad (7)$$

Although this decoupled design is acceptable in the conventional sense of Axiomatic Design, a close examination indicates that the operator is required to remember the sequence of adjustments to bring about the best sitting posture. In this case, the chair height needs to be adjusted first, then the table height, and finally the microscope height. If this sequence is not followed, repeated iterative adjustments will be necessary. Even though this decoupled design is good enough for axiomatics it is not good enough for ergonomics, since it would be necessary to train the operator.

Reducing coupling in design. To improve the usability, and thus the design itself, other design solutions were tried. An adjustable footrest could be used instead of a height adjustable chair to satisfy FR_1 (Support for feet), and DP_1 was changed:

DP_1’ = Adjustable footrest

DP_2’ = Adjustable table height

DP_3’ =Adjustable microscope height

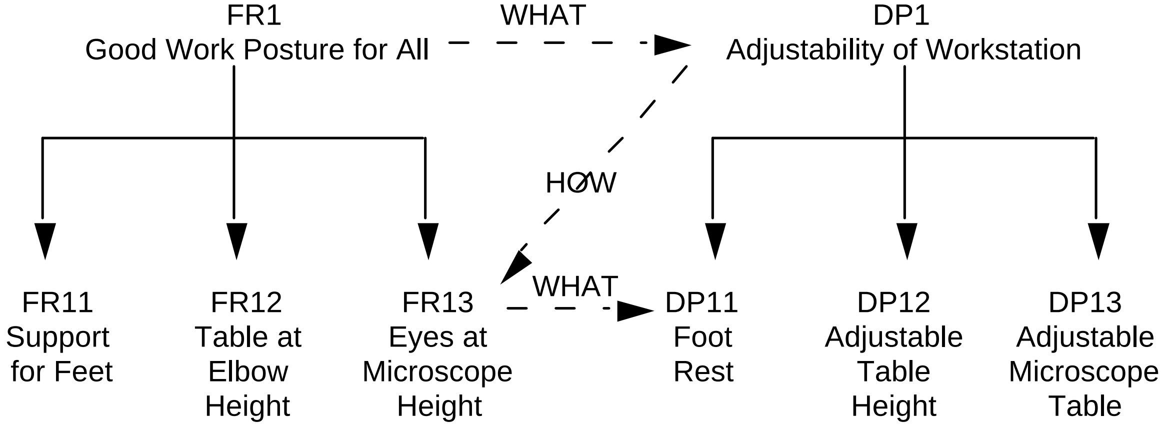

Figure 2: Hierarchical Structures and Decomposition of FRs and DPs. Note the zigzagging between abstraction levels.

The resultant design equation, with the modified design matrix [***A'***], is given in (8).

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11}' & 0 & 0 \\ 0 & A_{22}' & 0 \\ 0 & A_{32}' & A_{33}' \end{bmatrix} \begin{bmatrix} DP_1' \\ DP_2' \\ DP_3' \end{bmatrix} \qquad (8)$$

This improved solution uses an independently adjustable footrest, which replaces the adjustable chair in satisfying FR_1 (Support for feet). Obviously a non-adjustable chair is then necessary, and it should be sufficiently high to accommodate tall operators.

Since the coupling is reduced this is a better design solution. The operator will still, however, be forced to set the adjustabilities in a certain sequence. DP_2' (Adjustable table height) must be set before DP_3' (Adjustable microscope height) otherwise repeated adjustments will be necessary. (This is simply due to the fact that the microscope is placed on the worktable). To further improve the design, we provided a separate adjustable microscope table, standing free from the worktable, see figure 2. Thus the modified DPs are

DP_1'' = Adjustable footrest
DP_2'' = Adjustable table height
DP_3'' = Separate adjustable microscope table

The resultant design equation, with the further modified design matrix [***A''***] is:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11}'' & 0 & 0 \\ 0 & A_{22}'' & 0 \\ 0 & 0 & A_{33}'' \end{bmatrix} \begin{bmatrix} DP_1'' \\ DP_2'' \\ DP_3'' \end{bmatrix} \qquad (9)$$

By now we have achieved an uncoupled design that does not require any specified sequence to make the adjustments. Clearly, this is the best solution of all the ones proposed. It is however very unconventional, since it does not use a height adjustable chair. We have not seen this design solution documented in the literature.

Next we will discuss a difficulty encountered in ergonomic design when using the second axiom, *The Information Axiom.*

3. USING THE INFORMATION AXIOM IN ERGONOMICS DESIGN

3.1 Calculating the Information Content

In this section, we will give an example of how to calculate the information content in anthropometric design. As an illustration we use the microscope workstation in the previous example. The ranges of adjustment for the footrest, the table and the separate microscope table are defined based on anthropometric data of the intended user population. The next step was to buy adjustable furniture that was available on the market. Realistically, the design ranges for adjustability that were offered by furniture manufacturers were unlikely to fit our specific population - small Asian women. Below we demonstrate the use of the *Information Axiom* as a criterion to select the best furniture.

In Axiomatic Design the Design Range is specified as ”the tolerance associated with the DP specified by the designer.” In our case this could correspond to the desirable ranges of adjustment based on anthropometric measures. The System Range is defined as ”the capability of the current (manufacturing) system, given in terms of tolerances”. This could correspond to the ranges of adjustment offered by furniture manufacturers. Using these and the Common Range between them, the information content of each set of furniture may be calculated and the one with the least information content may be selected, according to *The Information Axiom*. However, a straightforward application of the AD principles would be misleading. Let us illustrate this with the following example. Tate (1999) also referred to the concept of meeting a Desired Range with a Supplied Range – he referred to this issue as "flexibility". He also integrated them with the normal definition of information content.

Suppose that by surveying a user group, we had determined the desirable adjustable table height ranges from 20-30 inches (Design Range = 10 in.), and there were two tables from two different manufacturers to evaluate. Table A had an adjustable range from 20-25 inches (System Range A = 5 in., and the corresponding Common Range A = 5 in.), and table B had a range from 20-35 inches (System Range B = 15 in., and the corresponding Common Range B = 10 in.). Using Equation (3) and assuming uniform distributions, the information contents of the two tables may then be calculated as:

Table A: $I_A = \log_2$ (System Range A/Common Range A) = $\log_2 (5/5) = 0$

Table B: $I_B = \log_2$ (System Range B/Common Range B) = $\log_2 (15/10) = 0.58$

According to Axiomatic Design, table A would have been selected because it has less information content than table B. However, table B clearly will satisfy the full range of user group while table A covers only half of them, and the correct choice would actually be table B.

This difficulty in calculating the information content, as a criterion for selecting alternative designs, stems from the special concern in ergonomic design, the human user. Once a selection is made, an individual user is merely a sample from the distribution of the user population. In other words, the furniture will be fixed once selected; a random user that follows a distribution of the Design Range would use it. This is contrary to the manufacturing case, where a product follows a distribution of the System Range. Therefore, this unique difficulty is ultimately from the definition of Design Range and System Range. To resolve this, we redefine the ranges to take human users into account.

3.2 Modification to the Calculation of Information Content in Ergonomics Design

We introduced new definitions of the information ranges according to the following notations. The ***Desired Range*** is the range implied by a functional requirement (FR). In our case a desired range was set by the 5th-95th percentile anthropometric measures. Thus, for an adjustable table the desired range is 20-29 in., see Table 3. The ***Supplied Range*** is the range supplied by the manufacturer. The Common Range then is the common area for the two distributions (overlap of Supplied Range and Desired Range). Here the probability of success is: p = Common Range/Desired Range. As with Axiomatic Design the definition for information content is:

$I = \log_2 (1/p)$. Thus, the information content is redefined as:

$I = \log_2$ (Desired Range/Common Range).

For the table height and manufacturer A, the Supplied Range is 23-32 in. and is calculated as 6 in. Using the simple case of uniform probability distribution, for manufacturer A we obtain:

$I_A = \log_2$ (Desired Range A/Common Range A) = $\log_2 (9/6)$ = 0.58 bits.

Design Problem: The next step is to choose the furniture offered by vendors. In our case we made the assumption that different vendors offers different ranges of adjustment, and we need to evaluate each vendor to make a final selection. *The Information Axiom* was used for this purpose, and the design with the minimum amount of information was used.

Design Solution: First the desired ranges were determined using anthropometric data. The desired ranges were: 0-5 inches for the footrest, 20-29 inches for the table, and 20-25 inches for the microscope table. As the two manufacturers, A and B, provided different adjustment ranges, their information contents were calculated using Equation (5), and the results are summarized in Table 3. We conclude that manufacturer A's workstation has total information content of 3.22 bits, and manufacturer B has 1.64 bits. Since there is less information in alternative B, this is a better design

Table 3. Information Content of Two Adjustable Microscope Workstations

		Manufacturer A		Manufacturer B	
	Desired Range (in.)	Supplied Range (in.)	Info. (bit)	Supplied Range (in.)	Info. (bit)
Adjustable Footrest	0 - 5	3 - 6	1.32	2 -5	0.74
Adjustable Table	20 - 29	23 - 32	0.58	21 - 27	0.58
Microscope Table	20 -25	23 - 28	1.32	21 - 27	0.32
Total Information			3.22		1.64

4 DISCUSSION

4.1 Conceptual support for Design

This paper has illustrated the use of Axiomatic Design in Anthropometric design of workstations. There were two examples, a driver's compartment and a microscope workstation. In the drivers compartment we provided examples of how decoupled design parameters simplify adjustments. It does not seem to be possible to find an uncoupled solution, unless design of vehicles is altered extensively. For example, the controls on the dashboard are in conflict with the steering wheel. An individual with a 5th percentile reach distance and a 95th percentile stomach girth may have difficulties to reach the dashboard controls. We could suggest several design solutions, such as a joystick for steering, putting the dashboard controls on the steering wheel, and so forth. However, they would violate existing design standards, and are therefore not so practical.

It would have been informative to explore how design parameters affect the extremes of the driver population. Usually the average driver has no problems, but the 5th and the 95th percentile drivers do. However, their problems are different and individual treatments of the 5th and 95 th percentiles may suggest new de-coupled solutions.

The design of the microscope workstation was different in that it was possible to suggest a practical, uncoupled design. BY using the independence axiom we were able to reason about the effect of alternative DPs. An unconventional design solution was accepted: the height adjustable chair was replaced by a footrest and an extra table was for the microscope was positioned inside the regular worktable. We discovered that height adjustable chairs were ineffective, since they impose a predetermined sequence of adjustability corrections that is difficult for the user to learn.

The design equations and some figures in this paper gave examples of the zigzagging between the functional domain and the design domain. The zigzagging procedure has a great advantage in that it can visualize how the choice of FRs and DPs at a high level of abstraction constrains the choice of FRs and DPs at the lower levels of abstraction. The zigzagging therefore introduces a method for constraint propagation, which is useful in delimiting the design space, and helps designers to arrive at reasonable solutions.

4.2 Information in Design

In the calculation of information in adjustability we introduced a new methodology to calculate information that is better suited to ergonomics than the existing methodology. The latter is shown in Figure 1.

"Desired range" and "supplied range" were suggested, and these concepts can then be used for calculating the amount of information in an adjustable workstation. Ideally the information H should be zero, which would indicate that all percentile users can be accommodates by the design.

According to the information axiom, one must minimize the information in a design solution. The principle is well known in ergonomics and has previously been formalized in two laws. These laws are important since they are insofar the only laws that have been formulated in ergonomics:

(1) Hick's law quantifies the information uncertainty H or entropy in a situation [4].

$$H = \Sigma -p_i \log_2 p_i \text{ (bits)}, \qquad (10)$$

where p_i is the probability of using information source I.

It is well established that human reaction time is a linear function of H. The greater the information uncertainty H, the longer the reaction time RT. This is expressed as follows:

$$RT = A + CH \qquad (11)$$

where A and C are constants.

In human factors design it is therefore considered desirable to reduce information in design. For example, the many options displayed in the menu for MSWord increase human reaction time. It would be better to display only those options that are actually used, and delete routines that are not useful. As an example, Tetra Pak, a Swedish Packaging Company formulated company wide requirement specifications for computer aided design. Based on the identified requirements (FRs), the CAD software packages were modified and all unnecessary functionality was removed. This simplified the operation of CAD routines, and training time as well as operational time decreased.

(2) Fitts' law can be used for calculating the information in a hand movement and the time it takes to perform a movement [1].

$$T = K \log_2 D/W \qquad (12)$$

where T is the time taken for a movement,
K is a constant,
D is the distance to a target, and
W is the width of the target.
D/W expresses the relative precision of a movement.

Fitts' law has been used to model human movement time for a variety of situations, such as movement time for cursor controls in computers, and movement time to pick items from bins in manufacturing, and sorting letters into mail slots. The smaller the size of the target and the longer the movement distance, the longer it takes to complete the movement. This leads to tradeoffs in design. For example, bins for assembly may be located in a semi-circular layout around the operator. The further away they are located, the greater the number of bins can be

The expressions used to calculate information for Hick's law and Fitts' law are computationally identical to those suggested by Suh [2]. To the ergonomics science the information axiom therefore carries much face validity, and it is possible that the information axiom in the future can be formalized in ergonomics design. Further research is necessary. In particular we advocate the use of case studies to further develop an understanding how AD can be used in design. The examples presented in the paper are easy to analyze. It would be particularly interesting to apply AD to real tasks including complex design with a mix of physical (anthropometry) and mental (information processing).

4.3 Process variables.

Process variables (PVs) are a set of variables used to achieve design parameters. Just like DPs are chosen so as to uncouple FRs, PVs should be chosen so that DPs are uncoupled. PVs usually refer to manufacturing machinery and processes. In the case of ergonomics, PVs refer to the functionality or capabilities the perceptual system and information processing, decision making, and the use of muscles to effectuate decisions. In other words, in designing a workstation one should consider human capabilities and limitations such as: information processing, decision making and muscular capability. These PV's can then be related to DP's through quantifications such as Hick's and Fitts' laws. In other words - a set of proposed design parameters can be evaluated in terms of the human processes that are necessitated through the design.

5 CONCLUSION

Axiomatic Design seems to offer a foundation for design methodology in ergonomics. There are several compelling reasons:

(1) Axiomatic Design offers a clear framework for the identification of functional requirements and the corresponding design parameters that may be evaluated with respect to user requirements.
(2) An analysis of the design matrix can reveal independence/dependence of functional requirements and point to possible ways of improving the design.
(3) The calculation of information content provides a quantitative evaluation of alternative designs so the best design can be selected; and
(4) The decomposition through the hierarchical structures of FRs and DPs by the zigzag process offers a procedure to constrain design solutions and at the same time identify critical design parameters.

Further research is now necessary to formalize the use of top-down design procedures in ergonomics. We believe that a top-down procedure, such as AD will have a promising potential in providing guiding principles for ergonomics research in the future.

6 REFERENCES

[1] Helander, M.G., *A Guide to the Ergonomics of Manufacturing*, London: Taylor & Francis, 1995. ISBN 0-7484-0122-9
[2] Suh, N., *The Principles of Design*. New York: Oxford University Press, 1990. ISBN 0-19-504345-6
[3] Helander, M.G., Grossmith, E. & Prabhu, P., "Visual and Postural Ergonomics in Design of Microscope Workplaces", *Applied Ergonomics, Vol.* 22, pp.36-42, 1990.
[4] Evans, W.A., Courtney, A.J. & Fok, K.F., "The Design of School Furniture for Hong Kong Schoolchildren", *Applied Ergonomics*, Vol. 19, pp.122-134, 1988.
[5] Verbreek, J., "The Use of Adjustable Furniture: Evaluation of an Instruction Programme for Office Workers", *Applied Ergonomics,* Vol. 22, pp.179-184, 1991.
[6] Helander, M.G., "Conceptualizing the Use of Axiomatic Design Procedures in Ergonomics", *Proc. of IEA World Conference*, pp.38-41. Rio de Janeiro: Associacao Brasileira de Ergonomia, 1995.
[7] Shannon, C.E. And Weaver, W., *The Mathematical Theory of Communication*, Urbana-Champagne, IL: University of Illinois Press, 1949
[8] Tate, D. (1999). A Roadmap for Decomposition: Activities, Theories, and Tools for System Design. *Dissertation.* http://axiom.mit.edu/thesis/dtate/index.htm Cambridge, MA: Department of Mechanical Engineering, MIT.