6 How Should We Select Functional Requirements?

Nam Pyo Suh

Abstract

The preceding chapters provided broad outlines of the design of various systems based on Axiomatic Design (AD). Two axioms were the basis of making design decisions: the Independence Axiom and the Information Axiom. The process of AD consists of the transformation of the problem identified in the "customer domain" into a set of functional requirements (FRs) in the "functional domain," which was in turn transformed as design parameters (DPs) in the "physical domain" that are chosen to satisfy FRs. DPs were, in turn, transformed into process variables (PVs) in the "process domain" to fulfill DPs. The mapping process was illustrated.

Once the highest FRs and DPs are finalized at the highest level of the system design hierarchy, we may have to decompose FRs and DPs, if the selected FRs and DPs lack sufficient details to complete the design. This decomposition process must continue until the design has enough details that can be implemented. To decompose, we should zigzag between FR and DP domains. Similarly, DP versus PV can be decomposed through zigzagging.

The resulting designs were classified as uncoupled, decoupled, and coupled designs. Coupled designs violate the Independence Axiom and, thus, should not be implemented. They are unreliable and require monitoring, resulting in the waste of resources, cost overruns, and delays in implementation. When a system design is uncoupled, it can readily be satisfied because each FR is a function of only one DP, irrespective of the total number of FRs and DPs that the system has to satisfy. The design matrix is constructed to identify coupling. Throughout these chapters, "real-life" examples were presented.

The quality of the design is determined by how well the problem is identified and how FRs are selected. Although every step of the transformation is essential,

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the selection of FRs ultimately determines the functional quality of the design output. It is helpful to have an in-depth understanding of basic sciences, engineering, and other relevant fields to be proficient in system design. It may also take different kinds of information, depending on the field. In designing commercial products, market information on the current state and prospect is critical in selecting the right set of FRs. In other fields, such as the economy, the set of information required to choose the right set of FRs would be entirely different. However, the basic system structure is similar. The domain-specific knowledge is field-specific.

In this chapter, the process of selecting FRs is elaborated further. One of the essential concepts to remember in selecting FRs is the idea of choosing them in a "solution-neutral environment," that is, the designer should not think of a design solution first and then define FRs for the assumed solution. Given the critical importance of selecting the right set of FRs for the problem identified, the designer should have a broad knowledge base and also access to extensive "database for scientific facts and various technologies," including the commercial database for existing products.

6.1 Importance of "Solution-Neutral Environment" in Selecting Functional Requirements

The preceding chapters provided broad outlines of the design of various systems based on AD. Two axioms were the basis of making design decisions: the Independence Axiom and the Information Axiom. The process of AD consists of the transformation of the problem identified in the "customer domain" into a set of FRs in the "functional domain," which was in turn transformed as DPs in the "physical domain" that are chosen to satisfy FRs. DPs were, in turn, transformed into PVs in the "process domain" to satisfy DPs. The mapping process was illustrated.

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Example 6.1 Lesson Learned: Role of *Solution-Neutral Environment* in Developing On-Line Electric Vehicle (OLEV)[1]

In Chap. 3, the basic design of OLEV (on-line electric vehicle) was presented by giving details of the design of the shaped magnetic field in resonance (SMFIR). In this chapter, the background story will be presented to illustrate the difficulties one may encounter in undertaking innovative R&D projects to show the importance of thinking in a "solution-neutral environment" in creating innovative products.

As mentioned in a previous chapter, in 2006, KAIST (Korea Advanced Institute of Science and Technology) designed a new plan to make it one of the best universities in the world in science and technology. To achieve this goal, one of the FRs chosen for the new KAIST strategic plan was to solve some of the most critical problems of the world in the twenty-first century. One of the issues identified was "global warming." To solve this problem, we decided to replace all internal combustion (IC) engines used in automobiles with electric drives (EV). Such a shift from IC to EV would reduce the anthropogenic emission of CO_2 by about 27%. Also, to avoid many problems associated with using a large number of batteries to propel all-electric vehicles, the decision was made to transmit electric power wirelessly to the vehicle from underground electrical power supply systems. We named it the on-line electric vehicle (OLEV). KAIST approached the government of the Republic of Korea for significant funding ($\sim$about $25 million during the first year, a large sum of money for research and development, by any measure).

[1]OLEV was partly introduced in Chap. 3 to illustrate the design process.

When the Korean government tentatively agreed to fund this OLEV project pending the congressional budget approval, two unexpected things happened. First, none of the KAIST professors who were specialists in electric power would be willing to lead this project, stating that the idea of transmitting 100 kW of electric power wirelessly over a distance of 20 $\sim$ 25 cm could not be done technologically. They claimed that the idea was meritless, although they were too polite to use these words! Therefore, the KAIST administration organized a project team led by professors who were not specialists in heavy electric power engineering. They did a great job because they were able to design a new system based on the first principles of electromagnetism and AD.

The second event was much more serious. Some of the professors at other universities, who were working on battery-powered electric automobiles, mounted a significant opposition to the KAIST project. They mobilized a member of the National Congress (equivalent to the U.S. Congress) with a Ph.D. in physics from a university in the U.S. and former professor of physics in Korea to mount a significant opposition campaign to the KAIST OLEV project. They argued that such massive electric power ($\sim$100 kW) could not be transmitted wirelessly over a distance of over 20 cm, similar to the argument presented by some specialists in KAIST. (For proprietary reasons, we could not reveal the basic idea behind OLEV.) They unduly interfered with the project proposal review process to stop the funding of the KAIST project. KAIST president was called in to answer questions at a special meeting of the National Assembly (i.e., counterpart the U.S. Congress) of Korea. The opposition to OLEV was based on their claim that the proposed idea was not technically feasible. This incident is similar to the opposition mounted in the United States against the NSF Engineering Research Centers (ERC) program when it was launched in 1985, albeit based on a different argument.

The professors who opposed the OLEV project were not thinking in a "solution-neutral environment." Instead of thinking about the goal of transmitting vast electric power over a considerable distance in a solution-neutral environment, they were thinking of the well-established designs that have been used in electric power transformers, where the primary coil is adjacent to the secondary coil. OLEV was based on the idea of creating an oscillating magnetic field of required shape and strength by controlling the distance between the two magnetic poles. The idea was generated based on the principles taught in undergraduate physics courses by people who were not specialists in heavy electric power transmission.

The KAIST project ultimately received its funding after a great deal of effort to overcome the opposition of influential professors at two leading universities and some members of the National Congress. It took 2 years—a short time after receiving the grant to develop OLEV and install it in Seoul Grand Park and entertain people around the park. Throughout the execution of the project, we made sure that there was no coupling of FRs by creating "system architects," who monitored design decisions made by various groups to be sure that no one in the design team introduced coupled designs. Now OLEV buses are running in five cities in Korea. AD played a significant role in achieving this feat.

Thinking in a solution-neutral environment is essential for creative design, which is a difficult thing to do for people with extensive design experience. The human instinct is to go directly to a solution without defining FRs.

Example 6.2 Space Life Support Systems[2]

The closed system human life support architecture now implemented in the International Space Station has been virtually unchanged for 50 years. In contrast, brief missions such as Apollo and Shuttle have used open-loop life support. As mission length increases, greater system closure and increased recycling become more cost-effective. Closure can be gradually increased, first recycling humidity condensate, then hygiene waste water, urine, carbon dioxide, and water recovery brine. A long-term space station or planetary base could implement nearly full closure, including food production. Dynamic systems theory supports the axioms by showing that fewer requirements, fewer subsystems, and fewer interconnections all increase system stability. If systems are too complex and interconnected, reliability is reduced, making operations and maintenance more difficult.

Using AD, we need to show how the mission duration and other requirements determine the best life support system design, including the degree of closure in a solution-neutral environment. The highest level FR and DP are as follows:

FR = Support human life in space;
DP = Life support system.

The next-level FRs and DPs may be stated in a solution-neutral environment by decomposing FR1 and DP1 as follows:

FR1 = Provide atmosphere (transmit oxygen to humans[3]);
FR2 = Provide water (maintain healthy level of water in humans);
FR3 = Handle waste (remove gas waste products);
FR4 = Suppress fire (restrict combustion to designated areas);
FR5 = Provide food (maintain healthy level of nutrition in humans).

DP1 = Atmosphere system;
DP2 = Water system;
DP3 = Waste system;
DP4 = Fire system;
DP5 = Food system.

H.W. Jones states the following:

"A key method of the AD approach is to match each requirement with its design implementation at each stage of the top-down elaboration of the requirements. The lower level requirements are more specific and detailed. This approach is a deliberate direct contrast to the usual method of creating a detailed multilevel requirements tree, freezing it, and then developing the hardware design to meet that set of detailed requirements. It is supposed, but rarely happens, that the requirements are developed without assuming some system design."

"While it helps in clarifying requirements, the main purpose of going back and forth between requirements and systems in the AD approach is to ensure maximum decoupling of each requirement from the systems implementing other requirements. The extent of decoupling obtainable can be limited by the environment and the available hardware systems."

[2]From Jones (2017).
[3]FRs in italics were suggested alternate statements by a reviewer of this chapter.

The design matrix [DM] for the above FRs and FPs is given as follows by Jones (2017):

	DP5: Food system	DP4: Fire system	DP3: Waste system	DP1: Atmosphere system	DP2: Water
FR5: Provide food	X				
FR4: Suppress fire		X			
FR3: Handle waste	X (food and packaging waste)		X		
FR1: Provide atmosphere		X (De- and re-pressurize)		X	
FR2: Provide water			X (extract water)		X

The above design given by H. W. Jones is a decoupled design given by the above design matrix. This design matrix satisfies the Independence Axiom.

Example 6.3 Consequences of Operating with Wrong FRs: Eastman Kodak Company

The importance of selecting the right set of FRs cannot be over-emphasized. Consider the case of Eastman Kodak. It was one of the most successful companies until about 1980. They dominated the camera and film business. They employed thousands of people and created the City of Rochester, New York. (The founder of the company, George Eastman, even gave a sizable gift to MIT to build the current campus on the bank of Charles River in Boston, changing the name from Boston Polytechnic Institute to the Massachusetts Institute of Technology. Without the money, MIT might have become a part of Harvard!) There were outstanding engineers, scientists, managers, and executives who made Eastman Kodak a leading industrial firm in the world. They pioneered silver-halide-based photography technologies well into the twentieth century.

Today, the company does not exist anymore. It is not appropriate to blame anyone or a group of people. However, the board of the company should bear the most blame because it is their function to be sure that the company is headed in the right direction by hiring an able leader as the Chief Executive Officer of the company. Apparently, "they dropped the ball." In many of these situations, however, it is the CEO who should bear the primary responsibility, because CEO's job is to steer that company toward success by taking appropriate actions to make the company successful. CEOs of companies are highly compensated because CEO's actions indeed determine the success of corporate goals. One of the last CEOs at Kodak, the board of directors hired, had made his reputation in semiconductor and electronics business, and yet he persisted, thinking that the silver-halide system could compete with the electronic photography business. He chose a wrong set of the highest level FRs!

When the electronic camera was being introduced, the upper management of Eastman Kodak continued to believe in the silver-halide system of making images on thin polymeric films and printing them on photographic paper. The irony is that Eastman Kodak was one of the first companies to develop electronic photography.[4] In hindsight, it is clear that the top management of Kodak chose a wrong set of FRs. They believed in the superiority of the silver-halide system because the company continued to improve the silver-halide system. Also financially, they had so much invested in old photography business based on the silver-halide system that they could not believe that digital technology could ever overtake their traditional business and obsolete their massive capital investment. When the digital camera was becoming popular, they even imported a top manager from electronics and semiconductor business, but he also became a convert to the old silver-halide system of photography. They did not fathom how fast semiconductor technology would miniaturize images (i.e., pixels per inch) and how digital technology would transform the communication technology involving images. Therefore, they did not fully support their digital technology group, although they got into digital photography first, because they could not foresee such rapid progress of electronic photography and demise of the old photography business in the marketplace. Because of the mindset of the top executives of Eastman Kodak, the lower level managers set the goal of saving cost and increasing productivity as their goals.[5] Many of them have done outstanding jobs, but they were not the captains of the ship.

The cited example above illustrates the importance of "knowledge" and the ability to make the right decisions in selecting the right set of FRs based on the available knowledge on a periodic basis. It also illustrates the conflict in decision-making between the short-term profits and creating new business by gutting an existing business that is bringing in cash, profits, and the current prosperity. The top management of Eastman Kodak failed to protect its employees and investors by having made a wrong decision and ultimately led to the demise of such a great technology firm. It is clear that when the CEO had a chance to choose a new set of FRs upon becoming a new CEO of Kodak, he stuck with the FRs his predecessors had chosen, which eventually bankrupted the company. The mystery is why a person who had a strong career in the semiconductor and electronics industry chose to stay with the silver-halide system. Is this because the system rewards the CEOs based on their short-term performance? This story highlights the importance of selecting the right person as the CEO of a company, who has the intellect, experience, and the ability to design a long-term strategy for the company.

Exercise 6.1: Design of Driverless Car

Many companies are developing driverless cars, such as the one shown below. Is the driverless car a good design? State FRs and constraints in a solution-neutral environment (Fig. 6.1).

[4]An engineer at Eastman Kodak, Steven Sasson, invented and built the first self-contained electronic camera. It used a charge-coupled device image sensor in 1975, which was initially used in mainly military and scientific application. Later, it was used in medical and news applications.

[5]This emphasis on cost-saving led to the creation of the microcellular plastics by MIT under the sponsorship of Eastman Kodak and other companies in the MIT-Industry Polymer Processing Program. Today, MuCell (tradename of Trexel, Inc., for microcellular plastics) is used in automotive industry to reduce the weight of cars so as to increase the fuel efficiency of automobiles. Reference: Wong et al. (2016).

Fig. 6.1 Driverless car. Reproduced with permission from Tim (2020)

Exercise 6.2: Unbeatable Combination: Human and Machine Intelligence

Many things people do every day depend on a combination of human and machine intelligence. People decide what to do, and machines take over the task and deliver the results to the person. For instance, people order goods through the Internet, and automated systems take over the order and deliver the good to the door step of the person who ordered it.

One of the least developed areas in human society is "politics." Politicians often lie to people and argue with other politicians with lots of heat but with limited enlightenment to resolve issues and establish policies. We wish to develop an intelligent machine system that can settle political arguments and make decisions. Develop FRs and constraints that can improve the democratic decision-making process.

Exercise 6.3: Admission to Leading Colleges

Colleges and universities accept students for their freshman class each year. Many students apply for admission to the colleges they would like to attend. Colleges use several different criteria for admission. Along one axis, they measure the scholastic aptitude of the students by several different means such as entrance examination, high school grades, and letters of recommendation. Along the orthogonal axis, they attempt to measure personal characteristics for future success, such as student activities, letters of recommendation, particular unique talents, and extracurricular activities. The problem that colleges and universities are facing is that the number of qualified students exceeds the number of students they can accept. Design an admissions system for screening students by stating FRs and DPs in a solution-neutral environment.

Exercise 6.4: Mission to Moon

The space agency of the United Nations decided to colonize the Moon by establishing a base where people can stay for an extended period. To achieve this goal of colonization of the Moon, heavy equipment and supplies must be transported to the Moon from Earth. There are two options. The first option is to use a large enough booster rocket to carry the cargo from Earth to Moon in one shot by being able to escape the gravitational force of the

Earth. Then, once it reaches a point where the gravitational pool of the Moon is greater than that of the Earth, it will travel to and ultimately go into Moon's orbit for final landing on the Moon by slowly descending to the lunar surface. The second option is to use smaller rockets to take the payload to an orbit around Earth in several launches. Then, assemble the parts into a larger container in space while circling the Earth. When the entire space vehicle is assembled in the earth orbit, it can fire a rocket to propel it to Moon.

If you are the director of this Moon mission, which option would you choose? Why? List FRs in solution-neutral environment and develop DPs that can satisfy the FRs. Discuss the pros and cons of these two different approaches.

Exercise 6.5: Stabilizing the Weather

It is desirable to change the weather pattern of Earth to prevent global warming. Weather is controlled by a series of instabilities in the atmosphere. When instability is initiated in a local region (e.g., due to the abnormally hot zone in the equator), it will create fast circulating vortices. These become tornados that will gather more and more energy by entrapping vapor from the ocean surface and then unleash the condensate when it encounters a cold atmosphere, creating a large pressure gradient and additional instability in the atmosphere. If these unstable natural phenomena can be created by first initiating local instabilities at a preselected region (e.g., west coast of Northern Africa), we may be able to change the weather pattern of Earth. How would you change the desert in North Africa next to the Atlantic Ocean into a green forest with many trees, making use of human-made instabilities in the atmosphere? List FRs and DPs at the highest level.

Exercise 6.6: Energy Storage

One of the issues in using electric power generated by solar and wind is the storage of excess electrical energy when the electric power generated is higher than the demand. Ideally, we should be able to store excess energy and use it when the demand is greater than supply. How would you store electric energy that may exceed the demand by tens of million watt-hours? List your FRs and DPs.

6.2 Functional Requirements and Zigzagging between Domains to Generate Lower Level Functional Requirements through Decomposition

At the highest level of design, the FRs may be stated based on the problem identified in the customer domain. However, we cannot identify the lower level FRs, without first identifying the corresponding DPs that can satisfy the FRs identified at the highest level. The lower level FRs can be stated after we first select and define the DPs at a higher level. These FRs are children-level FRs that represent the functions of the DP at one higher level. Therefore, mapping and zigzagging are essential concepts that the designer should be familiar with since they are the fundamental tools of AD.

Example 6.4 Designing Chemical–Mechanical Polishing (CMP) Machine for Silicon Wafers[6]

In manufacturing semiconductors, there are many steps involved. One of the processes is the chemical-mechanical polishing (CMP) process. Flat silicon wafers (diameter of up to 12 inches) is first coated with a thin layer of photoresist by spinning the wafer at high speeds after the photoresist is put on the surface. Then, electric circuits are printed on the photoresist with a lithography machine, using a short wavelength light (e.g., typically ultra-violet light (UV)) that goes through a mask with open slots in the form of electric circuits. Then, the resin is cured through a cross-linking chemical reaction, except the area that was exposed to light. When the uncured resin is removed, it exposes the original silicon surface area where the surface was exposed to light. Then it is etched, creating thin channels. Then copper is deposited, which covers the entire wafer. When the wafer is polished using abrasive slurry with polishing pads by the CMP machine, it removes the copper except where the etched channel exists, making a conducting path for electricity (see Fig. 6.2). Then, another layer of semiconducting material is deposited by vapor deposition, which is subjected to similar processes until a semiconductor device is created after the repetition of the above process. The task of the CMP machine is to remove unwanted materials to make the electric circuit layer by layer. Throughout this process, the CMP process must remove materials uniformly to prevent "dishing" of the surface where the center of the wafer is removed more than the edges or removing more materials at the edges of the wafer.

There are many FRs that must be satisfied. To simplify for illustration, we will choose a second-level FR and show how that FR is decomposed to create the next level of FRs and DPs (Melvin 2003a).

FR1.1 = Process wafer;
DP1.1 = Front layer removal.

The next-level FRs will be stated by decomposing FR1.1, which are really the FRs of DP1.1. They may be stated as follows:

FR 1.1.1 = Remove surface material;
FR 1.1.2 = Enable multi-step processes;
FR 1.1.3 = Control remaining thickness;
FR 1.1.4 = Exchange wafers.

The corresponding DPs are as follows:

DP 1.1.1 = Abrasive removal processing;
DP 1.1.2 = Multiple removal station design;
DP 1.1.3 = End point signal;
DP 1.1.4 = Wafer exchange sequence.

It should be noted that another designer might have decomposed it differently, which is equally acceptable if it is done consistently. In the design, there is no uniqueness theorem, but the decomposition must be consistent within the design framework chosen.

[6]The MIT Laboratory for Manufacturing and Productivity developed a commercial CMP machine in about 2 years. This example is based on the extensive design work done by Jason Melvin who received his Ph.D. partly based on this work and the work of other students. As discussed in Chap. 4, this project was sponsored by SVG Corporation, which was acquired by ASML. We are grateful to Papken Der Torossian, CEO of SVG, a man with a vision.

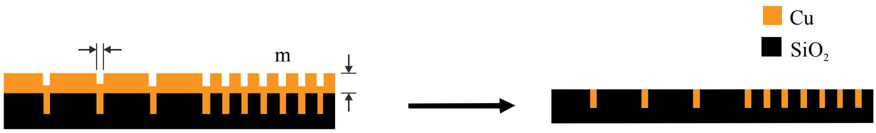


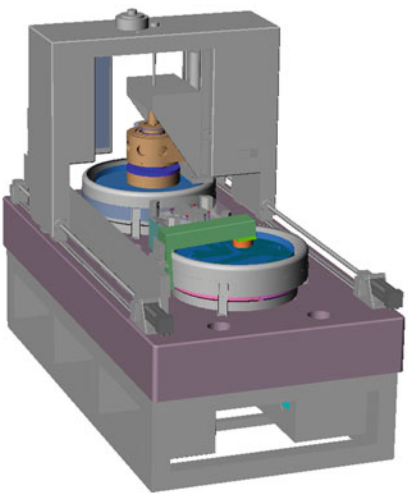
Fig. 6.2 Etched wafer after copper deposition (left) and after removing the copper layer by the CMP process (right). Reproduced with permission from Melvin (2003b)

The design matrix for the above design is given below:

$$\begin{Bmatrix} \text{FR1.1.1} \\ \text{FR1.1.2} \\ \text{FR1.1.3} \\ \text{FR1.1.4} \end{Bmatrix} = \begin{bmatrix} X & O & O & O \\ X & X & O & O \\ X & X & X & O \\ X & O & O & X \end{bmatrix} \begin{Bmatrix} \text{DP1.1.1} \\ \text{DP1.1.2} \\ \text{DP1.1.3} \\ \text{DP1.1.4} \end{Bmatrix}$$

The design is a decoupled design, which satisfies the Independence Axiom.

The above example is a small part of the overall design of the MIT CMP machine, which was presented in Chap. 4 as part of the discussion on the representation of design results, which is shown again in Fig. 6.3.



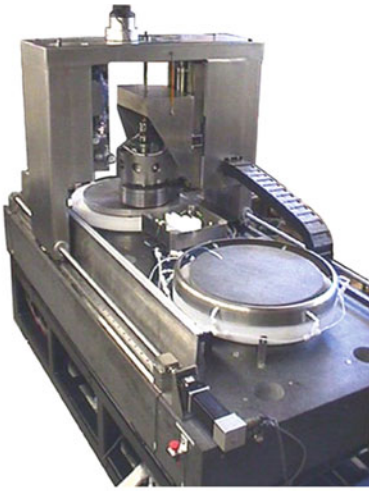


Fig. 6.3 The figure on the left is “Solidworks model” and the picture on the right is the actual fabricated machine. Reproduced with permission from Melvin (2003b)

6.3 Role of Broad Knowledge Base/Data Base in Formulating Functional Requirements

Problem identification is a critical step in the successful execution of the design. In previous chapters, the design was defined as the transformation process of going from domain to domain, e.g., to generate FRs from the problem identified in the customer domain, which is facilitated by "knowledge" and "data." At the beginning of the transformational process, we sometimes do not even know "the question" or "the problem." Initially, we depend on the "knowledge stored in our brain" or the "data stored in some accessible database" to generate questions and ideas to correctly identify the problem we need to solve in the customer domain, which precedes the selection of FRs or DPs or PVs. The generation of DPs and PVs is much easier than the generation of FRs, because we may not have adequately understood the "problem" that resides in the customer domain. Although the computer is powerful with extensive database and increasing intelligence with the use of artificial intelligence (AI), human imagination and the human brain are still the most critical factor in being able to define appropriate FRs.

6.4 On Selection of a Right Set of Functional Requirements—Need to Review Functional Requirements from Time to Time

In 1950, General Motors Company was the largest publically held company in the United States. In 2018, it was no longer. What happened?

> *General Motors dominated the U.S. economy in the 1950s. Since it was founded, it absorbed several companies and under the chairmanship of Alfred P. Sloan, and grew to became the largest automobile company in the world. When President Eisenhower nominated Charles Erwin Wilson, GM Chairman, for defense secretary, he faced the Senate Armed Services Committee in 1953. What he said at the hearing has been quoted widely: "because for years, I thought what was good for our country was good for General Motors, and vice versa."*

Some corporations go through a crisis when they cannot renew themselves in time as the world around them changes. Furthermore, some of the large companies become so bureaucratic that they are no longer creative and competitive. They do not attempt to identify new problems they should solve, establish new FRs, develop new DPs, and deal with resource issues (PVs) to continue to revitalize the business. Fortunately, many companies continue to do well by renewing themselves periodically.

Some universities have problems, too. One of the potential crises facing some of the leading universities is that the cost of operating their universities is exponentially escalating when the number of students and faculty has not changed. They often blame new government regulations, but that may not be the only reason or even the primary reason for the inefficient operation. When governments no longer expand the budget for research and do not guarantee student loans, these universities might have significant problems.

These issues boil down to the following question: how should these institutions renew themselves? The answer is that they should periodically review and re-establish FRs. The right set of FRs is the one that solves the problem identified in the customer domain. Once we select a new set of FRs, we must review the design and attempt to implement new DPs when the changes are required. These institutions are systems that should reinitialize themselves periodically, which is a subject matter discussed in the chapter on complexity.

Selecting the right set of FRs is the most important and the most challenging task in any decision-making process. Anybody can make decisions, but the question is: is the decision the right one? Fortunately, there is not only "one right decision" in that there are equally good equivalent decisions and FRs. Once the FRs are chosen, DPs and PVs must be created or adjusted. Often there are oppositions to institutional changes when they are introduced, especially during the early stages of a new administration.

Example 6.5 "You Should Quit for the Sake of Your Great Department!"

When the head of a distinguished academic department got promoted to a deanship, young faculty members of the department asked the university administration to name a specific senior faculty member of the department to take on the job. The concern was that the department has been living off its past laurels. They thought that it was time to change its direction to be ready for the twenty-first century. Notwithstanding the objections of some senior faculty in one major group of the department, the administration made the appointment as recommended by the search committee. He accepted the appointment because he agreed that the department was now ripe for renewal.

He introduced significant changes, including the renovation of old physical infrastructure, faculty personnel policy, research emphasis, faculty hiring policy, and raised a substantial amount of gifts. The fundamental problem he identified was that the department was dwelling on issues and problems of the late nineteenth-century and early twentieth-century engineering. The department was famous because the many well-known professors had made a fundamental contribution to automotive engineering, macro-scale heat engineering, experience-based instruction of design, and others. These were essential topics to teach, but in terms of research for the future, the department was not in sync with new emerging technologies, e.g., semiconductors, nanotechnology, software systems, biomedical engineering, modern materials, and design theory. The department needed different kinds of professors who can deal with the topics of the twenty-first century and forge a new mechanical engineering department. The department had to change from a discipline that is primarily based on physics into a discipline that is based not only on physics, but also computer science and engineering, biology, information, and modern materials. The department embarked on the task of hiring professors whose doctorate degrees were in disciplines outside of the traditional mechanical engineering to lead the department into a direction that is relevant in the twenty-first century. Also, the old defunct laboratory was demolished to create new updated physical facilities. He worked day and night to bring about these changes because he wanted to move onto other tasks after 3 years of this job. All these changes were conceived in a "solution-neutral environment," which can have unpleasant consequences.

About 5 months into this new task, the chairman of the department's outside advisory committee, who was also a member of the trustees of the university, knocked on the door of the new department head unannounced. They met each other 4 months earlier when the new department head went to see the chairman of the visiting committee at his home in the Midwest of the United States, hoping to raise money for the renovation project underway in the department. Unlike the last time the department head met him, he was not smiling and looked very serious. For a good reason!

He said that he met with the senior faculty members of the department at their request. He said that they had many complaints about the new direction the department was headed. Some of the senior faculty stated to the chairman of the visiting committee: "We must have been doing something right to be so highly ranked all these years. Then, why change?" He stated that 50% of those present at the meeting voted to have the department head removed. That was not a pleasant message. The top administration of the university met and asked the department head to appear and explain. The initial reaction of the department head was to step down for the sake of the department. However, others advised him against the idea, stating that "if you step down, no one else will be able to make unpopular changes, because the idea that faculty opposition can stop any changes can become a part of department legend." The fact that at least 50% of the senior faculty did not join the revolting group gave enough courage to continue the reform process.

The lessons of this story are the following: (1). Changes are hard to make, especially when they affect people. (2). Before making changes, one should clearly define FRs and DPs in a solution-neutral environment. (3). If one wants to be popular and have friends, do not make significant changes that will tilt the apple cart! (4) Be willing to sacrifice personally for the sake of the institution. It should be noted that if the new FRs were not conceived in a "solution-neutral environment," it would have been more challenging to go through a difficult period.

He stayed on the job for a long time to be sure that some of the younger professors brought in from other disciplines into mechanical engineering get tenure and sustain the changing culture of the department. It took about 10 years for this process! Indeed these "young" professors have become the leaders of the department and the new mechanical engineering field worldwide during the period. His contributions to the department and the university were later widely recognized because of the contributions of these "young" professors.

Factors that affect our ability to choose a right set of FRs:

There may be many factors that may affect decision-making ability, such as the following:

1. board and relevant knowledge that applies to the issue in hand;
2. in the case of innovation of technologies, a strong base in engineering and science disciplines;
3. relevant experience in the industry, government, universities, technology development, and other related fields;
4. for organizational design, experience in establishing and administering systems;
5. actual design experience for any systems;
6. innate creativity;
7. deep perspective in design thinking;
8. ability to think out of the box;

9. intense curiosity;
10. questioning mind;
11. asking “why” five consecutive times until the root cause is clearly explained;
12. ability to learn new subjects on one’s own;
13. willingness to collaborate with others;
14. an open mind to listen to opposing viewpoints;
15. ability to tolerate criticisms;
16. confidence in one’s knowledge and belief;
17. honesty with high ethical standards;
18. ability to admit mistakes made;
19. ability to listen to viewpoints of others;
20. abundant imagination.

The above list is long. No one person may have all those qualities, but they are personal characteristics that should be cultivated.

6.5 On Reverse Engineering to Determine the Functional Requirements of Existing Products

Some companies also try to determine the FRs of the competitor’s products through reverse engineering, which is difficult or impossible to do. For example, if someone gives you a hammer and ask you to determine its FRs, you, like most people, would describe one of its FRs as “drive a nail into wood.” However, your answer might be wrong if it is used primarily as a paperweight. In other words, it is possible to reverse engineer DPs because they can be measured, tested, and evaluated, but FRs can only be guessed.

Every manufacturer, especially those in consumer products, tries to learn about their competitors’ products. They break down or tear down their competitors’ products to learn about the merits and demerits of the competitor’s product. However, reverse engineering has significant limitations. Although it is possible to measure the geometric shape of the product and determine specific properties through measurements and testing, it is difficult to decide on the FRs of these products through reverse engineering.

Equally challenging is the determination of tolerances associated with the product, although the nominal dimensions can readily be measured, their tolerances cannot be measured. Although we have not covered the Information Axiom in detail yet, the information contents of a product are also difficult to determine through reverse engineering, since information content is a function of the tolerance and the nominal dimensions.

6.6 Minimum Number of Functional Requirements

The Information Axiom states that information content should be minimized. Consistent with this axiom, experienced designers try to satisfy a minimum number of FRs at any given level of design. It may be challenging to deal with many FRs at any level of decision-making, since as the number of FRs increases, it may become more challenging to satisfy the Independence Axiom.

Through the decomposition process, we can develop detailed designs. It is easier to come up with good design ideas and robust designs when we try to limit the number of FRs we have to satisfy at any given level of design hierarchy. If there is only one FR, it is always independent.

When we design large systems with many FRs and many decomposition branches, at any given node of FR and DP, it is better to minimize the number of FRs.

6.7 No Relative Ranking of the Importance of Functional Requirements

When we specify FRs, they are all *equally* important. However, the Information Axiom determines their robustness and the relative importance in terms of the information content, which will be further discussed in Chap. 7.

6.8 Interdisciplinary Background and Choice of Functional Requirements

Every designer is likely to choose a different set of FRs and DPs. People with broader disciplinary or multidisciplinary backgrounds may select better sets of FRs, because they may be able to access their information base for more appropriate FRs. For instance, the knowledge acquired on the mixing of liquids through the impingement of two streams of liquids enabled the creation of mixalloy. Similarly, if Crick and Watson did not get the information that DNA structure has a helical shape by visiting the laboratory of Dr. Rosalind Franklin, they might not have designed and discovered the structure of DNA molecule.

In the future, we will depend more on the database stored in computers to acquire knowledge on FRs and DPs. In some cases, access to the information will be facilitated by the use of AI.

6.9 Importance of Design Matrix and the System Architecture

In the early stage of the design process, it is easy to change FRs without incurring much cost and time. However, if we discover that we have chosen a wrong FR, we may end up redesigning the system from the beginning, incurring a higher cost and delayed implementation. Then, the designer should change it until the design adequately addresses the original problem. It is much easier to make changes before the design is committed to hardware or software development.

Like the example of the CMP machine design indicated, we have to construct the design matrix to be sure that we do not have coupled design. When a large project is undertaken, someone or a group of outstanding designers should be designated as the system architect to make sure that during the decomposition and design process, a coupled design is not introduced. The responsibility of the system architect is to construct the design matrix for the entire project to be sure that some of the decisions made by various participants have not created coupling of FRs.

6.10 Conclusions

Defining FRs is an essential step in design. If a wrong set of FRs is identified, one has to discard the whole design process and embark on a new process.

This chapter presented different means of defining FRs based on the problem statement. Sometimes FRs must be defined as part of the decomposition process, which was briefly reviewed.

The best way of learning how to define FRs is to practice it. By asking the right questions and by practicing the decomposition process correctly, designers learn how to decompose an FR and identify children-level FRs.

Once FRs are defined, we need to identify DPs. This process is where the designer's creativity may make a difference.

Problem

Six (6) exercise problems are given in the text of this chapter. Choose even-numbered exercise problems if your last name begins with an alphabet letter between "a" and "m." If your last name begins with the letter "n" to "z," answer the odd-numbered exercise problems.

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Further Reading

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