MODULE 6

Axiomatic Design (AD)

Atila Ertas
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Transdisciplinary modules are dedicated to Dr. Raymond T. Yeh and Mr. Bob Block, for their continued support of ATLAS, enthusiasm, dedication, and passion!

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MODULE 6

Axiomatic Design

The grand aim of all science is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypotheses or axioms.

Albert Einstein

6.1 Axiomatic Design (AD)

Axiomatic design (AD) provides discipline-independent representations of a general design process, general criteria for effective decision making, and scalability for complex systems development.[1] Axiomatic design process reduces product development risk, reduces cost, and speeds the time to market. AD was created and developed by Professor Nam Suh of MIT in order to create a science base for design and manufacturing[2]. AD is a valuable methodology for designing complex products and systems. AD theories offer a framework that is reliable for all disciplines and at all levels of detail – it is a transdisciplinary design tool. The AD theory and applications have been later advanced by Suh and others.[3,4,5]

As shown in Figure 6.1, the four domains in AD are called the customer domain, the functional domain, the physical domain, and the process domain. The customer domain is where we expect, "what does the customer want?" in a system, a process or a product. In the functional domain, we consider those customer needs (CN) and describe them in terms of the functional requirements (FR) and constraints (C) that will satisfy the customer needs. Functional requirements define what the system will do. The physical domain describes how to implement a system that satisfies the functional requirements and constraints through design parameters (DP). The process domain describes how to build the system that have been designed. In this domain, Process Variables (PV) will be determined that will allow us to implement the design parameters that have been chosen.

[1]Tate, D., Ertas, A., Tanik, M., and Maxwell, T.T., *A TD Framework for Engineering Systems Research and Education based on Design and Process,* ATLAS TD Modules, 2006.

[2]N. P. Suh, A. C. Bell, and D. C. Gossard, "On an Axiomatic Approach to Manufacturing and Manufacturing Systems," *Journal of Engineering for Industry,* vol. 100, pp. 127-130, 1978 .

[3]M. Nordlund, "An Information Framework for Engineering Design based on Axiomatic Design," in Department of Manufacturing Systems. Stockholm, Sweden: The Royal Institute of Technology (KTH), 1996.

[4]N. P. Suh, *The Principles of Design,* New York: Oxford University Press, 1990.

[5]N. P. Suh, *Axiomatic Design: Advances and Applications,* New York: Oxford University Press, 2001.

The process of moving among domains is called mapping. 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." In this figure, each domain has its own set of elements.

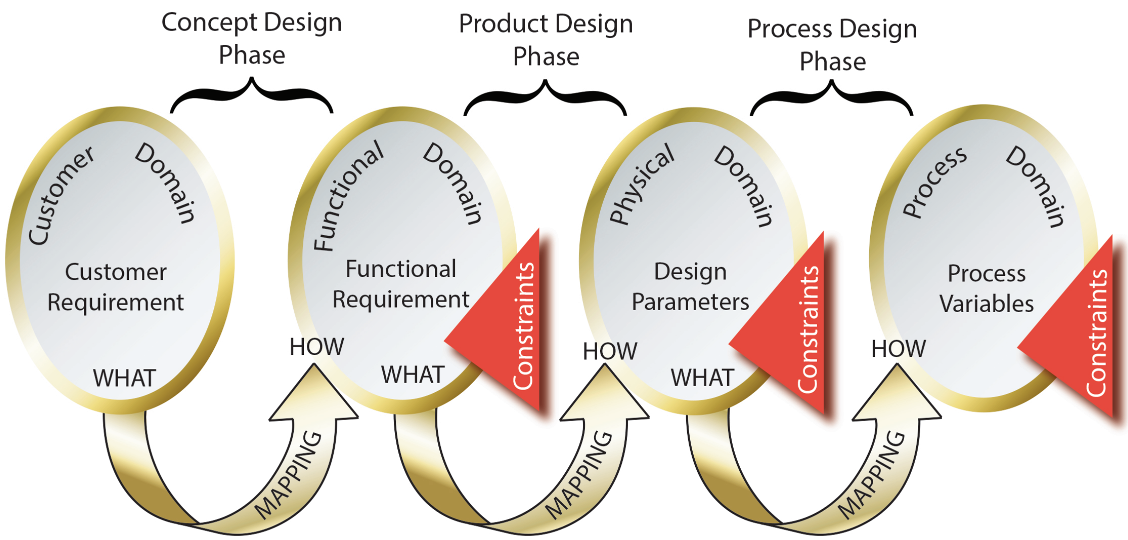

Figure 6.1: Four domains of the design.

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

$$\{\mathbf{CN}\} = [R]\,\{\mathbf{FR}\} \tag{6.1}$$

$$\{\mathbf{FR}\} = [D]\,\{\mathbf{DP}\} \tag{6.2}$$

$$\{\mathbf{DP}\} = [B]\,\{\mathbf{PV}\} \tag{6.3}$$

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

6.1.1 Uncoupled, De-coupled, and Coupled Design

Product design requires the functionality of the final product and how the product will achieve "functional requirements" and how it will achieve "design parameters". Two fundamental AD axioms offer a rational basis for the evaluation of given solution alternatives. The two axioms are defined as follows:[5]

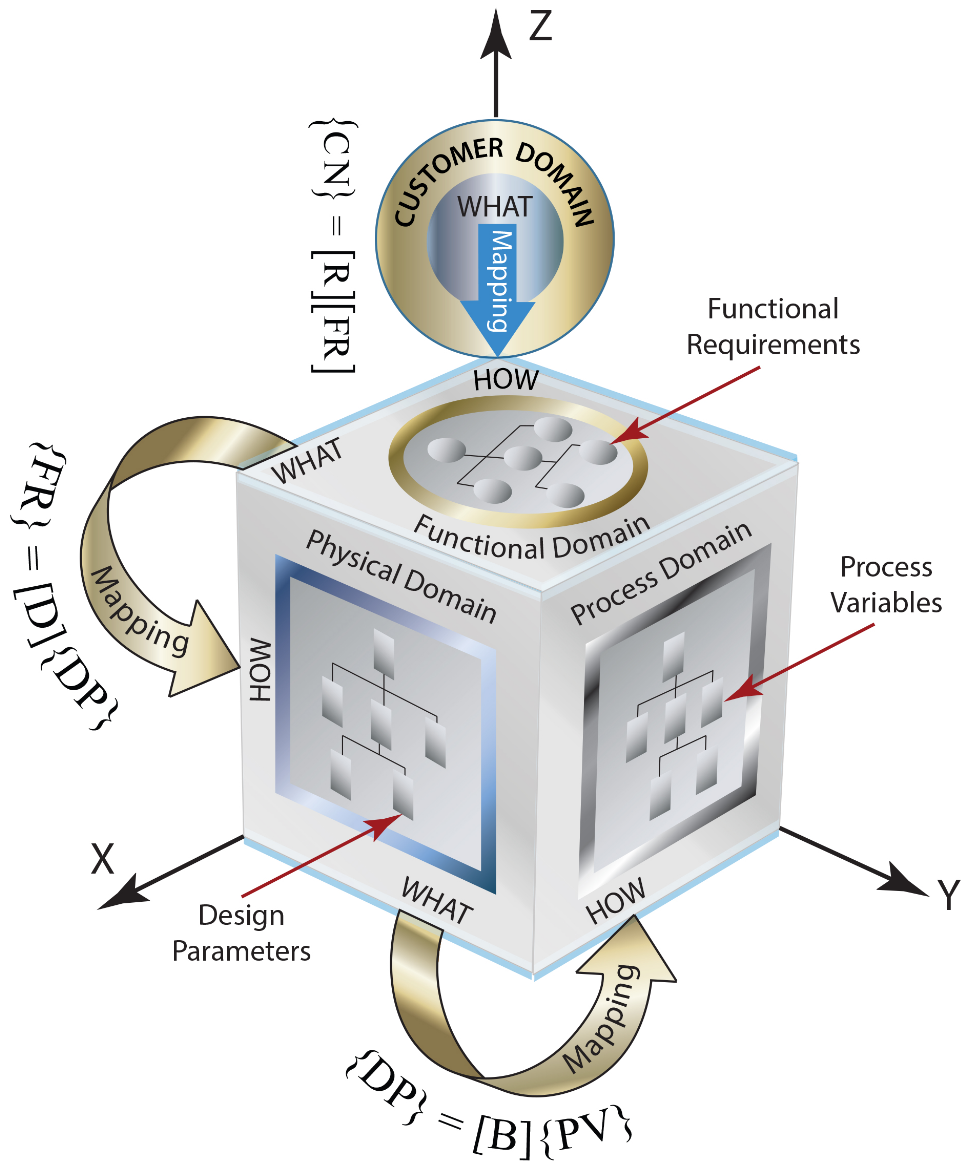

Figure 6.2: Design domains.

6.1.1.1 Independence Axiom

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

As defined in Eq. 6.4, the design matrix **D** shows the relationships between functional requirements and design parameters.

$$\{\mathbf{FR}\} = [D]\,\{\mathbf{DP}\} \tag{6.4}$$

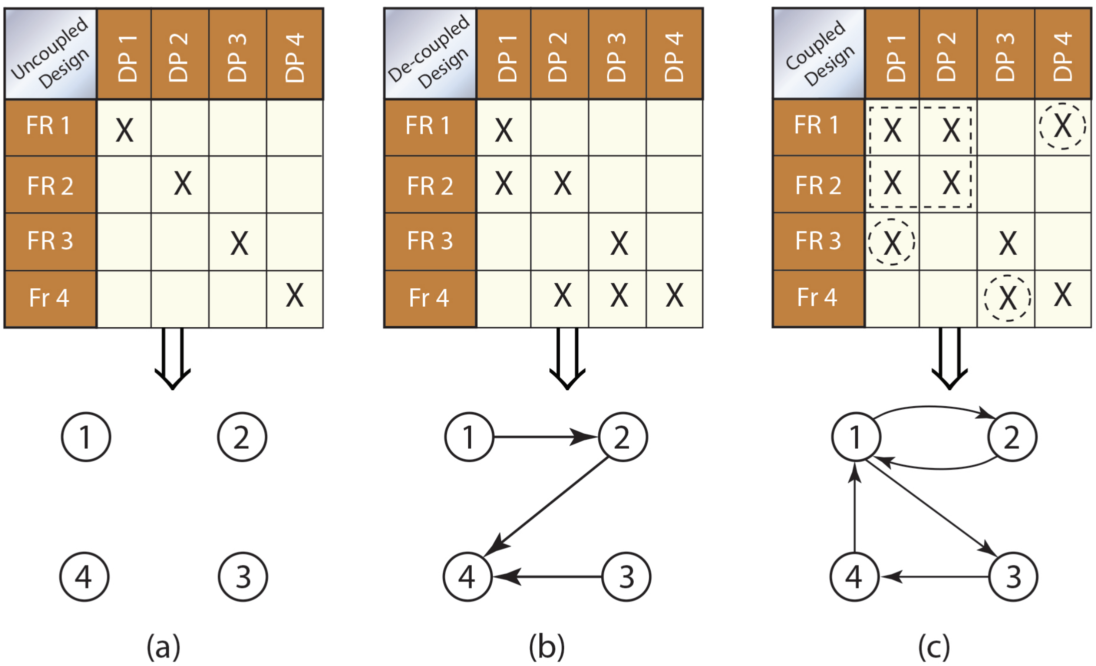

Figure 6.3: (a) Uncoupled design, (b) De-coupled design, (c) Coupled design.

As shown in Figure 6.3(a), each functional requirement is satisfied independently by its corresponding design parameter without affecting the other functional requirements. This is called an uncoupled design matrix and it satisfies the independence axiom. This is the ideal case but most design solutions will not have this situation.

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(c) is a coupled design as it has two cycles shown with dashed lines. In other words, the relationship between the design parameters and their functional requirements is circular – DP1 affects FR1 and FR2 and similarly, DP2 affects the same functional requirements (shown in square dashed lines). The other cycle is between DP1, DP3, and DP4. In previous sections of this chapter covered how to eliminate the effect of cycles so that the design map can be better understood.

6.1.1.2 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. The Information Axiom emphasizes design optimization, offering a solution that fully implements the functional requirements with the minimum set of components and interfaces – minimize the information content of the design. Among all the design alternatives that satisfy the independence axiom the one that possesses the least information is the best choice.

EXAMPLE 6.1

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

SOLUTION

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).

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

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

As described previously, in the physical domain, we determine how to implement the product (in this case two handle facets) that satisfies the defined functional requirements – our decisions will create design parameters. In other words, in the functional domain, the functional requirements answer the question of "what is the two handle facet supposed to do?" In the physical domain, we ask, "how do we build a product that will satisfy the functional requirements?" The answers to this question become the Design Parameters.

EXAMPLE 5.4 (Continued)

Two adjustments of two handle facets will have a hot water knob which provides DP1 (θ_1) and cold water knab which provides DP2 (θ_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:

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

Substituting FRs and DPs in Eq. 6.5, we have

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

As seen from the above 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.

Coupled Design	DP1	DP2
FR1	X	X
FR2	X	X

(a)

Uncoupled Design	DP1	DP2
FR1	X	
FR2		X

(b)

Figure 6.5: (a) Coupled design, (b) Uncoupled design.

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, θ 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.

6.1.2 Zigzagging and Decomposition

AD methodology proposes that the system design process should start from the high level (abstract) and continue through lower levels of more detail until the point where the system design is defined with enough detail – the highest-level design should be decomposed to develop design details that can be implemented. It should be noted that while decomposing the highest-level design, the lower-level design decisions must be consistent with the highest-level design goal. During every step of the design decisions, the Independence Axiom should not be violated. 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.

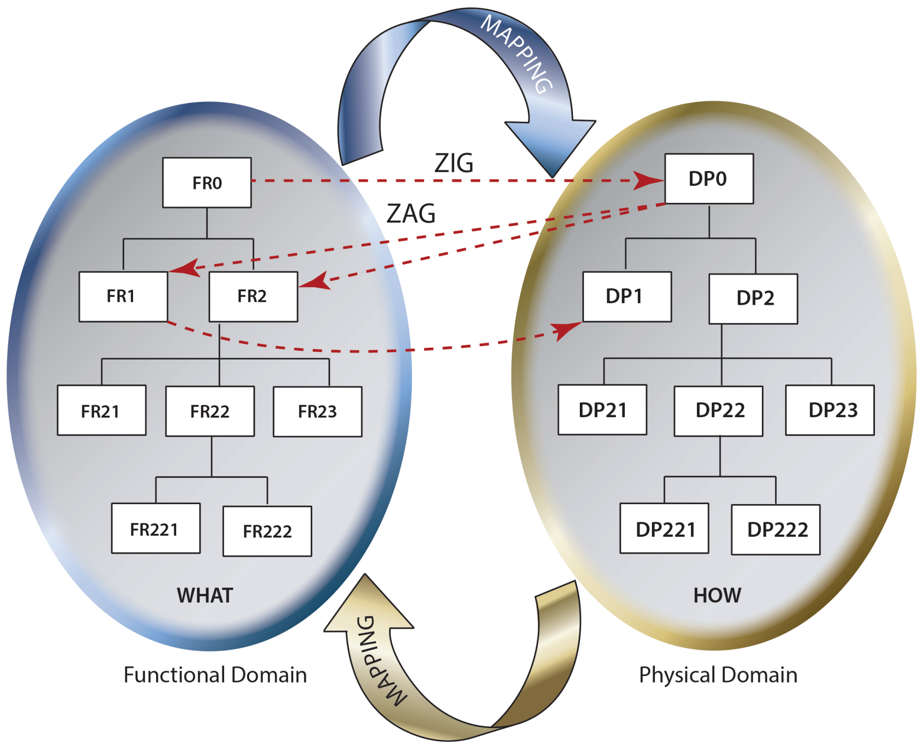

Figure 6.6: Zigzagging to decompose FRs and DPs.

After grouping and abstracting exercises and understanding the importance of each customer's need, a set of customer needs will be identified. Each of the customer needs will be then translated into top-level functional requirements (see FR0 in Figure 6.6). This initial step determines the starting point for the further decomposition into additional levels of FRs

The decomposition will allow us to the development of design matrices for each FR level. Each of the FRs will be evaluated with respect to the associated DPs. Using *zigzagging* and striving to maintain independence within each matrix, additional FR levels will be developed (see Figure 6.6). A list of design constraints will also be developed from the customer's needs.

CASE STUDY 6.1

Design a home entertainment system that will be used by a middle-aged male, living in a suburban setting. The system would typically be located in a medium-size room in a modest suburban home where neighbors are far enough away that a medium volume is tolerable by most neighbors. Use Axiomatic Design principles.[a]

SOLUTION

The first step is to develop a list of the customers' needs (requirements) (CRs). To define the customer needs, each member of the design team performed a survey of several people that fit the chosen customer profile. Each survey yielded a list of customer needs and constraints that were then compared and evaluated as a whole. Through the survey, after understanding and defining what the customer needs are, the design team performed a "grouping and abstracting" exercise to develop a brief, but concise list of high-level following customer needs.

CR1: The home entertainment system must have video capability

CR2: The home entertainment system must have audio capability

CR3: The home entertainment system must have storage capability

Each of the above Customer Need's were then translated into top-level following functional requirements.

FR1: Play audio media

FR2: Show video media

FR3: Storage

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.

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

DP1: Audio equipment

DP2: Video equipment

DP3: Storage capability

[a] Adapted from transdisciplinary class project submitted to Dr. D. Tate and Dr. A. Ertas by MS student team: Jim Hart, Tim Smith, and John Wright, (2003). Designing home entertainment system. Mechanical Engineering Department, Texas Tech University.

CASE STUDY 6.1 (continued)

The DPs that are selected to fulfill the high-level FRs provide some insights into the home entertainment system. Formulation of the design matrix for this initial level of decomposition is shown in matrix Eq. 6.7. The design matrix shown in Eq. 6.7 should be formulated for each level to avoid violating the Independence Axiom

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{6.7}$$

Eq. 6.7 reveals that the design is decoupled at the top level and the independence axiom is not violated. This conceptual design developed a minimum set of requirements that resulted in the first level requirements (FR1 - FR3) of playing audio, showing video, and storage. This initial step determined the starting point for the further decomposition into two additional levels of FRs. A road map for the first two levels of decomposition is presented in Figure 6.7.

Next, using zigzagging and striving to maintain independence within each matrix, the team developed additional FR levels. Since all the FRs will follow a similar decomposition format, for briefness, only FR1 (play audio media) decomposition will be shown.

FR1.1: Play cassette

FR1.2: Play CD

FR1.3: Play LP

FR1.4: Play MP3

FR1.5: Provide surround sound

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

DP1.1: Cassette player

DP1.2: CD player

DP1.3: Turntable

DP1.4: Computer audio interface

DP1.5: Emplifier and speaker equipment

Next, the following design matrix will be develop to ensure the second axiom is not violated.

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \\ FR1.3 \\ FR1.4 \\ FR1.5 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ X & X & X & X & X \end{bmatrix} \begin{Bmatrix} DP1.1 \\ DP1.2 \\ DP1.3 \\ DP1.4 \\ DP1.5 \end{Bmatrix} \tag{6.8}$$

Eq. 6.8 shows that the design is decoupled at the second level and the independence axiom is not violated.

CASE STUDY 6.1 (continued)

A road map for the first two levels of decomposition is presented in Figure 6.7.

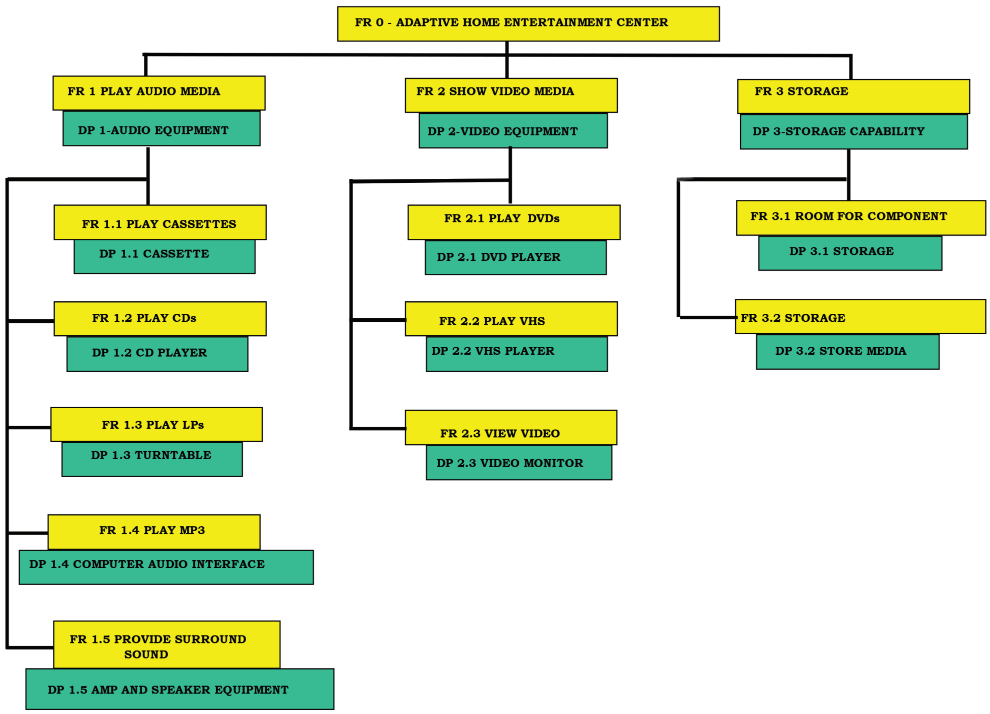

Figure 6.7: Design road map (from reference [a]).

The design team evaluated each of the FRs with respect to the associated DPs. Additional FR levels were developed using zigzagging and striving to maintain independence within each matrix. On the more complicated FRs, the team recognized the need to decompose to at least a fourth, and perhaps, fifth level, particularly on the more complex components (Audio Amplifier). In doing this, the team was able to uncouple each FR matrix and maintain independence between the FRs. Each of the FRs created led to a DP that could be used to clearly write a design specification with verification capability. The decomposition of the top-level FRs and constraints resulted in a thorough flow-down of the top-level design requirements. The first level decomposition structure and matrices are presented in Figure 6.8 and Figure 6.9.

CASE STUDY 6.1 (continued)

		DP1	DP2	DP3	
Play audio media	FR1	X			Audio equipment
Show video media	FR2		X		Video Equipment
Storage	FR3	X	X	X	Entertainment Center cabinet

FR 1-PLAY AUDIO MEDIA		DP1.1	DP1.2	DP1.3	DP1.4	DP1.5				
Play Cassette	FR1.1	X								Cassette player
Play CD	FR1.2		X							CD Player
Play LP	FR1.3			X						Turntable
Play MP3	FR1.4				X					Computer Audio Interface
Provide Surround Sound	FR1.5	X	X	X	X	X				Amplifier and speaker equipment

FR 1.1-Cassette Player		DP1.1.1	DP1.1.2	DP1.1.3	DP1.1.4	DP1.1.5	DP1.1.6			
Play Cassette	FR1.1.1	X								primary play head
Record another Cassette	FR1.1.2	X	X							dual-cassettes
Provide audio output to amplifier	FR1.1.3	X	X	X						Audio-output connections
Record other audio inputs	FR1.1.4	X	X		X					Audio input connection from amplifier
Keep track of tape	FR1.1.5					X				mechanical counter
Controlled from Amp remote	FR1.1.6	X	X	X			X			RF activated sensor
FR 1.2-CD Player		DP1.2.1	DP1.2.2	DP1.2.3	DP1.2.4	DP1.2.5	DP1.2.6			
Play CD	FR1.2.1	X								CD laser and drive
Music sequencing selectable/programmable	FR1.2.2	X	X							programming electronics
Multiple CD Loads	FR1.2.3		X	X						CD carousel
Provide audio output to amplifier	FR1.2.4				X					Audio output connection from amplifier
Keep track of CD/track play	FR1.2.5					X				Electronic status register
Remote controlled play/track selection	FR1.2.6	X	X	X			X			RF activated sensor
FR 1.3-Turntable		DP1.3.1	DP1.3.2	DP1.3.3	DP1.3.4	DP1.3.5	DP1.3.6			
Rotate LP	FR1.3.1	X								Table
Allow Speed control	FR1.3.2	X	X							Table speed control
Stabilize turntable speed	FR1.3.3	X	X	X						Rotation speed servo loop
Generate audio signal from LP	FR1.3.4				X					Stylus
Provide audio output to amplifier	FR1.3.5					X				Audio output connection from amplifier
Remote controlled play/track selection	FR1.3.6						X			RF activated sensor
FR 1.4-Computer Audio Interface		DP1.4.1	DP1.4.2	DP1.4.3						
Accept audio input from computer	FR1.4.1	X								Audio input jack
Pre-amplify MP3 input	FR1.4.2	X	X							pre-amplifier
Provide amplified audio output	FR1.4.3		X	X						Audio output jack
FR 1.5-Amplifier and speaker equipment		DP1.5.1	DP1.5.2	DP1.5.3	DP1.5.4	DP1.5.5	DP1.5.6	DP1.5.7	DP1.5.8	
Accept input from audio sources	FR1.5.1	X								input audio section
Select audio input for amplification	FR1.5.2	X	X							audio input select section
Decode audio input for surround sound	FR1.5.3	X	X	X						Audio decoder section
Amplify audio signal	FR1.5.4				X					Power section
Manage input power for other components	FR1.5.5					X				Power management section
Accept and translate remote signal	FR1.5.6						X			Remote control translator section
Provide audio drive to speakers	FR1.5.7							X		output connection section
Reproduce audio from drive input	FR1.5.8								X	Speaker section
AM/FM Tuner										

Figure 6.8: First level decomposition structure and matrices (from reference [a]).

Figure 6.9 shows the combined design matrix of all of the first-level FRs and DPs. It represents an uncoupled design. That is, each FR is satisfied by only one DP.

CASE STUDY 6.1 (continued)

Design Parameters

Functional Requirements

Numbers	1.1.1	1.1.2	1.1.3	1.1.4	1.1.5	1.1.6	1.2.1	1.2.2	1.2.3	1.2.4	1.2.5	1.2.6	1.3.1	1.3.2	1.3.3	1.3.4	1.3.5	1.3.6	1.4.1	1.4.2	1.4.3	1.5.1	1.5.2	1.5.3	1.5.4	1.5.5	1.5.6	1.5.7	1.5.8
1.1.1	X																												
1.1.2		X																											
1.1.3			X																										
1.1.4				X																									
1.1.5					X																								
1.1.6						X																							
1.2.1							X																						
1.2.2								X																					
1.2.3									X																				
1.2.4										X																			
1.2.5											X																		
1.2.6												X																	
1.3.1													X																
1.3.2														X															
1.3.3															X														
1.3.4																X													
1.3.5																	X												
1.3.6																		X											
1.4.1																			X										
1.4.2																				X									
1.4.3																					X								
1.5.1																						X							
1.5.2																							X						
1.5.3																								X					
1.5.4																									X				
1.5.5																										X			
1.5.6																											X		
1.5.7																												X	
1.5.8																													X

Figure 6.9: First level combined design matrix.

CASE STUDY 6.1 (continued)

FR 2-SHOW VIDEO MEDIA		DP2.1	DP2.2	DP2.3						
Play DVD	FR2.1	X								DVD Player
Play VHS	FR2.2		X							VHS Player
View Video	FR2.3			X						Video monitor
FR 2.1-DVD Player		DP2.1.1	DP2.1.2	DP2.1.3	DP2.1.4	DP2.1.5				
Play DVD Video media	FR2.1.1	X								DVD Player section
Accept remote control	FR2.1.2		X							Control section
Display play info	FR2.1.3	X	X	X						Display section
Accept Manual control	FR2.1.4	X	X	X	X					Front panel section
Provide S-video Output	FR2.1.4					X				Output connection
FR 2.2-VHS Player		DP2.2.1	DP2.2.2	DP2.2.3	DP2.2.4	DP2.2.5	DP2.2.6	DP2.2.7		
Play VHS Video media	FR2.2.1	X								VHS Play section
Record VHS	FR2.2.2		X	X	X					VHS Recorder section
Display status info	FR2.2.3			X			X			Display section
Accept Manual control	FR2.2.4				X					Front panel section
Provide TV/cable tuning	FR2.2.5					X				TV Tuner
Accept remote control	FR2.2.6						X			Remote control section
Provide Video Output	FR2.2.7							X		Output connections
FR 2.3- Video monitor		DP2.3.1	DP2.3.2	DP2.3.3	DP2.3.4	DP2.3.5	DP2.3.6			
Accept mutiple Video sources	FR2.3.1	X								Input Video section
Switch Video	FR2.3.2		X							Video Switch section
Provide PIP	FR2.3.3			X						PIP Generator
Display Status	FR2.3.4				X					Status display
Accept remote control	FR2.3.5					X				Remote control section
Show video	FR2.3.6						X			Video
Storage		DP3.1	DP3.2							
Room for components	FR 3.1	X								Stack-up
Storage for media	FR 3.2		X							Storage section
FR 3.2- Storage for media		DP3.2.1	DP3.2.2	DP3.2.3	DP3.2.4	DP3.2.5				
Room for DVD	FR3.2.1	X								DVD storage area
Room for CD	FR3.2.2		X							CD storage area
Room LP	FR3.2.3			X						LP Storgae area
Room VHS	FR3.2.4				X					VHS storage area
Room Cassette	FR3.2.5					X				Cassette storage area

Figure 6.10: Second level decomposition structure and matrices (from reference [a]).

Design Parameters (DPs)

Functional Requirements (FRs)

	2.2.1	2.2.2	2.2.3	2.2.4	2.2.5	2.2.6	2.2.7
2.2.1	X						
2.2.2		X	X	X			
2.2.3			X			X	
2.2.4				X			
2.2.5					X		
2.2.6						X	
2.2.7							X

(a)

Design Parameters (DPs)

Functional Requirements (FRs)

	2.2.1	2.2.4	2.2.5	2.2.6	2.2.7	2.2.3	2.2.2
2.2.1	X						
2.2.4		X					
2.2.5			X				
2.2.6				X			
2.2.7					X		
2.2.3				X		X	
2.2.2		X				X	X

(b)

Figure 6.11: Coupled design.

Figure 6.10 shows the second-level decomposition structure and matrices. As seen from Figure 6.11(a), FRs and DPs should be manipulated to form a lower triangular matrix. After obtaining the lower triangular matrix (see Figure 6.11(b), the combined design matrix of all of the second and third levels FRs and DPs is developed (see Figure 6.12)

CASE STUDY 6.1 (continued)

Design Parameters

Functional Requirements

Numbers	2.1.1	2.1.2	2.1.3	2.1.4	2.2.1	2.2.4	2.2.5	2.2.6	2.2.7	2.2.3	2.2.2	2.3.1	2.3.2	2.3.3	2.3.4	2.3.5	2.3.6	3.2.1	3.2.2	3.2.3	3.2.4	3.2.5
2.1.1	X																					
2.1.2		X																				
2.1.3			X																			
2.1.4				X																		
2.2.1					X																	
2.2.4						X																
2.2.5							X															
2.2.6								X														
2.2.7									X													
2.2.3								X		X												
2.2.2						X				X	X											
2.3.1												X										
2.3.2													X									
2.3.3														X								
2.3.4															X							
2.3.5																X						
2.3.6																	X					
3.2.1																		X				
3.2.2																			X			
3.2.3																				X		
3.2.4																					X	
3.2.5																						X

Figure 6.12: Second and third levels combined design matrix.

CASE STUDY 6.1 (continued)

A list of design constraints was also developed from the Customer Needs. The team developed a constraints matrix that was used to assign each constraint to DPs at the various levels (see Figures 13, 14, and 15).

		Capable of playing all existing tape technologies	RF remote control required	Be able to load a minimum of 3 CDs	All components must be off-the-shelf	Must support 33rpm and 45 rpm, minimum	Capable of playing all MP3 variations	Minimum of 100 watts per channel	Bose Acoustimas 7 system	Minimum requirement of DTS 5.0	DVD storage: 50 minimum	CD storage: 100 minimum	LP storage: 25 minimum	VHS storage: 25 minimum	Cassette storage: 25 minimum
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
	Audio equipment	X	X	X	X	X	X	X	X						
	Video Equipment		X		X					X	X				
	Entertainment Center cabinet											X	X	X	X
DP1.1	Cassette player				X										
DP1.2	CD Player			X	X										
DP1.3	Turntable				X										
DP1.4	Computer Audio Interface						X								
DP1.5	Amplifier and speaker equipment				X		X	X	X						
DP1.1.1	primary play head	X													
DP1.1.2	dual-cassettes	X													
DP1.1.3	Audio-output connections														
DP1.1.4	Audio input connection from amplifier														
DP1.1.5	mechanical counter														
DP1.1.6	RF activated sensor	X													
DP1.2.1	CD laser and drive														
DP1.2.2	programming electronics														
DP1.2.3	CD carousel			X											
DP1.2.4	Audio output connection from amplifier														
DP1.2.5	Electronic status register														
DP1.2.6	RF activated sensor														
DP1.3.1	Table					X									
DP1.3.2	Table speed control					X									
DP1.3.3	Rotation speed servo loop					X									
DP1.3.4	Stylus														
DP1.3.5	Audio output connection from amplifier														
DP1.3.6	RF activated sensor		X												
DP1.4.1	Audio input jack						X								
DP1.4.2	pre-amplifier						X								
DP1.4.3	Audio output jack						X								

Figure 6.13: Design constraints matrix (from reference [a]).

CASE STUDY 6.1 (continued)

		Capable of playing all existing tape technologies	RF remote control required	Be able to load a minimum of 3 CDs	All components must be off-the-shelf	Must support 33rpm and 45 rpm, minimum	Capable of playing all MP3 variations	Minimum of 100 watts per channel	Bose Acoustimas 7 system	Minimum requirement of DTS 5.0	DVD storage: 50 minimum	CD storage: 100 minimum	LP storage: 25 minimum	VHS storage: 25 minimum	Cassette storage: 25 minimum
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
DP1.5.1	input audio section						X								
DP1.5.2	audio input select section						X								
DP1.5.3	Audio decoder section						X								
DP1.5.4	Power section							X							
DP1.5.5	Power management section														
DP1.5.6	Remote control translator section		X												
DP1.5.7	output connection section								X	X					
DP1.5.8	Speaker section								X	X					
DP1.5.9	AM/FM Tuner														
DP2.1	DVD Player														
DP2.2	VHS Player														
DP2.3	Video monitor														
DP2.1.1	DVD Player section														
DP2.1.2	Control section														
DP2.1.3	Display section														
DP2.1.4	Front panel section														
DP2.1.5	Output connection														
DP2.2.1	VHS Play section														
DP2.2.2	VHS Recorder section														
DP2.2.3	Display section														
DP2.2.4	Front panel section														
DP2.2.5	TV Tuner														
DP2.2.6	Remote control section		X												
DP2.2.7	Output connections														
DP2.3.1	Input Video section														
DP2.3.2	Video Switch section														
DP2.3.3	PIP Generator														
DP2.3.4	Status display														
DP2.3.5	Remote control section		X												
DP2.3.6	Video										X				

Figure 6.14: Design constraints matrix (continued).

CASE STUDY 6.1 (continued)

		Capable of playing all existing tape technologies	RF remote control required	Be able to load a minimum of 3 CDs	All components must be off-the-shelf	Must support 33rpm and 45 rpm, minimum	Capable of playing all MP3 variations	Minimum of 100 watts per channel	Bose Acoustimas 7 system	Minimum requirement of DTS 5.0	DVD storage: 50 minimum	CD storage: 100 minimum	LP storage: 25 minimum	VHS storage: 25 minimum	Cassette storage: 25 minimum
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
DP3.1	Stack-up														
DP3.2	Storage section										X	X	X	X	X
DP3.2.1	DVD storage area										X				
DP3.2.2	CD storage area											X			
DP3.2.3	LP Storgae area												X		
DP3.2.4	VHS storage area													X	
DP3.2.5	Cassette storage area														X

Figure 6.15: Design constraints matrix (continued).

Note that, each of the lower-level FRs and DPs could be decomposed into even lower levels of FRs, DPs, and Cs (for example television types, television screen sizes, music sampling rates, etc); however, the design team decided not to proceed with any additional decomposition. These additional levels would; however, be required in "real-life" programs in order to further define the program into the clearest possible set of FRs, DPs, and Cs.