13 Axiomatic Design Application to Product Family Design

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Abstract

The basic concepts and the framework of Axiomatic Design (AD) provide powerful tools in the design of products and product families, especially for visualizing the design goals and improving the design process. When learning how to apply AD, however, nearly a half of the uninitiated designers like students may need to devote much effort to advance a sufficient number of different design concepts in terms of functional requirements (FRs) and/or design parameters (DPs), which is often done in abstract phrases like the first step in AD. The instructors must encourage them to think freely and squeeze out all the FRs and DPs they have in their minds and must guide them to integrate FRs functionally and DPs physically to obtain the desired design matrix.

13.1 Axiomatic Design Application for Product Family Design

13.1.1 Design Concept Description as the First Step in Axiomatic Design

The idea of AD shows powerful effects in designing product families.

By "product family," we mean a group of interacting or interrelated entities that form a unified entirety. In other words, a product family is a unified whole whose structural elements have effects on one another, thus, applying Independence

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N. P. Suh et al. (eds.), *Design Engineering and Science*,
https://doi.org/10.1007/978-3-030-49232-8_13

Axiom for decoupling such interference of FRs increases the possibility of satisfying all FRs; that is good design.

AD is a universal conceptual enabler without any constraints (Cs) of the design objects, thus, we can apply it to subjects including engineering designs of mechanical, electrical, buildings, or chemical processes, as well as such social demands as planning of structuring organizations, proposing policies, developing new products, or improving lifestyles; we can apply the method in any creation. AD, in other words, is a set of general axioms that can effectively support design no matter what the subject is.

In learning how to apply AD, one can read the methods described in detail in the earlier chapters. Just reading AD methods, however, may lead only half of the readers, to quickly acquire the skills in applying them, because they need to describe the design concept in a natural language as the first step in AD.

When learning AD with Suh's textbook (Suh 2001), half of the uninitiated designers like students may not even reach the stage of an axiom application. The reason is the difficulty for such designers in describing design concepts of FRs or DPs in abstract phrases instead of actual shapes laid out in drawings. Suh introduced a teaching method to list the FRs and DPs of a beverage can. The can has only three parts of the body, top lid, and the bottom, but it has more than 12 FRs. These three parts are physically integrated from more than 12 DPs. For example, about half of the students missed the FRs of the cylindrical body, the size of the pull tab, or the beautiful body print showing images about the beverage.

Another useful design example is an ongoing research topic for a bachelor's or master's degree (see problem 2). The students have to list up, at least, ten FRs and DPs related to arcs to construct the FR–DP charts, and identify the critical DP that signifies the novelty of the research. Although the students are always concerned about this requirement, only about half of the students may complete this task (Nakao and Iino 2018). A half dropped primary FRs or DPs that the instructor could recognize or made the mistakes of "mixing the FRs of the designer (the project budget, the project deadline, or so)" as pointed out by Thompson (2013). Without establishing the FRs and DPs that construct the design, the students cannot proceed to the next step of applying AD.

To guide the students, as we will describe with case studies in Sect. 13.2, we have them squeeze out all the FRs and DPs from their brains as a preparatory step for AD. General methods of mind mapping or work breakdown structure (Fig. 13.1) will work just fine.

13.1.2 Axiomatic Design Application with Proper Functional Requirements

For the next step, the students group the design concepts they generated into FRs and DPs, then connect related FRs and DPs with arcs to produce FR–DP charts. Next is a key technique in applying AD of listing up an equal number of FRs and DPs (Nakao and Iino 2018). This step leads to a regular design matrix (regular: invertible square matrix with a non-zero determinant) that can be decoupled into a diagonal or triangular one with proper row operations.

Failing to list up proper FRs and DPs blocks the students from reaching the entrance to AD application. Many students can describe DPs that are visible, however, they often cannot spell out the FRs that are hard to visualize. We have to loudly emphasize “FR first!” or “set FRs under a solution-neutral condition,” otherwise, they will end up with smaller numbers of FRs compared to those of DPs.

The AD textbook (Suh 2001) teaches that zigzag thinking is effective in setting FRs and DPs. The zigzagging starts from an abstract high-level concept toward low-level ones that are easier to picture and alternates between the functional and physical spaces going FR, DP, FR, DP, and so on. The method leads to an equal number of FRs and DPs, and at the same time, avoids describing multiple FRs with combinations of the same DPs. Therefore, the design matrix becomes regular, and its determinant is non-zero. The situation with students in the early stage, however, lacks efficient numbers of FRs and DPs in their minds. Thus, even with zigzag thinking, they overlook important aspects. It is just like an excellent recipe without the right materials, failing to produce a good dinner. Proper FRs are necessary for AD application.

The instructors twist the students’ arms to list up FRs and DPs, and they tend to list FRs chronologically and DPs spatially (Nakao and Iino 2018). The way they work comes from imagining how they would use the product, i.e., the sequence of work, to list up the FRs, and next referencing the bill of material (BOM) of similar existing products to list up the DPs. Listing up FRs and DPs in separate mindsets against the zigzag thinking process naturally leads to discrepancies in their numbers. Once the students produce their imperfect FR and DP lists, the instructors and teaching assistants (TAs) guide the students to integrate FRs functionally and DPs physically. This step is a grouping of low-level concepts of FRs and DPs, and it can rearrange the FR and DP vectors to have the same dimension. After this integration, retrying the above mentioned zigzag thinking can operate perfectly. The students have enough numbers of the right materials now.

Management professors teach the need for skills in setting the problem in a “mutually exclusive and collectively exhaustive (MECE)” manner if one wants to be a business consultant. The first part of mutual exclusiveness is the same as the Independence Axiom in AD, and engineering students can manage to set mutually independent FRs by avoiding trade-offs. The second part, collective exhaustiveness, is more challenging for the students who always have some mind slips. After a one-semester-long design class or seminar, for any objective designs, half of the young participants can directly build the design equations by tacitly setting FRs/DPs and integrating them in the brain.

13.1.3 Axiomatic Design Application with Many Functional Requirements

Generally, real product family design in industries have so many FRs that the designers cannot easily check the trade-offs or interferences with their brains or hands. In later chapters, however, AD shows positive and effective work for large or complex systems.

A software system design starts by listing up the FRs. This process, with a business consultant, describes what the customer wants to happen in natural language. Then a computer scientist translates the FRs into detailed specification, and programmers map the specifications to programs to realize the functions. A typical number of FRs, for these cases, easily exceeds 1,000 and the number of steps of checking for interferences among them turns out huge to reach 1 million cases, i.e., the square of the number of FRs. Testing in software design is said to take about the same number of days as designing takes, e.g., if the design took one year, its testing will take another 1 year because checking the interferences takes huge manpower.

AD can split the FRs into explicit ones FR_e and implicit ones FR_i as shown later in Fig. 13.8a. The former are those that the customer wants with the design, i.e., FRs that AD explained up to the previous chapters. The latter, on the other hand, are those without customer voices. If the design cannot meet the voice of the customer, the customer may file claims, and so the makers prepare those FRs to prevent some risks of future claims. For example, large-scale programs like one for an automatic teller machine (ATM) in banking is said to have 70% of its program lines to realize implicit FRs. Examples of these implicit FRs include operation schedules, future development plans, recovery plans upon problems, transition plans for new systems in the future, prevention of unauthorized access, aseismic reinforcement, installation weight, electrical power consumption, and so on. These problems will arise in situations like; a 24 h a day, 365 days a year operation without not even a minute of margin for update to program modifications; expanding the capacity to eight times after a successful operation caused congestion due to narrow data bus; or loss of electrical power following an earthquake caused loss of live data, and thus, the makers have to prepare against such emergency states.

AD often teaches to set these requirements into Cs, such as cost, safety, physical proximity, durability, and so on, as shown later in Fig. 13.8b. It is adequate if narrowing the tolerable ranges for DPs alone can satisfy Cs, however, if the narrowing lowers the probability of realizing FRs, the solution is not desirable. A different method, frequent in practice, is to prepare a separate DP for satisfying an implicit FR. For example, in preparation against the above problems; halt the operation for 10 min every day starting at 2 o'clock in the middle of the night; design the system in advance with a high data transfer frequency to allow 16 times the expected information transfer volume, or place a mirror server in a city located 1,000 km away. In general, describing the FR_i gives better chances of finding interferences with other FRs, as shown in Fig. 13.8a. For example, security and electric power consumption relate to all programs, and they result in rows with all Xs meaning interference with everything.

13.1.4 Creating New Design Using Axiomatic Design

Design assignments of creating new designs, instead of improving existing ones are now globally common, especially in the information business. This type of new assignment, however, gives further hurdles in listing up all the FRs and DPs, especially the FRs. The problem is not in the lack of linguistic ability to express concepts but in the overlooking of FRs that will surface later. The main cause is not recognizing the values of customer attributes (CAs). Some examples are; a change in a rival organization disturbing the designer, a competitor filing suit on a patent issue, a customer applying the product in ways the designer did not expect, a sudden change in regulation that prohibits using the product, or a workers' strike unrelated to the designer's responsibility. In such cases, the designer has to set a new set of CAs and FRs, and creation is always faced with such changes in reaching a successful design.

To find what element is missing from the formation, relying on imagination while sitting in the office will never lead to discovery. One will have to quickly go through the cycle of the first prototype, testing, improvement, the second prototype, testing, improvement, and so on, to find what concepts are missing from the formation. Mark Zuckerberg said, "Done is better than perfect."

The design solution is not necessarily unique. The FR itself, changes with the customer and situations that surround the society, forcing changes in the optimum DP. This transformation makes the design different from mathematics that has a single unique and eternal solution, and that is what gives compelling attraction to the act of designing. One of the most effective design methods is AD when we want to teach the philosophy of design to young designers visually.

13.2 Product and Product Family Design Cases Using Axiomatic Design

13.2.1 Automatic Driving

Figure 13.1 shows the method for exhausting design concepts with the example of designing an automatic driving system. Figure 13.1a is the result of applying mind mapping, and (b), work breakdown structure. Both methods start from a single concept and reach multiple concepts following the association game method. They also allow grouping of concepts so the player can exhaust all concepts without leaving out any. In the end, the designer separates the FRs and DPs, for example, by collecting verbs for FRs and nouns for DPs, and in step (c), they are aligned in the FR–DP chart with arcs connecting related FRs and DPs. As noted with gray balloons in (c), the discrepancy in the counts of FRs and DPs is evident, as well as design interference indicated with intersecting arcs.

When a designer is at the stage in (c), the design matrix is irregular and coupled, and advancing to the decoupling phase is quite discouraging. These problems look complicated in design. We thus tried concept integration. As the dotted boxes of stage (d) shows, for example, "shoulder, pedestrians, and vehicles" are all obstacles and can form a single group FR, and "GPS + map, steering, brake, and gas pedal" are all in constant use to form a single group DP. The resulting design equation for

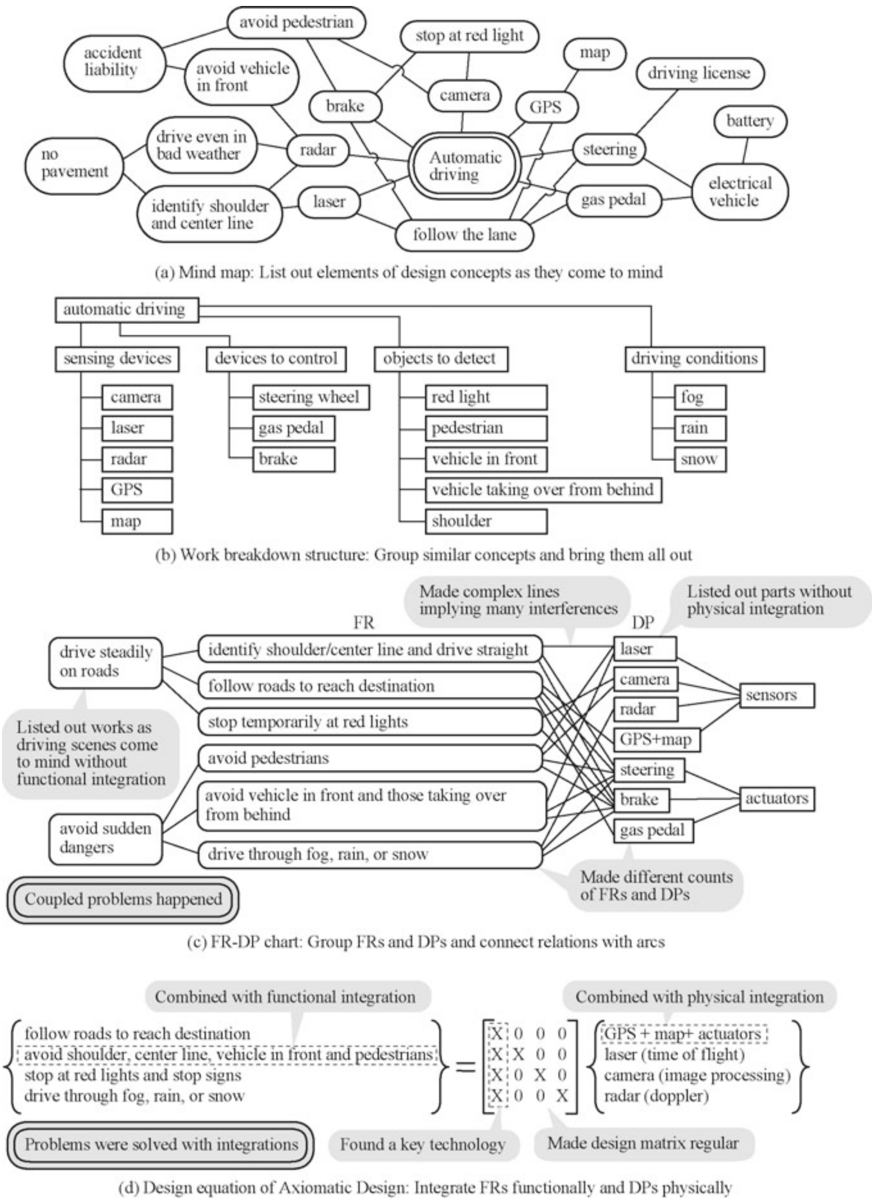

Fig. 13.1 Design of automatic driving. (Reproduced from Nakao and Iino (2018), originally published open access under a CC BY 4.0 license: https://doi.org/10.1051/matecconf/201822301011)

(d) is 4D and is easy to understand the design definition. An interference is seen in the column in the dotted box for DP1, "GPS + map + actuators." Without them, no matter how sophisticated the sensors may be, there is no way to accomplish automatic driving. In other words, they are the key technologies. The design equation in (d) solved these problems, and now we can use the axioms of AD for decoupling.

13.2.2 Fan Design

Automatic driving we saw in Fig. 13.1, with a great deal of attention from the society and a large number of articles about it in a variety of journals and magazines, allows the students to search the internet and easily collect articles and pick up concepts of FRs and DPs from them. A fan design in Fig. 13.2, on the other hand, is a mature product, and there are no articles that discuss it. The students have to think for themselves. Figure 13.2a is a typical FR–DP chart by a student who visualizes a fan in the air and sets the FRs following the process of activating one, while on the other hand, the student virtually disassembles one and sets the DPs following the BOM. Naturally, the two methods force different mental processes. Thus, the numbers of FRs and DPs do not match with intersecting arcs for related FRs and DPs. In this unstructured situation, zigzag thinking does not work well, either.

To escape the situation, we rearrange the breakdown by integrating multiple lower level FRs into a single FR at a higher level like "set airflow power" or "stop upon falling asleep," or combine related DPs into a higher level module DP like "motor + fan" or "motor + knob." For the DP "cover" without a corresponding FR in (a), we add the hidden FR of "injury-free finger poking" in (b). A hidden FR is one unnoticed during the early stage of design. The DP with influences on all FRs, shown with a corresponding column with all Xs is "motor + fan." This interference shows that this DP is the key technology for the product fan.

Figure (c) shows the design equation for the bladeless fan that was a recent hit product. Its shape is clearly different from a conventional model, but it only has an additional attractive FR of "hide blades." All the remaining FRs are carried over from a conventional model. The attractive FR, however, was so effective. The FR brought the large value of being "bladeless," and led consumers to purchase them at $300 even though a conventional model would only cost $50. Within the set of DPs, the novel technologies are "ring-shaped blower" and "place blades inside the base." The key technology remained with "motor + fan," but a new small synchronized motor with rare-earth magnets hid the motor in the base.

13.2.3 Entrance Exam Administration

Figure 13.3 shows the case of "Planning administration of admission exam." Shown in (a) is the first FR–DP chart. A student listed up the FRs following the schedule and wrote down the DPs looking at the list of stakeholders. Naturally, the

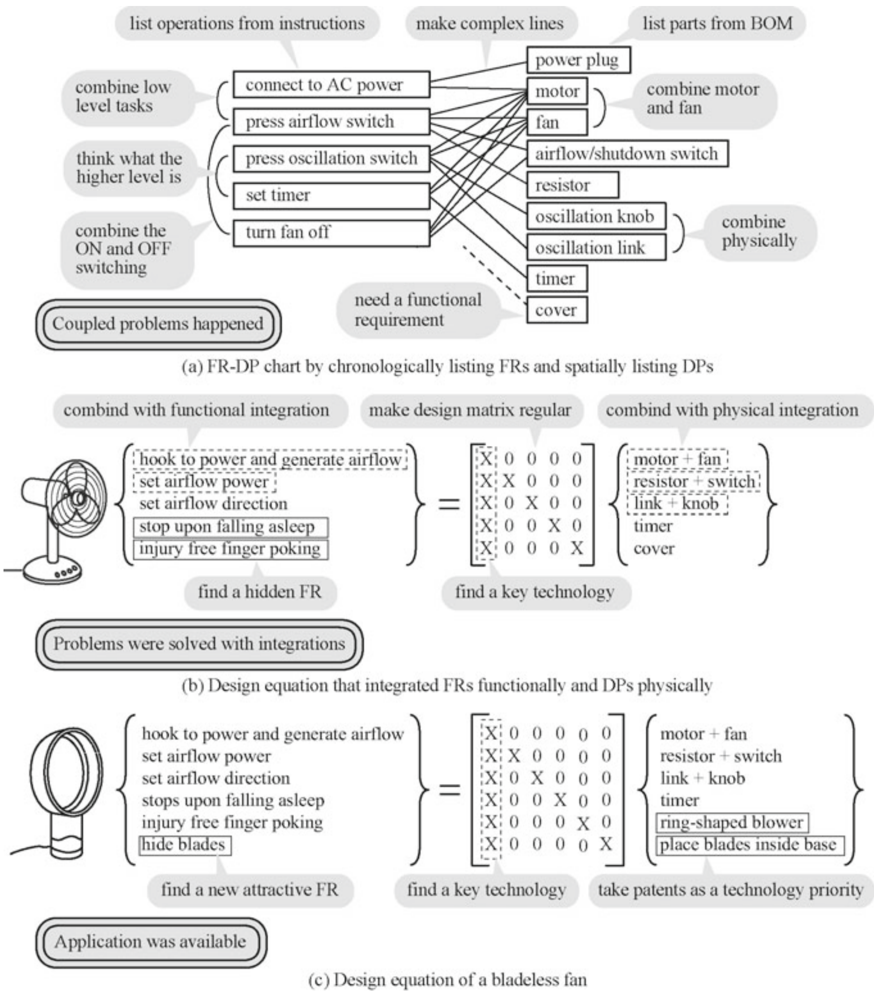

Fig. 13.2 Fan design. (Reproduced from Nakao and Iino (2018), originally published open access under a CC BY 4.0 license: https://doi.org/10.1051/matecconf/201822301011)

FR and DP counts did not match, and intersections were there among their relations. Applying the integration techniques, respectively, to the FRs and DPs led to a 4D design equation in (b). In the end, a column with all Xs in the design matrix that influenced all FRs was the DP of "exam committee." The committee takes the leading role in all aspects with the responsibility to all the FRs. As shown in (c), a flaw in the exam questions one year was found after the exam was over, and the university received social blame. For the following year's exam, a hidden FR of "eliminate errors in questions" was added with a corresponding DP of "exam review committee" consisting of young teaching staff tackling the exam questions in advance of the real exam. The DP of "exam committee" appears to also have influence on this FR, however, such an influence would discourage the young staff to point out errors by tenured professors. Thus, this exam review committee alone was kept independent on purpose.

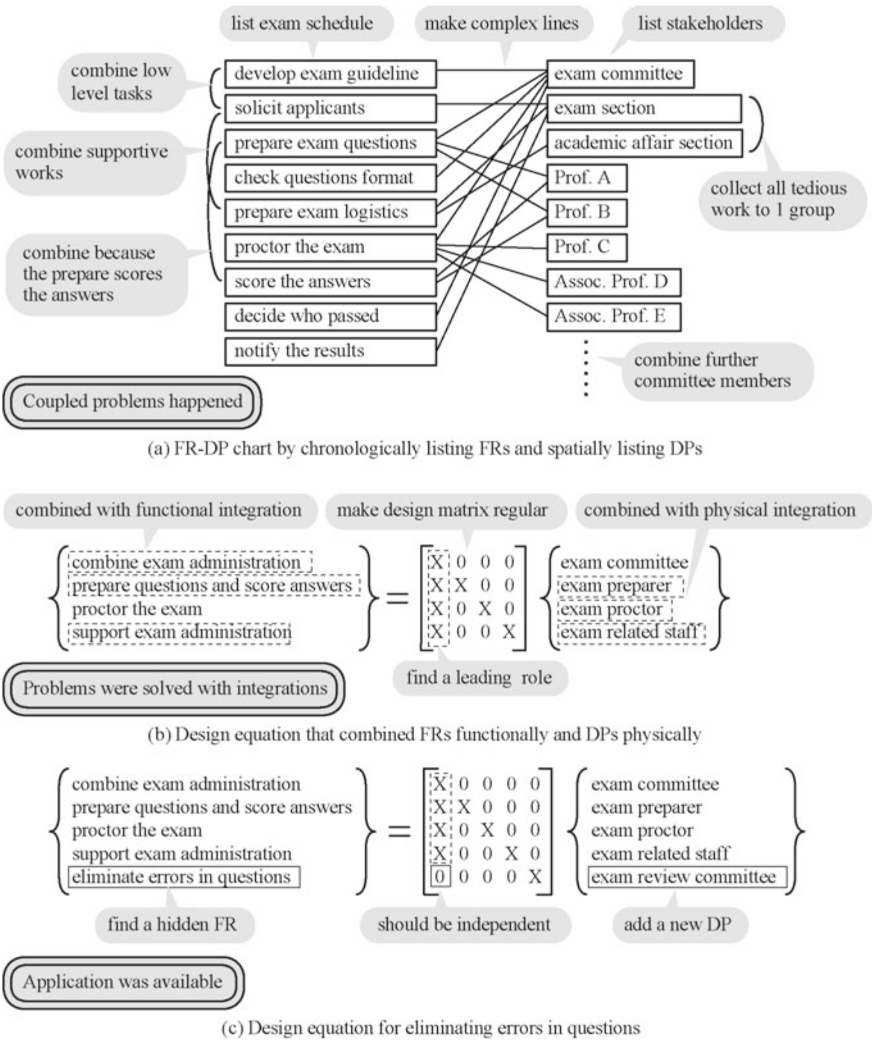

Fig. 13.3 Planning administration of admission exam. (Reproduced from Nakao and Iino (2018), originally published open access under a CC BY 4.0 license: https://doi.org/10.1051/matecconf/201822301011)

13.2.4 Umbrella that Follows the Owner

Figure 13.4 is the design of an "Umbrella that follows the owner." It was a student creation in a design exercise class. The first idea was to mount an umbrella on a drone. However, that resulted in a noisy follower like a mosquito above the head. The next design iteration was a helium-filled balloon to counter the weight of the umbrella and a pair of propellers mounted on the two sides to control forward/backward, and left/right turns. A camera mounted on the umbrella balloon recognized a red hat and controlled the propellers to follow its motion. The test session resulted in the balloon flying away after 20 s or so following the hat, and the testers had to pull the balloon back with the "emergency string." The designers had failed to recognize the FRs of controlling rolling and pitching. Only two propellers were insufficient to control rolling and pitching additionally. Looking into an airplane design led the team to find the need for a tail wing. Also, the camera had a narrow view angle and would easily lose sight of the red hat. The students placed a fish-eye lens on the camera to counter this problem.

What improvements to make are easy to find through quick prototyping and testing. Many large-sized corporations like to "start with a perfect solution" and extend the development period. However, they often lose their business chances. Startups like to quickly place products still under evaluation into the market and have the market tell them what improvements to make. The latter attitude is needed for creative design to find hidden FRs.

13.2.5 Stirling Engine

Figure 13.5 shows two sets of FRs of a Stirling engine, one when they are set following the chronological operation, and the other following functional evaluation of laws of thermodynamics. The former referenced the case of setting FRs for a steam engine in Suh's textbook (Suh 2001). Four FRs of producing hot air, raising the piston, producing cold air, and lowering the piston form a lower triangular matrix. The latter FR set, on the other hand, from the point, that the difference in injection and extraction of heat produces work, sets four FRs of injecting heat, extracting heat, doing work, and repeating the cycle. The two designs are physically different from different sets of FRs and DPs. Both design matrices, however, are also lower triangular ones. In other words, both approaches lead to correct answers for decoupling. The difference in their descriptions comes from matrix multiplication, just like performing a coordinate transformation to FR and DP. The burner also heated the air cooler; the difference between hot and cold temperatures became zero; the engine eventually stopped.

This discussion showed that there are cases of describing FRs and DPs of the same machine in design equations with different concepts, but both descriptions are correct.

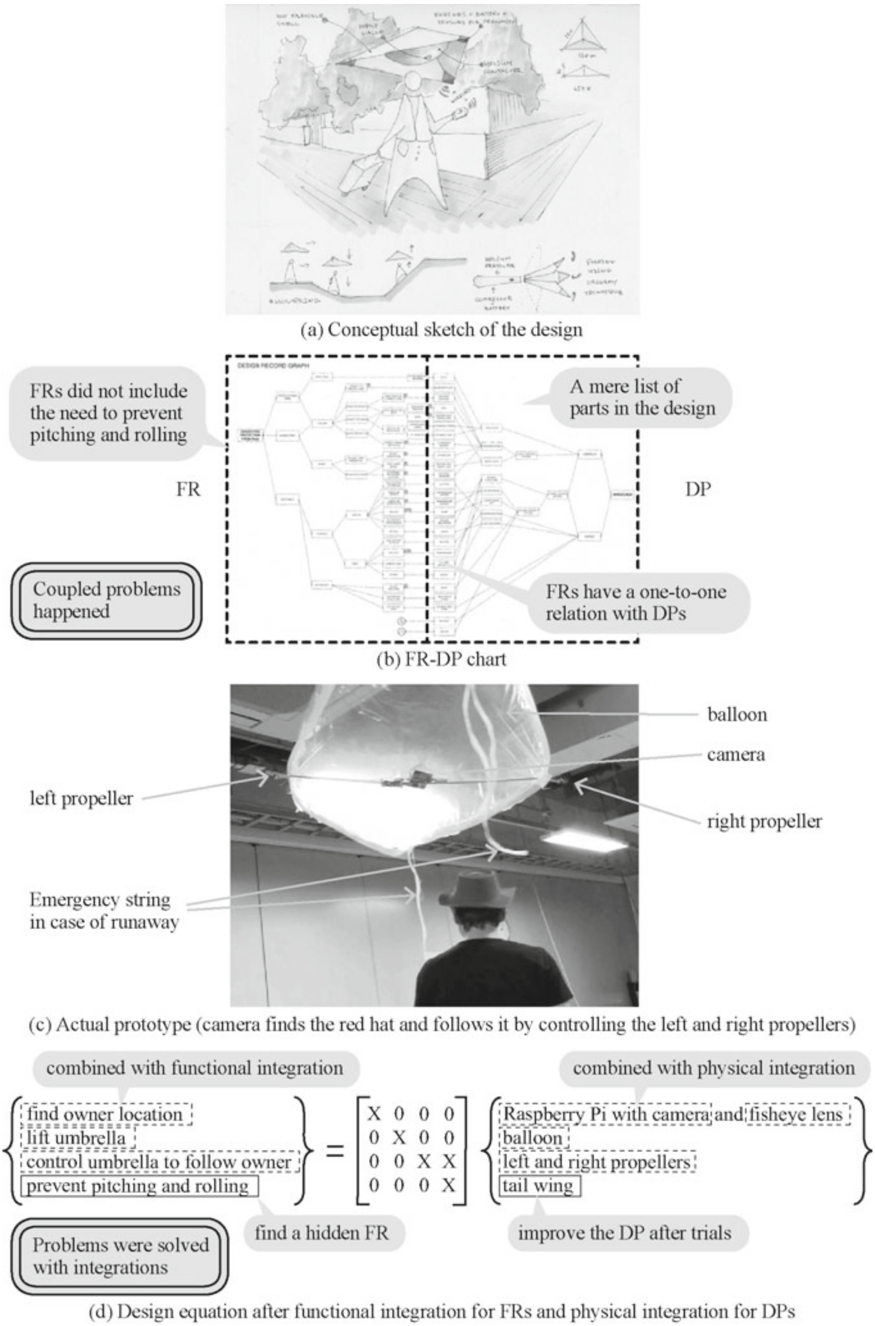

Fig. 13.4 Design of umbrella that follows the owner. (Reproduced from Nakao and Iino (2018), originally published open access under a CC BY 4.0 license: https://doi.org/10.1051/matecconf/201822301011)

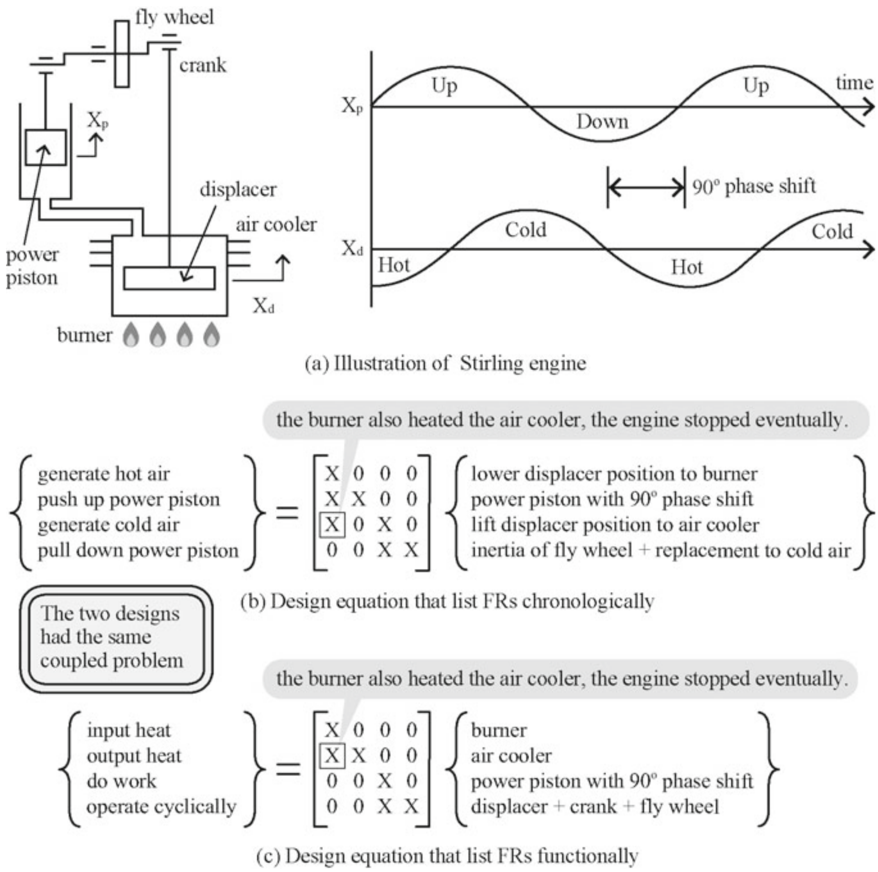

Fig. 13.5 FRs of Stirling engine that are listed chronologically or functionally. (Reproduced from Nakao and Iino (2018), originally published open access under a CC BY 4.0 license: https://doi.org/10.1051/matecconf/201822301011)

13.2.6 CurcurPlate for Managing Peoples in a Building

This section introduces "curcurPlate," a software system designed for monitoring people's whereabouts. Implicit FRs, mentioned in Sect. 13.1.3, are introduced and Fig. 13.6a illustrates the implicit FRs (FR_is), compared with Cs. Although AD allows both methods, preparing new solutions (DP_is) for a set of new FR_is usually is more feasible than narrowing the DP ranges against new Cs. Both FR_is and Cs may have many couplings with other DPs as shown in FR_{i1} or C_1 in Fig. 13.6.

Figure 13.7a shows the presence display panel, a hardware system placed at our office entrance that lab members can flip their nameplates to show their presence and absence (FR_1). If one is running an experiment in a lab other than the office, a little magnetic sticker with the name of the lab placed on the steel nameplate shows

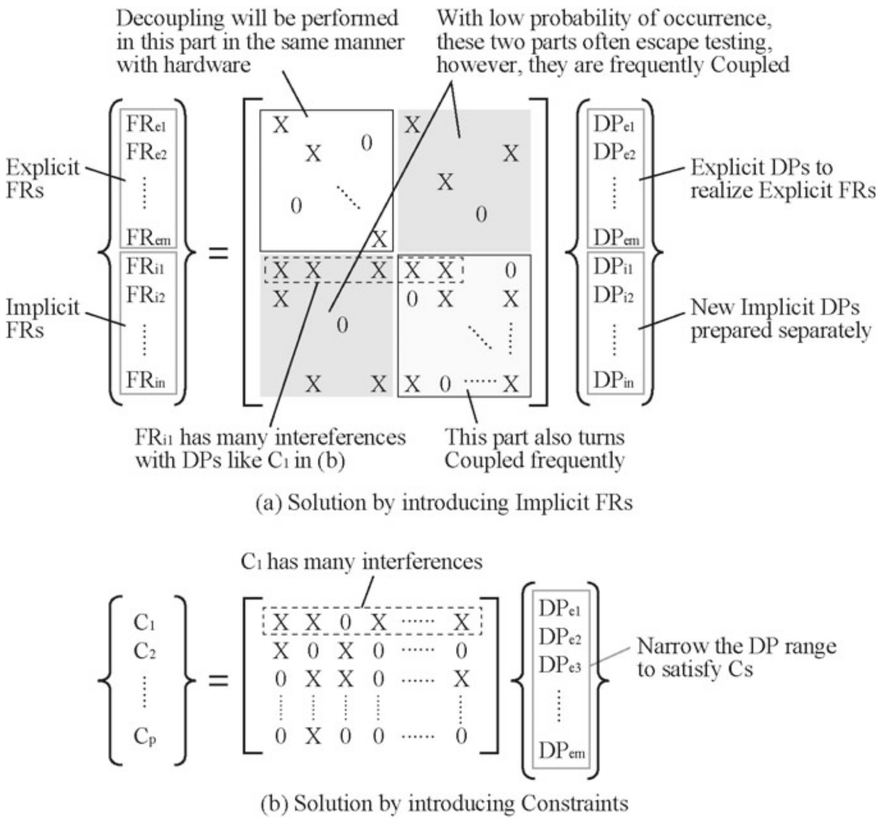

Fig. 13.6 Implicit FRs versus constraints for preventing the future trouble

the whereabouts (FR_2). Further, in case of an emergency like an earthquake or fire, any lab member can take the entire frame to the evacuation site and if someone present is not around at the site, others can head out for rescue (FR_3).

Figure 13.7b is “curcurPlate” the tablet version of this tool. The phrase “kurukuru (curcur)” is the onomatopoeic word for flipping a nameplate. DP_{e1} and DP_{e2} are input by tapping, and DP_{e3} is to store the data in a remote server so one can output the data in case of evacuation. The structure is simple and free of interference even with 200 laboratories using it.

When put in practice, however, everyone trying to update their whereabouts information caused a delay in the server response, and an increased number of labs further pushed back the response and the system needed to counter this problem (FR_{i1}). Moreover, if an earthquake or fire shuts down the server, data immediately before the evacuation are unavailable as well as the state of evacuation (FR_{i2}). Another requirement rose to register the whereabouts information from off-campus

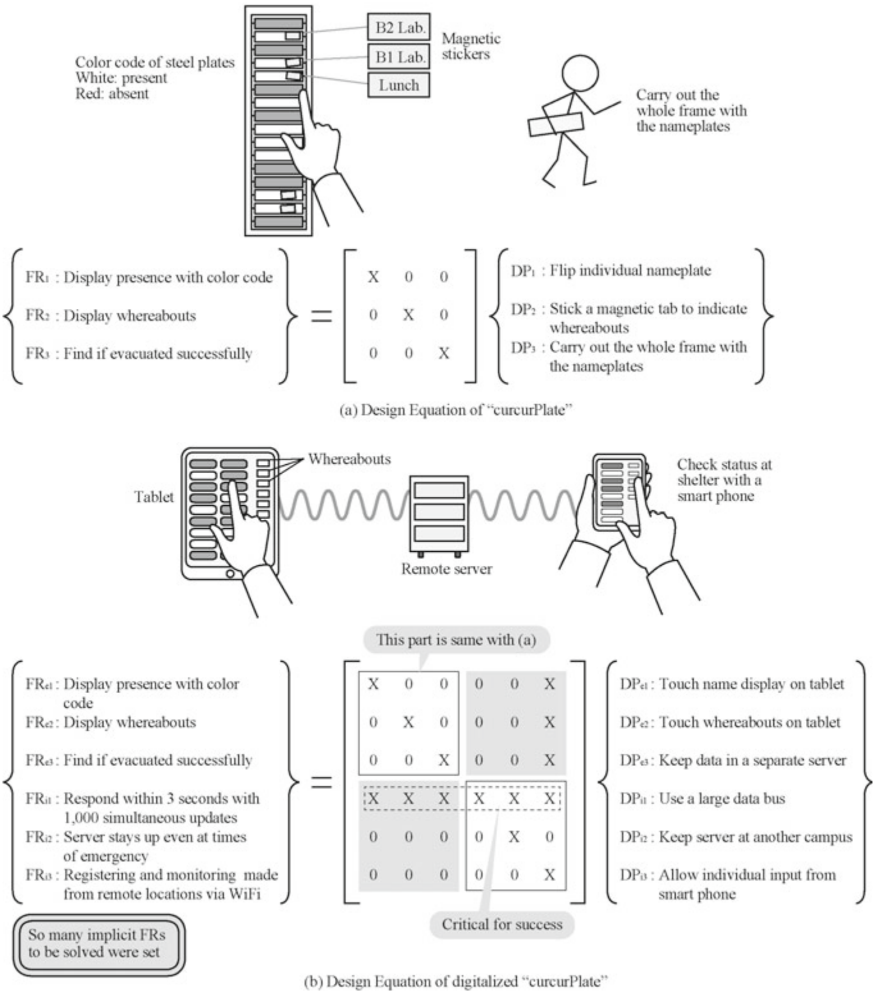

Fig. 13.7 "CurcurPlate" design with implicit FRs

locations (FR_{i3}). These implicit FRs greatly affected the success of the tool, especially "FR_{i1}: Respond within 3 s with 1000 simultaneous updates" led to its acceptance.

13.2.7 Tool for Brushing the Back of Teeth

This section discusses a tool for brushing the back of teeth with some constraints. The target is to design a tool that allows brushing the back of teeth for elderlies that cannot open their mouths widely and avoid aspiration pneumonia at the same time. The conventional solution has a caregiver insert a thin toothbrush into a gap of only about 1 cm and blindly brush the back of teeth as Fig. 13.8a shows. FR_1 is "brush the back of teeth after meal" and FR_2 "insert the brushing tool through a 1 cm gap between the upper and lower teeth." The conventional method used a toothbrush (DP_1) and a small brush head (DP_2) to insert it. However, the small brush head failed to give a good thorough brushing and interfered with FR_1. We set the third

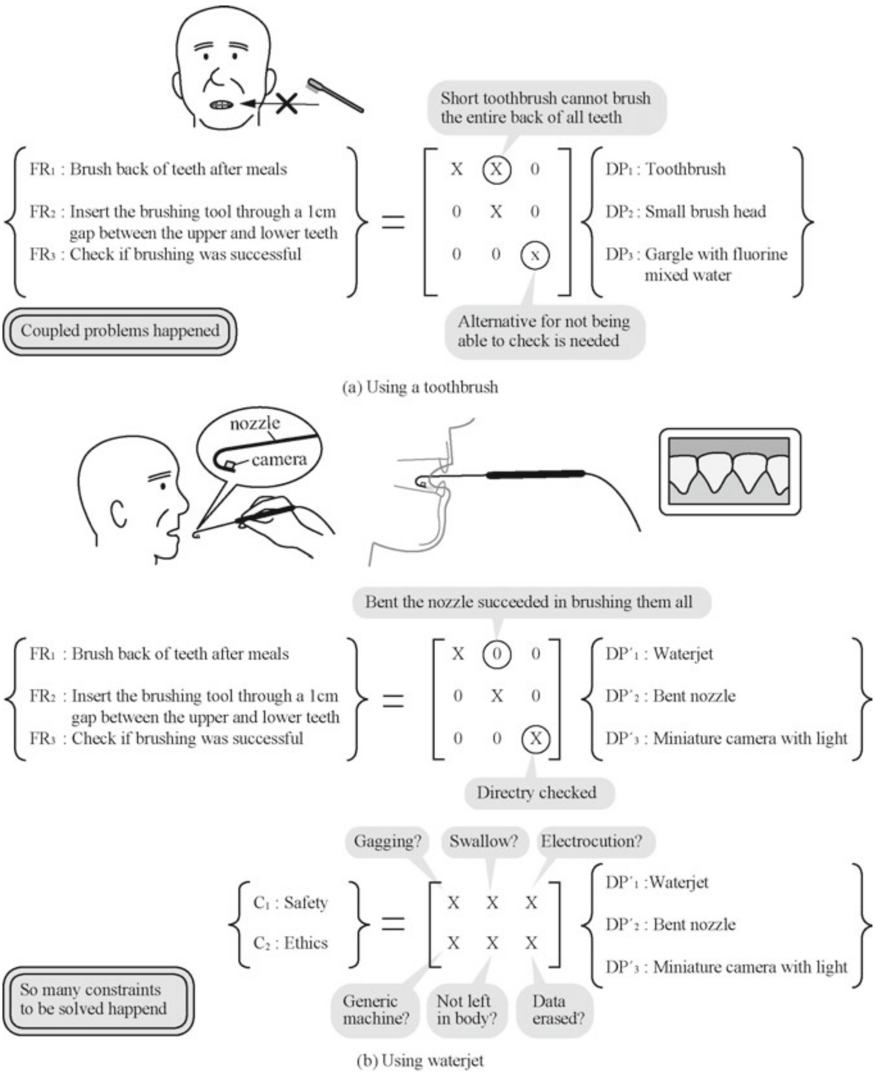

Fig. 13.8 A tool for brushing the back of teeth

requirement FR_3, "check if the brushing was successful," however, there was no way of looking at the back of the teeth so the third parameter DP_3 "gargle with fluorine mixed water" did not satisfy FR_3. In the end, sniffing the mouth was the method for judging how good the brushing was.

We then replaced the toothbrush with water jet (DP'_1), as Fig. 13.8b shows. After the nozzle was inserted past the teeth, waterjet squirted out through a bent nozzle (DP'_2), and the tool successfully cleaned the entire back of teeth without interference with FR_1. We even attached an LED mounted miniature camera (DP'_3) by the nozzle to directly check if there is still food debris left especially between teeth. So far, so good.

When we, however, wanted to apply the solution to visitors that cannot open their mouths wide, safety (C_1) turned into a large obstacle. We claimed that "it is just brushing of the teeth," however, if a dentist or hygienist uses the tool, it is a medical procedure. We had to demonstrate through experiments that the user will not gag with water, and the nozzle will not come off to choke the user, or the electricity to the camera with illumination will not electrocute the user. Next, we had to run the experiments against a variety of people, mandatorily thinking, ethics (C_2). We had to repeat explaining that waterjet is a device available to the general public and anyone can use one, the cleansing tool will not stay within the body, and that we will not keep the private information of teeth data and will erase them, but the ethics committee gave us a hard time to reach approval to use it.

13.3 Conclusions

The idea of AD shows powerful effects, especially for visualizing the design definition and improving design problems in product family design no matter what the subject is as shown in Figs. 13.1, 13.2, 13.3, 13.4, 13.5, 13.6, 13.7 and 13.8. When learning how to apply AD, half of the beginner designers, however, fail to describe enough numbers of design concepts of FRs or DPs in abstract phrases. The instructors have them squeeze out all the FRs and DPs in their minds as a preparatory step for AD with general methods of mind mapping or work breakdown structure as Fig. 13.1 shows. For the next step, the instructors guide them to integrate FRs functionally and DPs physically for getting a regular design matrix, as shown in Figs. 13.1, 13.2, 13.3, 13.4. We also discussed further applications. Finally, some tacit requests which customers do not claim should be set as implicit FRs or Cs, as shown in Figs. 13.6, 13.7 and 13.8.

Problems

1. Design your future life. Here, you need to set money as FR, DP, or C: the dream to become a millionaire (FR), the inevitable tool to eat enough meals or enjoy the hobbies (DP), or one of the minimum necessary resources like health or academic background to realize your FRs (C).

2. Make the design equation on your current research or your job. You should clarify the purpose (FR) and the method (DP), at least. Do not mix the FR of the designers, that is, the project budget, the project deadline, the promotion, the thesis, and so on.

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