Introduction of the Anthropometry in the Early Design of a Nuclear Main Control Room

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Abstract. A nuclear main control room (MCR) is a crucial part of nuclear power plant (NPP) where qualified staffs are monitoring and controlling the function and productivity of the whole plant. In a safely operated NPP, the performance of the MCR personnel is critical. The full height range of the users and the size they exhibit depend primarily on age, gender, body physical characteristics and other data within a population of people. In this case, properly designing MCR and human-system interface (HSI) is central to safe and efficient operations of the plant, since it reduces the occurrence of incidents, accidents and the risks of human related errors.

Therefore, it is essential that the design of the large display panels, control consoles, vertical control panels and machinery rooms must be adequately performed and the application of the anthropometric principles in all design stages of the MCR is a requirement. When human anthropometry is taken into considerations in the design process, the MCR suits better the capabilities and limitations of the operators. During the design process, manufacturers and designers should consider the sizes, shapes, abilities and constraints of the people for whom they are designing. Anthropometric data varies significantly between different communities in various geographical territories.

Keywords: Anthropometric measurement · Human-system interface · Human factors standards · Human capabilities and limitations

1 Introduction

Human lifestyle and the environment are also changing so quickly and consequently affect human anthropometry. Therefore, while designing products, developers are advised to take into considerations two important aspects: First, the data collected over 25 years might not be matching the current population, since measurements such as heights may have changed.

Secondly, there are cases when the target population is not represented by the anthropometric database being used [1]. Besides, the job to carry out more experiments

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and constitute new anthropometric databases is tough, too demanding, and extremely expensive and requires a well knowledgeable technical team. And again, there is a very tight market competition and a far-reaching globalization network that push manufacturers and designers to reach various communities from across the world in a very limited time.

Also, some researchers emphasized the importance of taking into account the right high-level requirements in the early design stages to avoid a series of endless modifications that are always necessary to update an incorrect model [2, 3]. To overcome all those challenges, the researchers have developed a UG nx model that complies with the Human-System Interface Design Review Guidelines (NUREG0700). It presents four advantages:

- First, it interconnects all critical parts and equipment of the nuclear control room with the operator's size and keeps them together as one unit.
- Secondly, it presents the capability of allowing the designer to change boundary dimensions when it is necessary.
- Thirdly, it has the high capability of quickly responding to designer's modification, resizing different control room parts and adjusting the remaining parameters automatically.
- Fourthly, it calculates and rebuilds the model using mathematical formula without changing the original design principles.

This paper achieves its goal through the development of the UG nx model that applies human factors standards (HFS) and creates an interconnection between human physical measurements and nuclear MCR parts. Furthermore, a series of mathematical expressions was developed with the pure intention to govern the UG nx MCR model, make it capable of quickly responding to any designer's modification and holding it as one body. This study accomplished its objectives through the following steps:

- First, construction of geometric diagrams that show the relationship between human dimensions, workstation dimensions, console dimensions, large display screen (LDS) dimensions, and control panel dimensions.
- Secondly, developments of mathematical formulas that interlinks human physical measurements with different design characteristics of the structure and hold all the MCR parts together as one unit.
- Thirdly, construction of a UG nx MCR model and insertion of appropriate mathematical expressions that will make it flexible and able to rebuild its parameters whenever there is a designer's modification.
- Fourthly, carrying out experiments and verifying the results to avoid redesign process.
- Lastly, after performing a series of tests, design tables that may serve as designers' guides and system backups were developed for people who may not have access to the model. They contain different measurements of MCR parts and equipment corresponding to the operator's anthropometry.

For the comfort of the users, this report has found that by introducing a new full height range and body size in the early design stages, the MCR model is capable of computing and rebuilding the console and bench-board heights to allow easy reach of controls and keep contact eye on a display area. It was found that this design method will significantly cut down design time, reduce costs and promote the adaptation to rapid changes in the market demand.

1.1 Literature

Human factor engineering at the workplace has attracted researchers' attention for the last few decades. Researchers were concerned about the mismatch between equipment design and anthropometric principles, biomechanics and how they can address complaints reported at the workplace that subsequently reduces accidents and increases productivity. Therefore, an adequate design of the MCR in combination with appropriate HSI is central to the efficient and healthy operation of the plant. They help reduce the occurrence of incidents, accidents and the risks of human error [4]. Previous studies were conducted on Human Factors Engineering (HFE), but HFE alone did not adequately address the issues of human errors since it did not take into account the individuals' variability such as personnel size. Consequently, the operators' performance is affected by unsuitable design features that cause human fatigue and discomfort [5, 6]. Some studies have examined the mismatch between the equipment and operator's dimensions by taking anthropometric measurements of students and the dimensions of their desks and chair and confirmed that most of them could not find a suitable seat [7–9].

While designing a nuclear power plant console panel, the designers must ensure the physical placement of the controls and displays are at a reachable distance and meet operators' visibility requirements [10]. In their studies, Seminara and Parsons [11] identified major and minor deficiencies associated with human factors aspects in nuclear control room such as equipment component located at distant locations or in confined spaces that might reduce operator's performance and cause injuries [11]. Nuclear control room developers have put in many efforts to overcome deficiencies at early design stages, but little is known about combining human factor engineering study with the diversification of human physical characteristics and workplace layout. The objective of this study is to develop an NX model that combines human physical characteristics with MCR equipment and design layout and meets operators' capabilities and limitations.

2 Design of "MCR" Model

In designing interactive systems such as processes, products, and spaces, the designers must explore working conditions, communication and how human beings can interact with the designed system or product. Prototypes are developed to represent any given design before producing a final product and help in the design process and design decisions [12]. The fundamental design principle of this model takes a reference to the international standard guidelines (NUREG0700) (see Table 1). This model is capable of quickly responding to any designer's modification and rebuilding all MCR equipment to match the changes and maintain standard guidelines.

Table 1. Anthropometric data [5]

Standing (without shoes)	Bounding measurements inches (mm)	
	5th %-ile adult female: (mm)	95th %-ile adult male (mm)
Stature	60.0(1524)	73.5(1866.9)
Eye height from floor	55.5(1409.7)	68.6(1742.4)
Shoulder height	48.4(1229.4)	60.8(1544.3)
Elbow height	37.4(949.96)	46.8(1188.7)
Fingertip height	24.2(614.68)	28.8(731.5)
Functional reach	25.2(640.08)	35.0(889)
Extended functional reach	28.9(734.06)	39.0(990.6)
Central axis of body to leading edge of console	5.0(127)	5.3(134.6)
Eye distance forward of central axis to body	3.0(76.2)	3.4(86.4)

2.1 Determination of the Lower Limit (L)

Let's take a random shoulder height (Y_1) (see Fig. 1).

$$\begin{aligned} Tan(\alpha) &= \frac{\Delta y}{\Delta x} = \frac{1544 - 1229}{889 - 640} = \frac{315}{249} \\ \Leftrightarrow \Delta x &= \frac{\Delta y}{Tan(\alpha)} = \frac{\Delta y}{\frac{315}{249}} \\ \Leftrightarrow \Delta x &= \frac{249\Delta y}{315} \end{aligned} \tag{1}$$

$$\begin{aligned} Tan(\alpha) &= \frac{h}{249 - \Delta x} = \frac{315}{249} \\ \Leftrightarrow h &= (249 - \Delta x) \times \frac{315}{249} \end{aligned} \tag{2}$$

$Y_1 = 1544 - h$, Hence,

$$Y_1 = 1544 - \frac{315}{249} \times z(249 - \Delta x) \tag{3}$$

And

$$Y_1 = 1229 + \Delta y \tag{4}$$

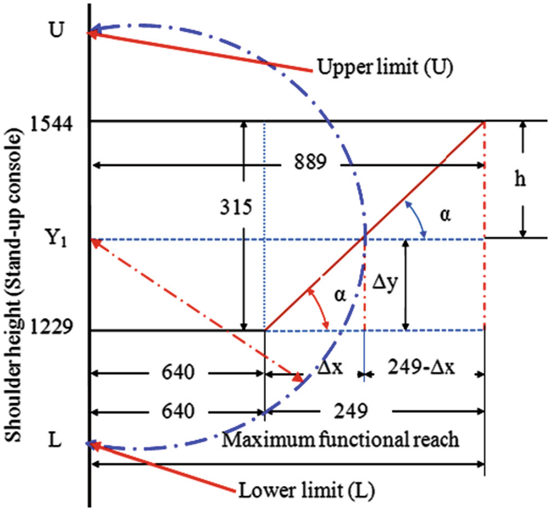

Fig. 1. Shoulder heights and functional reach (Sketch)

By combining Eqs. 3 and 4

$$\begin{aligned} \Delta y &= 1544 - \left(\frac{315}{249} \times (249 - \Delta x)\right) - 1229 \\ \Leftrightarrow \Delta y &= 315 - \frac{315}{249} \times (249 - \Delta x) \end{aligned} \tag{5}$$

By replacing Δx with its expression in Eq. 3

$$Y_1 = 1544 - \frac{315}{249} \times \left(249 - \frac{249\Delta y}{315}\right)$$

Lower limit (L) according to Fig. 1 becomes:

$$\begin{aligned} L &= Y_1 - (640 + \Delta x) \\ \Leftrightarrow L &= Y_1 - \left(640 + \frac{249\Delta y}{315}\right) \end{aligned} \tag{6}$$

2.2 Determination of the Upper Limit

If we consider a random point Y_1 on the vertical axis (see Fig. 1),

$$\begin{aligned} Y_1 &= 1229 + \Delta y \\ U &= Y_1 + (640 + \Delta x) \end{aligned} \tag{7}$$

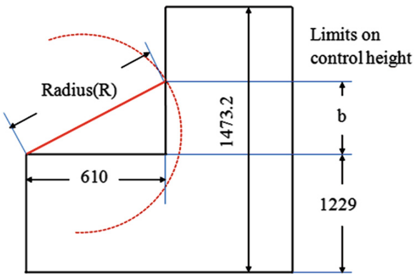

Fig. 2. Functional reach-radius (Sketch)

Replacing Δx by its value the equation becomes:

$$U = Y_1 + \left(640 + \frac{249\Delta y}{315}\right) \tag{8}$$

2.3 Determination of the Limits on Control Height

Control height coincides with the point of intersection between the console and the functional reach radius of the 5th %-ile female (see Fig. 2) (Tables 2 and 3).

$$\begin{aligned} R^2 &= b^2 + 610^2 \\ \Leftrightarrow b^2 &= R^2 - 610^2 \\ \Leftrightarrow b &= \sqrt{R^2 - 610^2} \end{aligned} \tag{9}$$

From Fig. 1 Radius (R)

$$R = \left(640 + \frac{249\Delta y}{315}\right)$$

Replacing R by its value in Eq. 9, we obtain

$$b = \sqrt{\left(640 + \frac{249\Delta y}{315}\right)^2 - 610^2} \tag{10}$$

Control height (C_h) from the floor (see Fig. 2) is equal to:

$$\begin{aligned} C_h &= 1229 + b \Leftrightarrow \\ \Leftrightarrow C_h &= 1229 + \sqrt{\left(640 + \frac{249\Delta y}{315}\right)^2 - 610^2} \end{aligned} \tag{11}$$

Table 2. Random designer's modification on operator's eye and shoulder heights

Design parameters		Operator's eye height	Bottom of the screen (height)	Top of the screen (height)	Screen length	Console height	Benchboard height	Shoulder height	Control height
Min. Eye height (Ehmi)	1410	1308	1542.03	3372.12	2113.21	1188.29	641.78	N/A	N/A
Max.console height (Chmax)	1473	1359	1593.03	3423.12	2113.21	1216.42	669.92	N/A	N/A
Functional area (Fa)	610	1410	1644.03	3474.12	2113.21	1244.55	698.05	1229	1422.65
Console width (Cw)	1016	1461	1695.03	3525.12	2113.21	1272.69	726.18	1249	1469.80
Passageway (Pw)	1250	1512	1746.03	3576.12	2113.21	1300.82	754.32	1309	1578.92
Distance between operator and screen stand (Z)	2266	1563	1797.03	3627.12	2113.21	1328.95	782.45	1381.5	1683.24
Arc of view	60	1613	1847.03	3677.12	2113.21	1356.53	810.03	1432	1747.31
LCD screen rotation	150	1664	1898.03	3728.12	2113.21	1384.67	838.16	1483	1807.63
Min. display height(Dh)	1041	1715	1949.03	3779.12	2113.21	1412.80	866.30	1544	1875.70
Min. benchboard height (Bmin)	686	1743	1977.03	3807.12	2113.21	1428.25	881.74	N/A	N/A
Benchboard thickness (Bth)	12.05	1794	2028.03	3858.12	2113.21	1456.38	909.88	N/A	N/A
		1845	2079.03	3909.12	2113.21	1484.51	938.01	N/A	N/A

Table 3. Random designer's modification on LCD screen rotation angle and arc of view

Design parameters		LCD screen rotation angle	Arc of view	Operator's eye height	Stand height (Sh)	Screen length (D1)	Height on top of screen
Min. eye height	1410	135	69	1715	1949.03	2455.75	3685.51
Console height	1473	150	60			2113.21	3779.12
Functional area	610	155	51			1809.93	3589.38
Console width	406	160	42			1526.41	3383.38
Passageway	1250	163	33			1247.55	3142.07
Length between operator and screen stand	2266	165	24			959.25	2875.60
		171	15			645.40	2586.48
		177	6			283.93	2232.57

2.4 Design of Giant Screen and Its Orientation

Design of the Stand Height. Screens are inclined at an angle greater or equal to 45^o and less than 90^o and suspended at a distance of 1250 mm (passageway) for single a person behind the consoles [5] (see Fig. 3).

$$\begin{aligned} Tan(\theta) &= \frac{1473 - 1410}{610} = \frac{C}{Z} \\ \Leftrightarrow \mathrm{C} &= \frac{63 \times Z}{610} \end{aligned} \tag{12}$$

The stand height (S_h):

$$S_h = 1410 + C + \Delta y \tag{13}$$

$$\Leftrightarrow \theta = \arctan\left(\frac{1473 - 1410}{610}\right) = 6^o$$

$$Hyp^2 = Z^2 + c^2 \Leftrightarrow \mathrm{Hyp} = \sqrt[2]{Z^2 + C^2}$$

Design of the Screen Length. Considering the triangle Hyp, D & E in Fig. 3, the arc of 75^o is reduced by 6^o (θ) while the arc of 45^o is increased by 6^o (θ) (see Fig. 4). "D" stands for the maximum screen length.

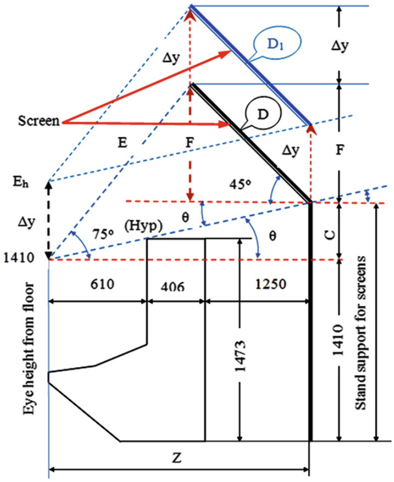

Fig. 3. Large screen position and orientation (Sketch)

$$\begin{aligned} &\frac{D}{Sin(\beta)} = \frac{Hyp}{Sin(\gamma)} = \frac{E}{Sin(\varphi)} \\ &\Leftrightarrow \frac{D}{Sin(69)} = \frac{Hyp}{Sin(60)} \\ &\Leftrightarrow D = \frac{Hyp \times Sin(\beta)}{Sin(\gamma)} \end{aligned} \tag{14}$$

Taking into account the economic aspect, material utilization, and owner's requirements, the MCR designer, can reduce the length (D) of the LDS. The length of the screen should vary by decreasing the total arc of view (β), keeping the angle (φ) unchanged and the top angle (γ) continues changing according to the variation of (β) (see Fig. 4).

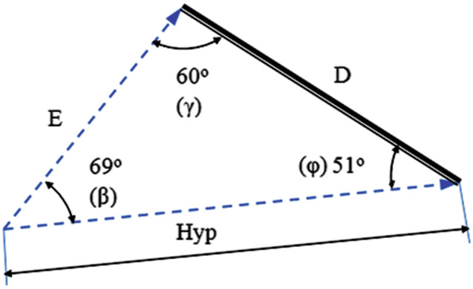

Fig. 4. Determination of screen length (Sketch)

Consequently, when LDS length reduces, the height of the screen also decreases that ultimately helps the designer predict the height of the MCR that can accommodate it (see Fig. 5).

And the Eq. 14 becomes

$$\begin{aligned} D &= \frac{Hyp \times Sin(69 - \Delta^o)}{Sin(180 - 51 - (69 - \Delta^o))} \\ \Leftrightarrow D &= \frac{Hyp \times Sin(69 - \Delta^o)}{Sin(60 + \Delta^o)} \end{aligned} \tag{15}$$

Where Δ^o is a change in visual field (degrees).

Screen Orientations. The MCR designer has capabilities to reorient the large display screen (LDS) by rotating it either in a forward or backward direction to comfortably suit operator's viewing requirements. In this case, the screen length keeps constant but, the height on the top of the screen varies with a variation of angle (φ) (see Fig. 5).

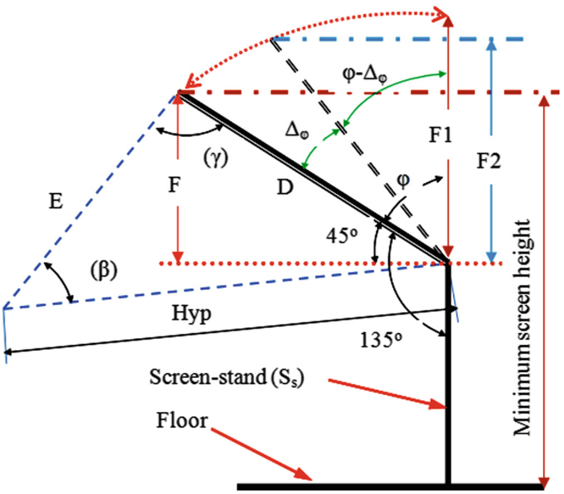

Fig. 5. Screen rotation (Sketch)

The angle between screen stand and the LDS (D) is equal to 135° (see Fig. 5)

$$F_1 = D \times Cos(\varphi)$$

And $F_1 = D \times Cos(180 - 135)$
Let's take any small change in angle ($\Delta\varphi$) (see Fig. 5)

$$F_2 = D \times Cos(45 - \Delta\varphi))$$

So, vertical projections (F_s) of the screen are given by the following formula:

$$F_s = D \times Cos(45 - \Delta\varphi_s) \tag{16}$$

Height on Top of the Screen (Htop)

$$H_{top} = 1410 + C + \Delta y + D \times Cos(45 - \Delta\varphi_s) \tag{17}$$

2.5 Design of Console Height

The maximum console height is recommended not to exceed 58 in. (1,473.2 mm). The console height must allow the operator a continuous view of the control panel, especially at control panel display height which requires constant monitoring [5].

At initial eye position (Ehmi), the eye cuts through the height of console and makes an angle "Ψ" with the back edge of the console and points to the control panel at the minimum display height (see Fig. 6).

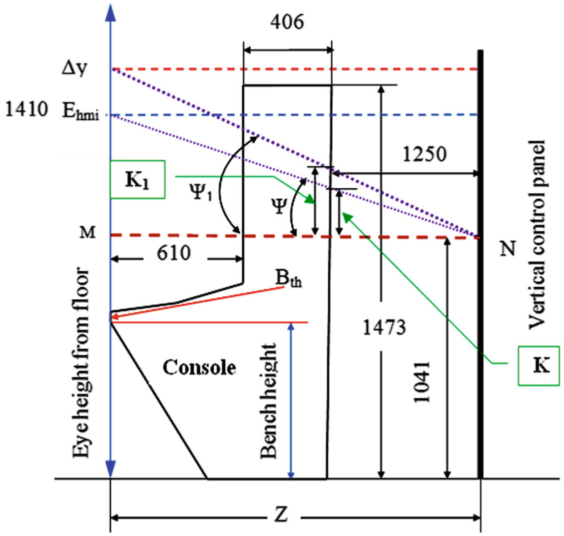

Fig. 6. Console height

$$Tan(\psi) = \frac{E_{\mathrm{hmi}} - 1041}{Z} = \frac{K}{1250} \tag{18}$$

$$\Leftrightarrow K = \frac{1250 \times (E_{\mathrm{hmi}} - 1041)}{Z} \tag{19}$$

The minimum console height ($\mathrm{H_{min}}$) that allows the 5th %-ile female to look over is equal to: $H_{min} = 1041 + K$

Let's consider "Δy" change in eye height

$$Tan(\psi_1) = \frac{E_{\mathrm{hmi}} - 1041 + \Delta_y}{Z} = \frac{K_1}{1250} \tag{20}$$

$$\Leftrightarrow K_1 = \frac{1250\mathrm{x}(E_{\mathrm{hmi}} - 1041 + \Delta_y)}{Z} \tag{21}$$

Console Height Increment ($\boldsymbol{\Delta}\mathbf{y}_{\boldsymbol{c}}\cdot$)

$$\begin{aligned}
\Delta \mathrm{y}_c &= K_1 - K \\
\Delta \mathrm{y}_c &= \frac{1250 \times \left(E_{\mathrm{hmi}} - 1041 + \Delta_y\right)}{Z} - \frac{1250 \times (E_{\mathrm{hmi}} - 1041)}{Z} \\
\Leftrightarrow \Delta \mathrm{y}_c &= \frac{1250\Delta \mathrm{y}}{Z}
\end{aligned} \tag{22}$$

3 Results and Discussion

The UG nx MCR model was developed, and all parts, equipment, and layout of the MCR were governed and dimensioned using mathematical expressions. Parameters used to establish formulas interlink personnel measurements with consoles, LDS, passageways, controls and display panels. Mathematical equations hold the model as a single entity and make it capable of responding quickly to any designer's modification.

3.1 MCR Model and How It Works

The process of compiling the data shown in different tables follows five steps:

a. Modify the size of one, two or more parameters at once in the model
b. Click ok
c. The model rebuilds itself
d. Display dimension
e. Take record of new dimensions

Therefore, for design purpose, it is recommended to take records of new dimensions and compile them in a table anytime there is a designer's change. There is the unlimited number of tables that can be developed; it all depends on the part of the model the designer is interested in or the customer requirements. Data compiled in tables will serve as designers' guides for people who may not have access to the NX model.

Eg. When we set the Eye height (Eh) to 1715 mm and functional reach (Fr) to 610 mm in the UG nx MCR model, it resizes and adjusts different parts, then rebuilds to accommodate changes. The NX model resizes the console height and minimum display height to maintain visibility condition (see Fig. 7) and also the bench board height is adjusted to suit the operator's shoulder height, etc. (see Fig. 8).

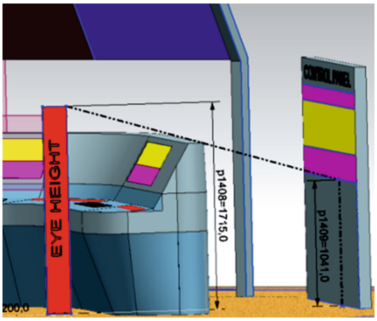

Fig. 7. visibility condition and console height

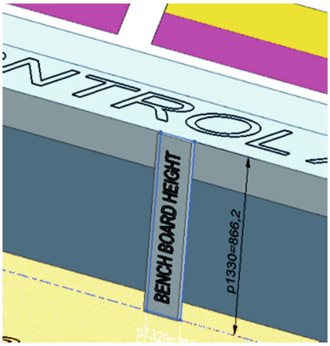

Fig. 8. Reach capability

3.2 Experimental Validation

After conducting a series of test and workshop experiments, the researchers have successfully constructed five different prototypes using data resulting from this model. This study confirmed that this NX model is a successful inclusive design tool because it is capable of dealing with data that do not fit in the defined NUREG0700 standard. Also, it presents an advantage to adapt to any other data within a population of people classified according to age, gender or body physical characteristics (see Fig. 9).

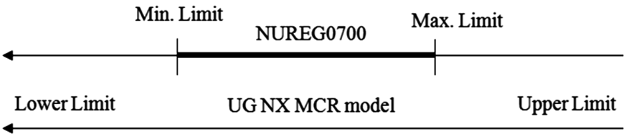

Fig. 9. Comparison between NUREG0700 and NX model

4 Conclusion

The introduction of the anthropometric measurements in the early stage of the MCR design addresses the issue of major and minor deficiencies associated with human factors aspects such as equipment component located at distant locations or in confined spaces. This paper confirmed that the NX model will eliminate design errors that are the root causes of redesign process and a series of endless modifications that are always necessary to update. This design method will significantly cut down design time and substantially reduce costs. It was found that this model is capable of adapting itself to rapid change in market demand.

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