Instructor’s
Title & Name

Course Title….

Axiomatic design (AD) provides discipline-independent representations of a generic design process, general criteria for effective decision making, and scalability for complex systems development.

Axiomatic design process reduces product development risk, reduces cost, and speeds time to market.

As shown in Figure 6.1, to move between any two nearby domains, the domain to the left signifies “what we want to achieve”, and the domain to the right signifies “how it will be achieved.”

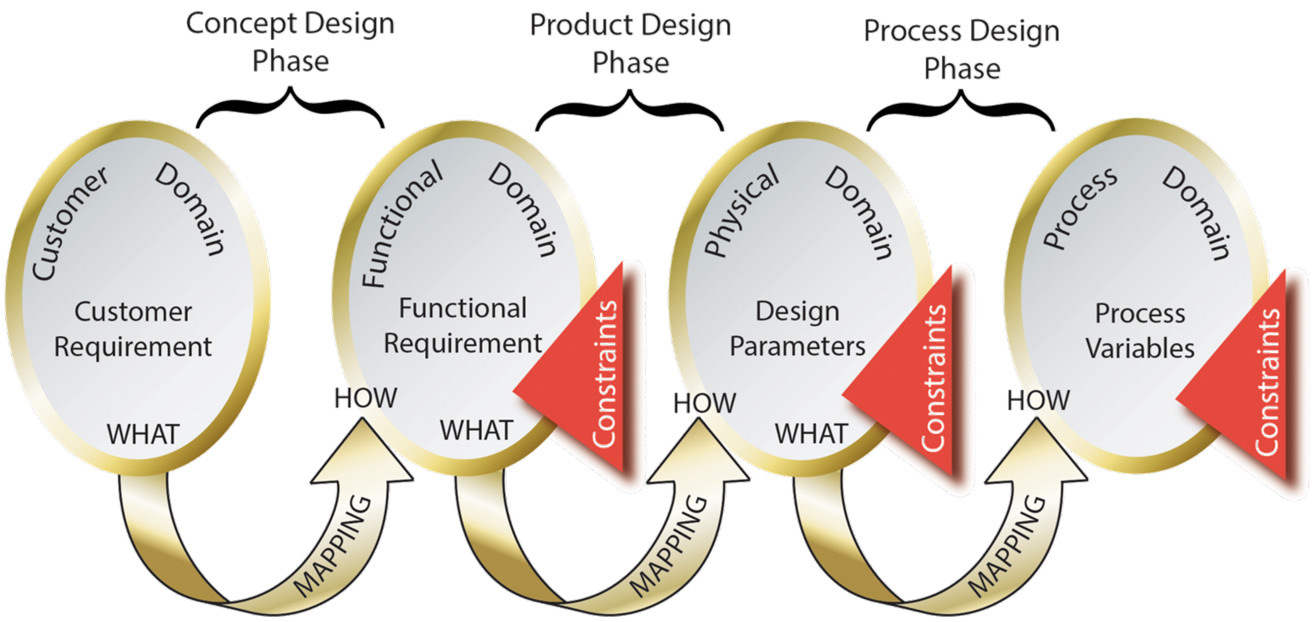


Figure 6.1: Four domains of the design.

As shown in Figure 6.2, the mapping between domains is defined by a set of matrices as:

$$\{\mathbf{CN}\} = [R]\,\{\mathbf{FR}\} \qquad (6.1)$$

$$\{\mathbf{FR}\} = [D]\,\{\mathbf{DP}\} \qquad (6.2)$$

$$\{\mathbf{DP}\} = [B]\,\{\mathbf{PV}\} \qquad (6.3)$$

where, [*R*] is the requirement matrix, [*D*] is the design matrix, and [*B*] is the component matrix.

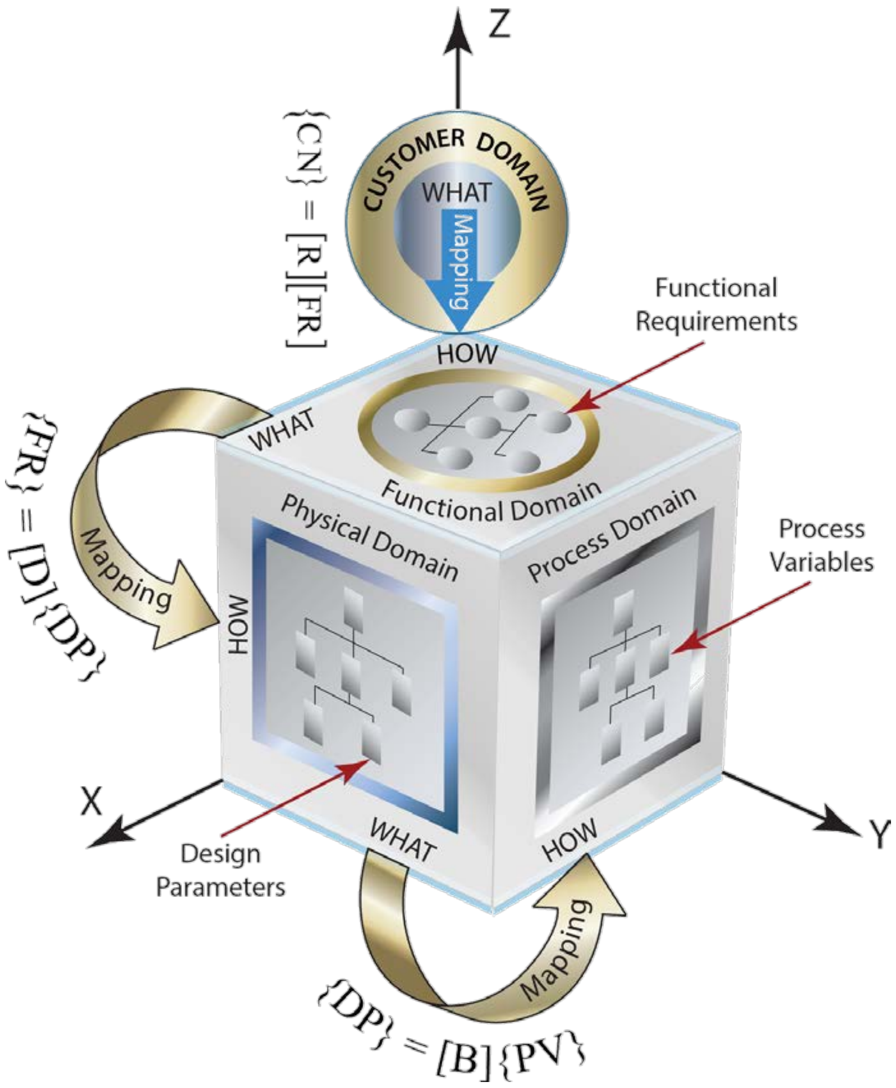


Figure 6.2: Design domains.

Uncoupled, De-coupled, and Coupled Design

Two fundamental AD axioms offer a rational basis for the evaluation of given solution alternatives.

1. Independence Axiom

“Maintain the independence of the functional requirements (FRs).” Each functional requirement should be satisfied by its corresponding design parameters (DP) without affecting the other functional requirements. In other words, one design parameter satisfies one and only one functional requirement.

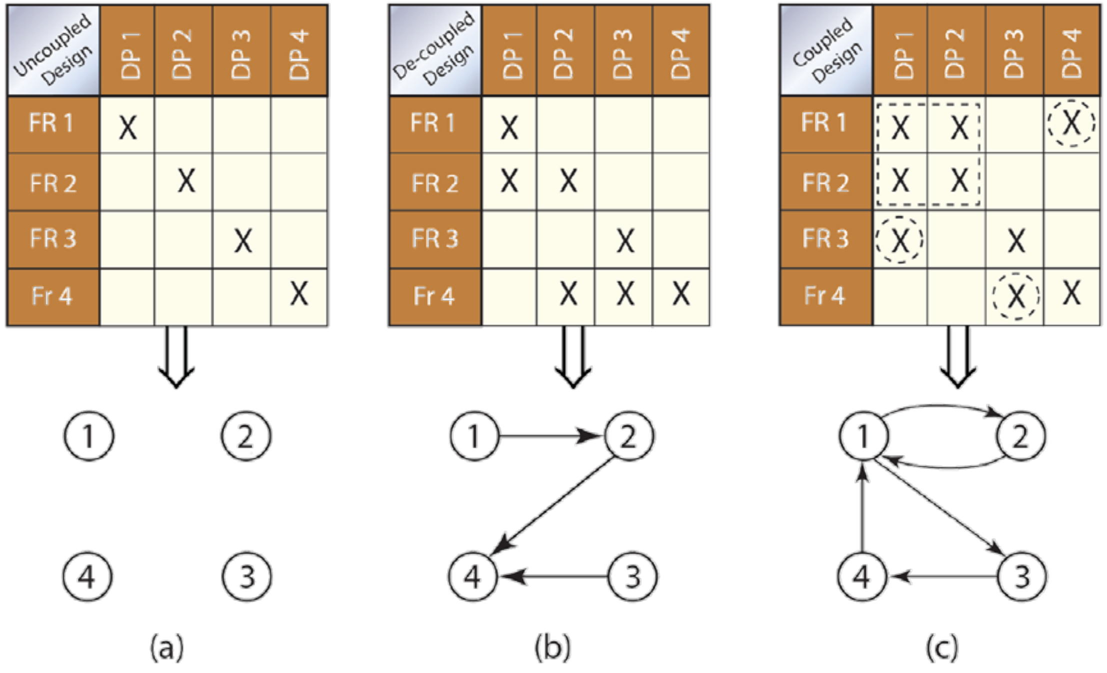


Figure 6.3: (a) Uncoupled design, (b) De-coupled design, (c) Coupled design.

Uncoupled, De-coupled, and Coupled Design

When design parameters are constrained, for example, by weight, size, cost, etc., they will have secondary effects on the other functional requirements as shown in Figure 6.3(b) – DP1 is affecting FR1 and FR2, DP2 is affecting FR2 and FR4, and DP3 is affecting FR3 and FR4. A triangular matrix is shown in Figure 6.3(b) represents a decoupled design.

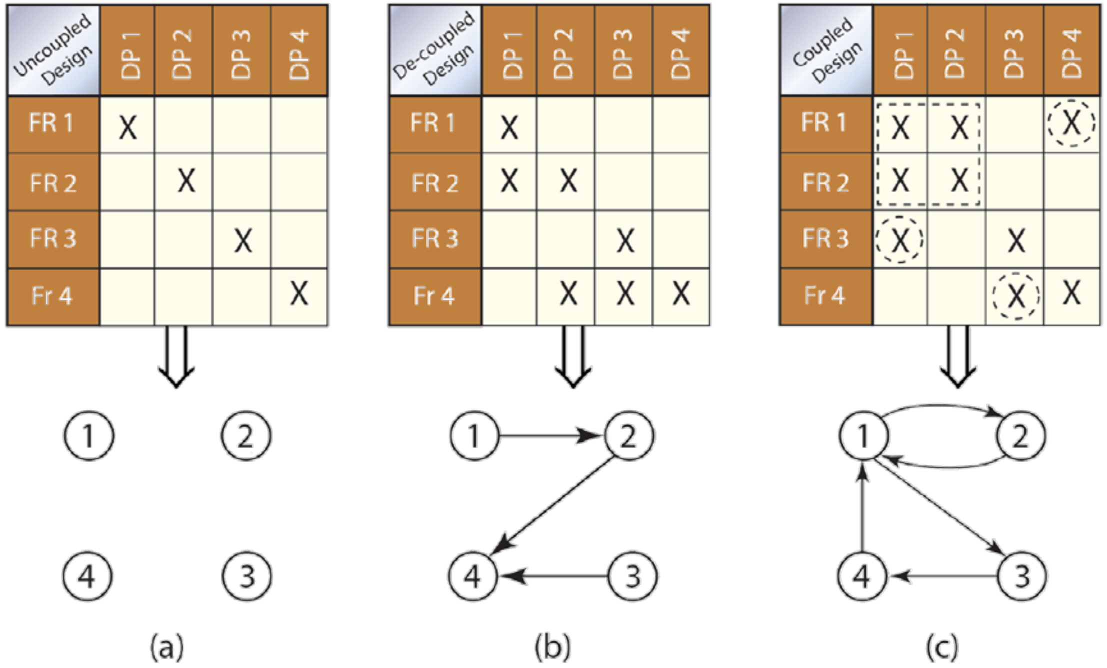


Figure 6.3: (a) Uncoupled design, (b) De-coupled design, (c) Coupled design.

2. Information Content Axiom

“Minimize the information content of the design”. After satisfying the Independence Axiom, the Information Axiom is used to select the best design among several acceptable design choices.

Among all the design alternatives that satisfy the independence axiom the one that possesses the least information is the best choice.

The Information Axiom is related to the complexity of a design. It indicates that the simpler design is the better one.

EXAMPLE
Use independence axiom for a typical water faucet shown in Figure 6.4.

There are two functional requirements for the water faucet is shown in Figure 6.4. They are:

FR1: Control flow rate (Q) of water
FR2: Control temperature (T) of water

Figure 6.4: (a) Two-handed water faucet, (b) One-handed water faucet. (Adapted from Frederickson B., 1994, Holistic Systems Engineering in Product Development, in Saab-Scania Griffin, vol. 1994/95, Linköping, Sweden: Saab-Scania AB, S-581 88, pp. 23-31, 1994).

Two adjustments of two handle facets will have a hot water knob which provides $DP1 = (\theta_1)$ and cold water knab which provides $DP2 = (\theta_2)$. Both design parameters, *DP1* and *DP2* will satisfy both functional requirements of flow rate, *Q* and temperature, *T*. Using Equation (6.4), the design matrix can be written as:

Figure 6.4: (a) Two-handed water faucet, (b) One-handed water faucet. (Adapted from Frederickson B., 1994, Holistic Systems Engineering in Product Development, in Saab-Scania Griffin, vol. 1994/95, Linköping, Sweden: Saab-Scania AB, S-581 88, pp. 23-31, 1994).

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \qquad (6.5)$$

Substituting FRs and DPs in Eq. 6.5, we have

$$\begin{Bmatrix} Q \\ T \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} \theta_1 \\ \theta_2 \end{Bmatrix} \qquad (6.6)$$

As seen from the matrix, flow rate control (FR1) will be satisfied by both DP1 (hot) and DP2 (cold) and temperature control (FR2) will be also satisfied by both DP1 (hot) and DP2 (cold) – DP1 affects FR1 and FR2 and similarly, DP2 affects the same functional requirements. This is called a coupled design as shown in the relationship matrix (see Figure 6.5(a)) and doesn't satisfy the independence criterion.

Figure 6.4: (a) Two-handed water faucet, (b) One-handed water faucet. (Adapted from Frederickson B., 1994, Holistic Systems Engineering in Product Development, in Saab-Scania Griffin, vol. 1994/95, Linköping, Sweden: Saab-Scania AB, S-581 88, pp. 23-31, 1994).

Figure 6.5: (a) Coupled design

Coupled Design	DP1	DP2
FR1	X	X
FR2	X	X

(a)

With a one-handed facet, as shown in Figure 6.4(b), the flow rate is adjusted by the vertical motion of the lever to satisfy FR1 and the temperature is adjusted by the angle, to satisfy FR2. DP1 affects only the functional requirement of FR1 and DP2 affects the other functional requirement, FR2 – each DP is satisfying one functional requirement – this design is called an uncoupled design, and it satisfies the independence criterion.

Figure 6.4: (a) Two-handed water faucet, (b) One-handed water faucet. (Adapted from Frederickson B., 1994, Holistic Systems Engineering in Product Development, in Saab-Scania Griffin, vol. 1994/95, Linköping, Sweden: Saab-Scania AB, S-581 88, pp. 23-31, 1994).

Uncoupled Design	DP1	DP2
FR1	X	
FR2		X

(b)

Figure 6.5: (b) Uncoupled design

Zigzagging and Decomposition

As shown in Figure 6.6, the decomposing process is performed by *“zigzagging”* between FR and DP domains. Namely, we start out in the "what" domain and go to the "how" domain.

High-level functional requirements will be the starting point for the further decomposition into additional levels of FRs.

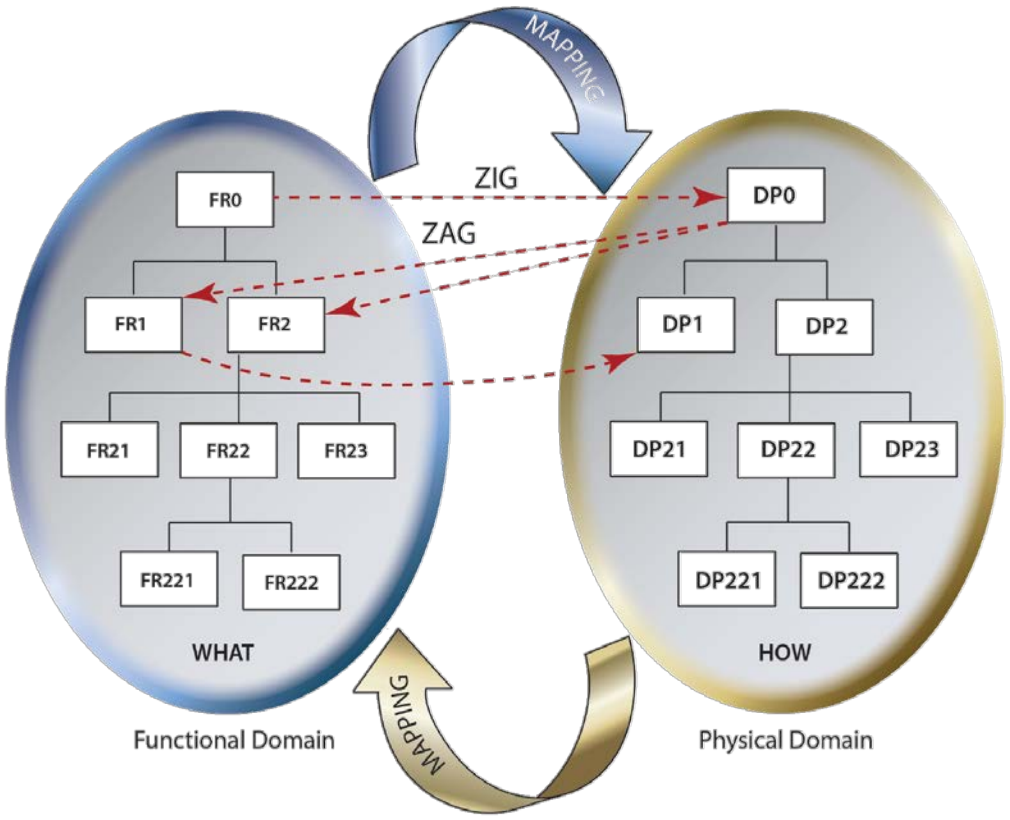


Figure 6.6: Zigzagging to decompose FRs and DPs.

CASE STUDY 6.1

Develop the design parameters (DPs) of the design solution of the finger rehab device shown in Example 7.1 (Figure 7. 16) to satisfy the specified FRs. Use Axiomatic Design principles.

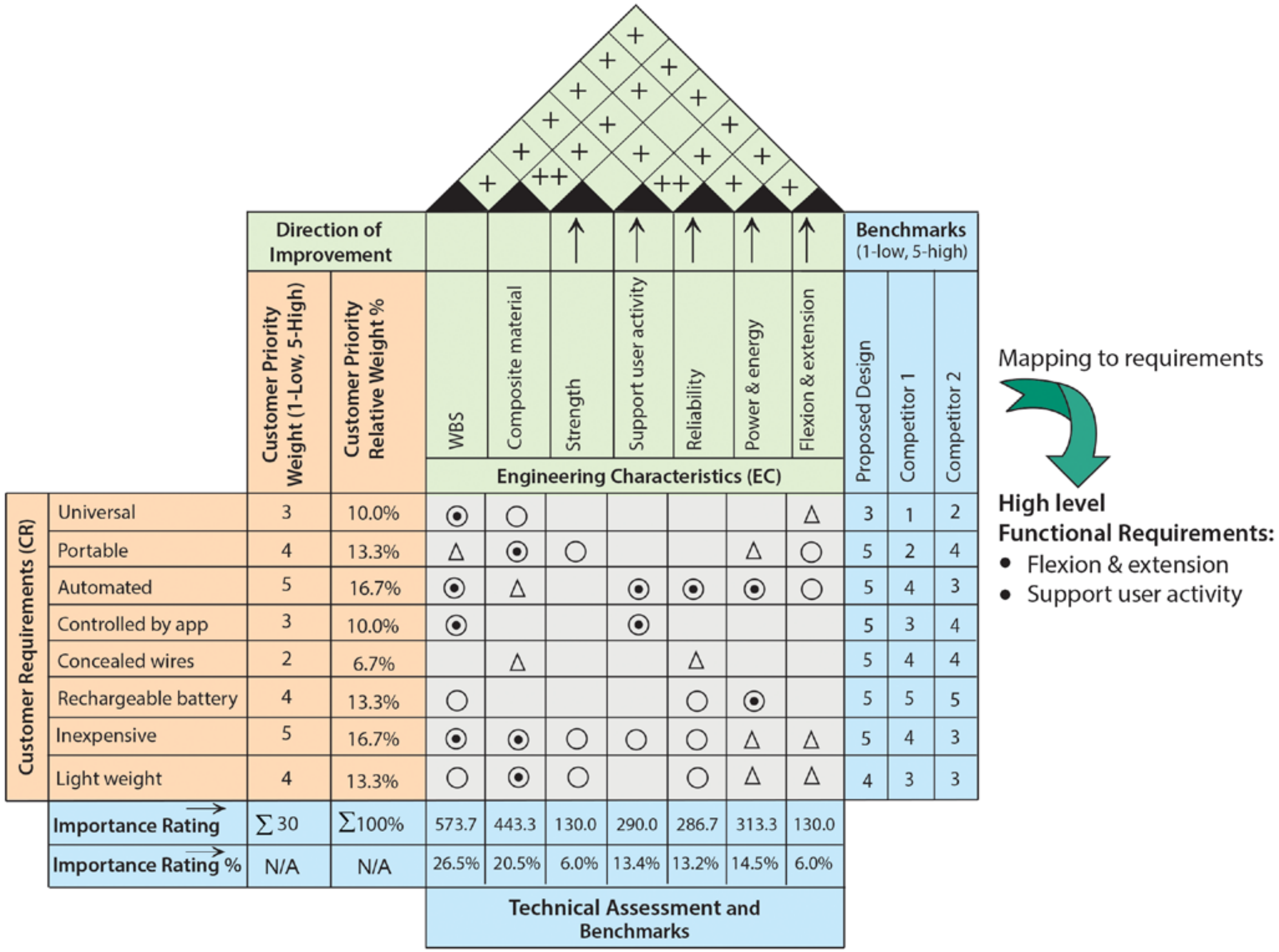
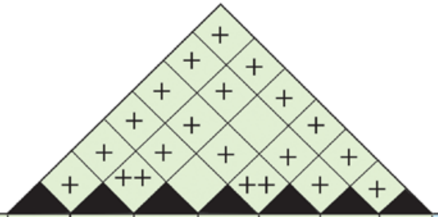


Figure 6.7: New re-build HOQ.

HIGH LEVEL FUNCTIONAL REQUIREMENTS

- The product shall be capable of Flexion & extension
- The product shall be capable of supporting user activity

As seen from the above top-level FRs, they don't give us too much information, but this initial step determines the starting point for the further decomposition by using AD zigzag methodology.



Customer Requirements (CR)	Customer Priority Weight (1-Low, 5-High)	Customer Priority Relative Weight %	WBS	Composite material	Strength	Support user activity	Reliability	Power & energy	Flexion & extension	Proposed Design	Competitor 1	Competitor 2
Direction of Improvement					↑	↑	↑	↑	↑	Benchmarks (1-low, 5-high)		
Universal	3	10.0%	◉	○					△	3	1	2
Portable	4	13.3%	△	◉	○			△	○	5	2	4
Automated	5	16.7%	◉	△		◉	◉	◉	○	5	4	3
Controlled by app	3	10.0%	◉			◉				5	3	4
Concealed wires	2	6.7%		△			△			5	4	4
Rechargeable battery	4	13.3%	○				○	◉		5	5	5
Inexpensive	5	16.7%	◉	◉	○	○	○	△	△	5	4	3
Light weight	4	13.3%	○	◉	○		○	△	△	4	3	3
$\overrightarrow{\text{Importance Rating}}$	$\sum$30	$\sum$100%	573.7	443.3	130.0	290.0	286.7	313.3	130.0			
$\overrightarrow{\text{Importance Rating}}$ %	N/A	N/A	26.5%	20.5%	6.0%	13.4%	13.2%	14.5%	6.0%			
			Technical Assessment and Benchmarks									

Engineering Characteristics (EC)

Mapping to requirements

High level Functional Requirements:
- Flexion & extension
- Support user activity

Figure 6.8: New re-build HOQ.

Using high level FRs the following design parameters (DPs) are selected to fulfill each of the FRs:

FR1 Product shall be capable of Flexion & extension
DP1: Soft robotic

FR2 Product shall be capable of supporting user activity
DP2: Activity monitoring tool

Design matrix is shown in Eq. 6.6 should be formulated for each level to avoid violating the Independence Axiom.

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \qquad (6.6)$$

Eq. 6.6 reveals that the design is uncoupled at the top level and the independence axiom is not violated.

A road map for the levels of decomposition is shown in Figure 6.9.

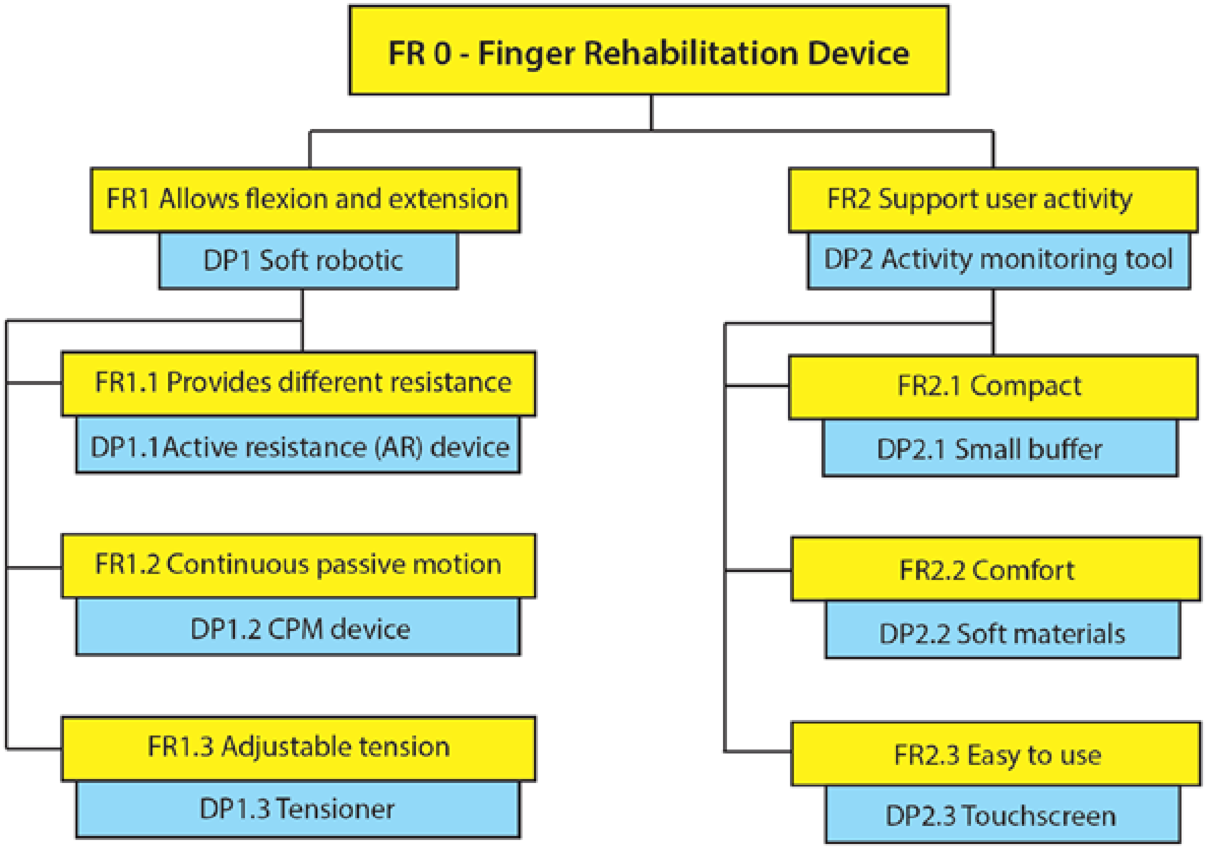


Figure 6.9: Design rod map.

Next, using zigzagging and maintaining independence within each matrix, the additional FR levels were developed. Since all the FRs will follow a similar decomposition format, for briefness, only FR1 (Allows flexion and extension) decomposition will be shown.

FR1.1: Provides different resistance

FR1.2: Continuous passive motion (CPM)

FR1.3: Adjustable tension

The following design parameters (DPs) are selected to fulfill each of the above FRs:

DP1.1: Active resistance (AR) device

DP1.2: CPM device

DP1.3: Adjustable tensioner

The following design matrix has been developed to ensure the independent axiom is not violated.

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \\ FR1.3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1 \\ DP1.2 \\ DP1.3 \end{Bmatrix} \tag{6.7}$$

Eq. 6.7 shows that the design is uncoupled at the second level and the independence axiom is not violated. Figure 6.10 shows the remaining part of the decomposition of the high-level functional requirement of FR1.

FRs		DP1	DP2	DPs
Allows flexion and extension	FR1	X		Soft robotic
Support user activity	FR2		X	Activity monitoring tool

FR1 Allows flexion and extension		DP1.1	DP1.2	DP1.3	DPs ↓	
Provides different resistance	FR1.1	X			Active resistance (AR) device	(1)
Continuous passive motion (CPM)	FR1.2		X		CPM device	(2)
Adjustable tension	FR1.3			X	Tensioner	(3)
FR1.1 Provides different resistance		DP1.1.1	DP1.1.2			
Durations of resistance	FR1.1.1	X			Timer device	(4)
Range of resistance	FR1.1.2		X		Control unit	(5)
FR1.2 Continuous passive motion		DP1.2.1	DP1.2.2			
Range of motion (ROM) in degrees	FR1.2.1	X			Goniometers	(6)
Number of cycles	FR1.2.2		X		Counter device	(7)
FR1.3 Adjustable tension		DP1.3.1	DP1.3.2			
Force measurement	FR1.3.1	X			Load cell	(8)
Range of force	FR1.3.2		X		Force sensor	(9)

Figure 6.10: Decomposition of FR1.

Figure 6.11 shows the decomposition of high-level functional requirement of FR2.

FRs		DP1	DP2	DPs
Allows flexion and extension	FR1	X		Soft robotic
Support user activity	FR2		X	Activity monitoring tool

FR2 Support user activity		DP2.1	DP2.2	DP2.3		
Compact	FR2.1	X			Small buffer	(10)
Comfort	FR2.2		X		Soft materials	(11)
Easy to use	FR2.3			X	Touchscreen	(12)
FR2.1 Provides different resistance		DP2.1.1	DP2.1.2	DP2.1.3		
Easy to carry	FR2.1.1	X			Pack with handle	(13)
Portable	FR21.2		X		Modular parts	(14)
Light weight	FR2.1.3			X	Composite material	(15)
Comfort	FR2.2	DP2.2.1	DP2.2.2			
Prevents swelling	FR2.2.1	X			Ice pad	(16)
Easy flexion of PIP or DIP joints	FR2.2.2		X		Wire-Foam and pad	(17)
Easy to use	FR2.3	DP2.3.1	DP2.3.2			
Consistent	FR2.31	X			Software	(18)
Automated	FR2.32		X		Automation Integrator	(17)

Figure 6.11: Decomposition of FR2.

Figure 6.12 shows the combined design matrix of all the levels of FRs and DPs. It represents an uncoupled design. That is, each FR is satisfied by only one DP.

FRs \ DPs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
FR1.1	X																		
FR1.2		X																	
FR1.3			X																
FR1.1.1				X															
FR1.1.2					X														
FR1.2.1						X													
FR1.2.2							X												
FR1.3.1								X											
FR1.3.2									X										
FR2.1										X									
FR2.2											X								
FR2.3												X							
FR2.1.1													X						
FR2.1.2														X					
FR2.1.3															X				
FR2.2.1																X			
FR2.2.2																	X		
FR2.3.1																		X	
FR2.3.2																			X

Figure 6.12: Combined design matrix.