MANAGING SYSTEM COMPLEXITY

Through Integrated TD Design Tools



Atila Ertas
Utku Gulbulak

This book is dedicated to the memory of
Bob Block.
One of the most innovative individuals
we have ever known.

Managing System Complexity through Integrated Transdisciplinary Design Tools

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and
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Preface

The global competitive economy is bringing about rapid technological development and convergence, which is producing disruptions in the job market today and going forward. In response, a paradigm change in engineering education is needed. to reduce unemployment and equip engineers to handle issues requiring a convergence of disciplines in response to these job market concerns.

This book's coverage of the Transdisciplinary (TD) design process enables the integrated application of TD tools, strategies, and methods—which are employed by different disciplines to tackle complicated problems. It offers the foundation for TD education to progress the body of knowledge needed to handle convergent issues both now and in the future.

Modern workforce education approaches must be bolstered by the process of standardizing different approaches and instruments employed by the many important industries that have an impact on the world economy. Students who read this book will learn how to become adept at swiftly shifting and adapting to various job sectors.

This book's major objective is to educate students broadly and get them ready for an increasingly transdisciplinary, collaborative, and global job market by teaching them integrated transdisciplinary methodologies, tools, and skills that can be used to work at the intersection of different disciplines and adapt to changes.

Atila Ertas

CHAPTER 1

Complex Problems and Transdisciplinarity

> When you first start off trying to solve a problem, the first solutions you come up with are very complex, and most people stop there. But if you keep going, and live with the problem and peel more layers of the onion off, you can often times arrive at some very elegant and simple solutions.
>
> **Steve Jobs**

1.1 Complex Problems and Transdisciplinarity

Several intricate matters have started to emerge as significant worries for the 21st century. Some of the most pressing concerns facing the globe today are complex ones including those related to the environment, climate change, immigration, hunger, water crises, global population, disease, and energy. Disciplines by themselves are unable to address these cross-disciplinary problems: Through the provision of new abilities and resources targeted at creativity, invention, and cooperation across knowledge domains, transdisciplinary approaches can provide answers to these problems.

> "Convergence: facilitating transdisciplinary integration of life sciences, physical sciences, engineering, and beyond is an approach to problem-solving that cuts across disciplinary boundaries. It integrates knowledge, tools, and ways of thinking from life and health sciences, physical, mathematical, and computational sciences, engineering disciplines, and beyond to form a comprehensive synthetic framework for tackling scientific and societal challenges that exist at the interfaces of multiple fields. By merging these diverse areas of expertise in a network of partnerships, convergence stimulates innovation from basic science discovery to translational application. It provides fertile ground for new collaborations that engage stakeholders and partners not only from academia, but also from national laboratories, industry, clinical settings, and funding bodies."
>
> **National Research Council of the National Academies**

Research problems and organizations that are defined from complex and heterogeneous domains, characterized by high levels of uncertainty, multiple perspectives, and multiple interlinked processes from local to global scales are the focus of transdisciplinarity; concerns

related to public health, the environment, and climate change are a few examples of such problems.[1,2] As an illustration of complexity in action, consider the COVID-19 pandemic, which is a transdisciplinary societal challenge requiring coordinated systemic thinking and collective intelligence in the face of uncertainty.[3]

> "Effective responses to the complexity, emergence, and uncertainty of coronavirus SARS-CoV-2 and the compound nature of health, economic and social impacts of COVID-19 require understanding and implementing the virtuous relations between disciplinary knowledge and professional know-how, several types of resources, coordinated multi-level governance, and individual and collective behaviors that should be combined in transdisciplinary contributions."[3]
>
> **Roderick J. Lawrence, 2020**

To handle complex problem challenges, researchers can develop collective information of knowledge by working together with diverse knowledge domain holders (actors) to co-create solutions – Transdisciplinary research enables the building of a range of actors and various stakeholders to create collective impact to solve unstructured problems.[4] Transdisciplinarity is about respecting non-research stakeholders, respecting their knowledge, engaging with them, and helping them do better through their research. It's this moral basis of transdisciplinarity that is believed that can be applied to just about all settings, because it's grounded in something so deep that it makes sense irrespective of context.[5]

Across academies, many scholars have been contributed to interdisciplinarity, transdisciplinarity, and integrated research concepts. Multidisciplinary activities bring together researchers from different disciplines working separately, each from their own discipline-specific viewpoint, to solve a common issue. In interdisciplinary activities, researchers from diverse disciplines work together on common problems by exchanging methods, tools, concepts, and processes among them to find integrated solutions. Both multidisciplinary and interdisciplinary activities cross discipline boundaries but their goal remains within the framework of disciplinary research.[6] Numerous articles have been published by Basarab Nicolescu on the scientific transdisciplinary research approaches.[7,8]

Transdisciplinarity creates new key frameworks, such as general systems theory and sustainability. It also involves stakeholders in the research activities. The main actions are tran-

[1]Apgar, J.M., Argumedo, A. & Allen, W. Building transdisciplinarity for managing complexity: lessons from indigenous practice. *International Journal of Interdisciplinary Social Sciences*, Vol. 4, No. 5, pp. 255-270, 2009.

[2]Lawrence, J. R. Deciphering interdisciplinary and transdisciplinary contributions. *Transdisciplinary Journal of Engineering & Science*, Vol. 1, pp. 111-116, 2010.

[3]Lawrence, J. R., (2020). Responding to COVID-19: What's the Problem? J Urban Health, The New York Academy of Medicine, https://doi.org/10.1007/s11524-020-00456-4.

[4]Vogel C. Transdisciplinary research for complex wicked challenges. Global Change Institute. https://www.wits.ac.za/gci/media/, Accessed January 2, 2020.

[5]Strunz, S. Is conceptual vagueness an asset? Arguments from the philosophy of science applied to the concept of resilience. *Ecological Economics*, 76: pp. 112–118, 2012. Online (DOI): 10.1016/j.ecolecon.2012.02.012.

[6]Ertas, A. Understanding of transdisciplinary and transdisciplinary process. *Transdisciplinary Journal of Engineering & Science*, 1(1), pp. 1-12, 2010.

[7]Nicolescu, B. Methodology of transdisciplinarity levels of reality, the logic of the included middle and complexity. *Transdisciplinary Journal of Engineering & Science*, vol 1, pp. 17-32, 2010.

[8]Nicolescu, B. *Manifesto of transdisciplinarity.* State University of New York Press, Albany, 2002.

scending, transforming, and transgressing.[9] The anticipated outcomes of transdisciplinary research and education are: emphasis on teamwork; searching for information from experts; developing and sharing of new concepts, methodologies, processes, and tools; all to create fresh, inspiring ideas that expand the boundaries of possibilities. The TD approach teaches people to seek collaboration outside the bounds of their professional experience to make new discoveries, explore different perspectives, express and exchange ideas, and gain new insights to solve difficult problems of contemporary societies of today's world.[10]

1.2 Defining Complexity

Complexity is difficult to understand due to the range of opposing proposed solutions and explanations for what creates complexity. Many researchers have suggested that complexity can be defined by size, entropy, information content, and computational capacity, as well as others.[11] Many of the suggested definitions of complexity are created on identifying a quantifiable parameter for a system or problem; however, proposals to date have not provided an agreed-upon definition.[11]

There is a difference between complex and complicated systems/problems. Complicated and complex systems may have various interactive components. Although complicated problems can be hard to solve, people with the right skills and expertise are addressable. However, there is no straight way to a solution for complex problems–they have too many unknowns and too many interrelated factors that are constantly changing in unpredictable environments.

The goal of this section is to provide a basic understanding of complexity rather than the theory of complexity studies or mathematical models. For example, our concern would be problems related to large-scale systems with numerous components and subsystems that interact in multiple and intricate ways with engineering, social, political, managerial, commercial, biological, and medical systems.[6]

Pierce stated "Complexity is that sensation experienced in the human mind when, in observing or considering a system, frustration arises from lack of comprehension of what is being explored."[12] With this theory, complexity is dependent on the individual judge of a system, not the system itself.

Critical thinking scholar Richard Paul stated "Governmental, economic, social, and environmental problems will become increasingly complex and interdependent... The forces to be understood and controlled will be corporate, national, transnational, cultural, religious, economic, and environmental, all intricately intertwined."[13] However, many universities do not practice transdisciplinary learning to train the next generation of science, engineering, and business undergraduate and graduate students for a world of problems we currently cannot

[9]Klein, T, J. Integration – Part 1: The "what" Integration and Implementation Insights, 2016. https://i2insights.org/2016/08/30/what-is-integration/, accessed January 4, 2020.

[10]Ertas, A., Greenhalgh-Spencer, H., Gulbulak, U., Baturalp, T. B., Frias, K. Transdisciplinary collaborative research exploration for undergraduate engineering students. *International Journal of Engineering Education,* Vol. 33, No. 4, pp.1242-1256, 2017.

[11]Mitchell, M., Complexity: A Guided Tour, Oxford University Press, Oxford, 2011.

[12]Peirce, C. S., "How to Make Our Ideas Clear," *Popular Science,* pp. 286-302, 1878.

[13]R.W. Paul, The logic of creative and critical thinking. *American Behavioral Scientist*, 37 (1) (1993), pp. 21-39.

solve.

Simon specifies the four characteristics of complex systems as:[14]

1. Complex systems are frequently hierarchical.
2. The structure of complex systems emerges through evolutionary processes and that hieratic systems will evolve much more rapidly than non–hierarchic systems.
3. Hierarchically organized complex systems may be decomposed into sub-systems for analysis of their behavior.
4. Because of their hierarchical nature, complex systems can frequently be described, or represented, in terms of a relatively simple set of symbols.

Simon's third view of complex systems indicates a possibility that they can be decomposed for study and analysis. This characteristic, which provides the likelihood of dealing with complex systems, may not be easily realized. The interconnections and interactions of the parts of a complex system will not typically be obvious without considerable study. Finally, Simon notes that complex systems can often be represented by apparently simple arrangements of symbols that follow the hierarchical structure of the system. Herb Simon also stated that:[15]

> "Today, complexity is a word that is much in fashion. We have learned very well that many of the systems that we are trying to deal with in our contemporary science and engineering are very complex indeed. They are so complex that it is not obvious that the powerful tricks and procedures that served us for four centuries or more in the development of modern science and engineering will enable us to understand and deal with them. We are learning that we need a science of complex systems, and we are beginning to construct it."
>
> **Herb Simon**

In The Sciences of the Artificial Simon further states:[14]

> "The proper study of mankind is the science of design, not only as of the professional component of a technical education but as a core discipline for every liberally educated person."
>
> **Herb Simon**

Warfield states his view of complex systems as:[16]

> "For better or worse, our society has accepted the idea of large and complex systems. If we are going to have them, it behooves us to learn how to manage them."
>
> **Warfield, 1994**

[14]Simon, H.A., *The Science of Artificial* Third Edition, Cambridge, MIT Press, 1999.

[15]Simon, A. H., Keynote Speech, 2000 Integrated Design and Process Technology (IDPT) Conference, Dallas.

> "One of the primary motivations comes from recognizing that society today involves large sociotechnical systems whose performance is far from ideal. Many of these large systems have taken their present forms primarily through evolutionary change that did not involve any systematic overview design but may have involved some systematic design of parts. Other systems are said to have been designed, but still fail in ways that produce disasters."
>
> **Warfield, 1994**

In Warfield's analysis, the human observer is involved with every obligation of complexity. Complexity has been described as a degree of unawareness. Objects are more or less complex depending on our unawareness or lack of information we have about it, our ability to make differences and insights about it, and our ability to conclude information from it. Warfield defined the complexity as:

> "That sensation experienced in the human mind when engaged in observing or considering a system, frustration arises from lack of comprehension of what is being explored."
>
> **Warfield, 1996**

1.3 Characteristics of Complexity

The two different characteristics of complexity were described by Warfield as *cognitive complexity* and *situational complexity*. Situational complexity is the complexity inherent to the system under question. Cognitive complexity describes the complexity associated with analysis by the observer. When the mind becomes oriented towards a complex situation, there is a possibility that cognitive complexity will start and then may escalate.[16]

Both situational and cognitive complexity must be considered when describing complexity. Every system with some number of components will have some level of situational complexity. There will be also some level of cognitive complexity due to the limited cognitive abilities of humans.[14] Human cognitive capabilities must always be thought of as the human is involved with all aspects of complexity, according to Warfield.[17]

As shown in Figure 1.1, a concept of situational complexity framework can be illustrated in four categories based on the degree of certainty and level of agreement on the issue in question: simple, socially complicated, technically complicated, and complex.[18,19] The two main futures of the matrix shown in Figure 1.1 is the level of agreement and the certainty/comprehension about how to solve the problem. Certainty describes the predictability about how to solve the problem, and agreement describes the level of conflict about how to solve the problem.[20]

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[16]Warfield, J. N., *A Science of Generic Design: Managing Complexity Through Systems Design,* Ames: Iowa State University Press, 1994.

[17]Warfield, J.N., "Structural Thinking: Organizing Complexity Through Disciplined Activity," *Systems Research,* 13, 47-67, 1996.

[18]Zimmerman, B. (2001). Ralph Stacey's agreement & certainty matrix. Toronto, Canada: Schulich School of Business, York University.

[19]Stacey, R. D. (1996). Complexity and creativity in organizations. San Francisco, CA: BerrettKoehler

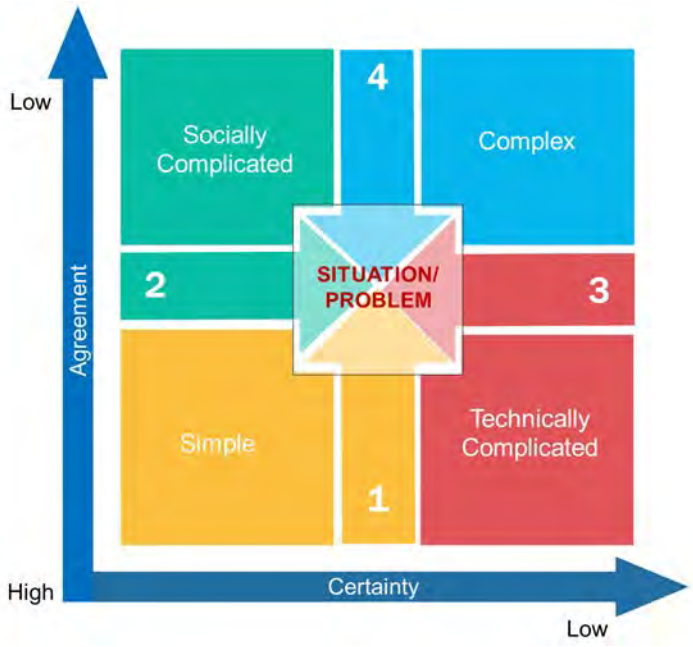


Figure 1.1: Agreement & certainty matrix (adapted from Zimmerman and Stacey).

Issues or problems are close to certainty when cause and effect linkages can be defined – a situation is simple, comprehendible and it can be solved with confidence. It is complicated when experts are required to formulate a complicated solution that will yield the anticipated results with certainty. An issue is complex when frustration arises from a lack of comprehension of what is being explored. In the following, in Figure 1.1, the four quadrants are described separately and distinguished.[21]

The first quadrant (simple) on the matrix shown in Figure 1.1 which is close to certainty and close to an agreement, data are collected from the past and use to predict the future. This is a good management practice for problem-solving and decision-making that falls in this area. The purpose is to repeat what works to increase efficiency and effectiveness.

The second quadrant (socially complicated) of Figure 1.1 shows that some issues have a high level of certainty about how outcomes are created but low levels of disagreement about which outcomes are desired. Neither plans nor shared missions are likely to work in this situation. Instead, politics become more important. Coalition building, negotiation, and compromise are used to create the best solutions. Coalition building, negotiation, and

---

Publishers.

[20]Scott Chazdon and Samantha Grant (2019). Situational Complexity and the Perception of Credible Evidence. *Journal of Human Sciences and Extension*, Volume 7, Number 2, pp. 36-60.

[21]The Stacey Matrix: http://adaptknowledge.com/wp-content/uploads/rapid intake/PI_CL/media/Stacey_ Matrix.pdf, accessed June 27, 2020.

compromise are used to create the best solutions.

The third quadrant (technically complicated) shows that some issues have a high level of agreement but a low level of certainty as to the cause-and-effect linkages to create the expected results. In these situations, monitoring against a predetermined plan will not work. In this situation, a transdisciplinary approach could be used–a strong sense of shared mission or vision may replace a plan. In this region, the goal is to head towards an agreed-upon future state even though the specific paths cannot be determined.

The fourth quadrant (complex) shows situations where there are very low levels of uncertainty and agreement. These situations often result in a breakdown or disorder. The traditional methods of planning, visioning, and negotiation are inadequate in these situations.

1.3.1 Subjective and Objective Situational Complexity

> "If I had an hour to solve a problem and my life depended on the solution, I would spend the first 55 minutes determining the proper question to ask... for once I know the proper question, I could solve the problem in less than five minutes."
>
> **Albert Einstein**

Situational complexity provides a framework to begin exploring evaluation questions.[22] Evaluation designs in complicated situations should take into consideration the system, stakeholders, and the situation of the problem under study. This will guide to more complex questions to investigate the linkages in the system.[20]

In certain situations, decision-makers select their decision based on multiple, diverse, and possibly incomplete information, thus, they face uncertainty regarding the situation at hand and the relationship between information (cues) and potential outcomes. This means that a decision-maker can't be certain that an individual judgmental decision option is the best choice in a given situation. The concept of complexity is closely related to the nature of a judgmental decision – judgmental decision always includes some aspects of complexity.[23]

The situational complexity has two important dimensions: the perceptibility of information (cues) and the degree of uncertainty in a given situational environment.[24] We may discuss situational complexity in two groups the subjective and objective types. The subjective perception of the complexity of the situation in question takes the observer into account, but varying importance is given to individual differences of the observer. On the other hand, objective complexity refers to the amount or degree of complexity physically present in a stimulus. Another important concept within the field of human factors is situational awareness.

The term awareness emphasizes the importance of memory which in part determines consciousness and awareness.[25] Our situational awareness will be limited if our attention is

[22]Patton, M. Q. (2011). *Developmental evaluation: Applying complexity concepts to enhance innovation and use.* New York, NY: Guilford Press.

[23]Steigenberger, N., Lübcke, T., Fiala M. H., Riebschläger, A. (2017). *Decision Modes in Complex Task Environments.* CRC Press.

[24]Kahneman, D., Klein, G. (2009). Conditions for Intuitive Expertise: A Failure to Disagree. *American Psychologist*, Vol. 64, No. 6, pp. 515-526.

[25]Baddeley, A. (1999). *Essentials of Human Memory.* Hove, UK: Psychology Pres.

EXAMPLE 1.1

Analyze the situational complexity of the partially autonomous cars in which the driver's responsibilities are reduced.[26]

BACKGROUND

Autonomous vehicle technologies are developing at a faster pace in recent years. Think about a future where fully autonomous vehicles dominate the roads and how this will impact our lives. How will the way we live change when we expect vehicles to be able to drive themselves safely on the road and make a gesture at any time?

ANALYSIS

Automation of driving will only work during predictable situations such as driving on the highway. Driver must be prepared to *takeover* when the situation suddenly changes or automation fails. The takeover is a complex task – maintaining a level of awareness that permits the driver to re-engage attention when sudden action is required: situation awareness must be re-gained and the driver will return to the driving task. This process has to happen in a very short time but at the same time a safe and comfortable *takeover* should take place.

First, the *takeover* process is affected by the complexity of the surrounding traffic environment that can be defined as *objective situational complexity*. Secondly, other factors, such as weather conditions, road structure, etc. can also contribute to objective situational complexity. In particular, when taking over the driving task, the objective situational complexity can impact the quality of the *takeover* process.[28] For example, when a lane change is necessary during crowded traffic, takeover quality will reduce – because the choice of lane change is more complex than other driving activities.

Besides the objective situational complexity, the current state of each individual driver's (e.g., stress level, vigilance, the workload of non-driving related task) behavior can be different during the *takeover* situation. Since the individual perception of complexity is affected by the road traffic condition awareness, different drivers' subjective perceptions of complexity in a certain traffic situation can be different. For example, because of the state of awareness, one driver may feel very comfortable with high traffic density and rate the complexity of the situation as low, another driver might perceive the situation as more complex. This is called *subjective situational complexity*.[28]

directed to inappropriate elements of the environment.[26] People's failure of selective attention such as talking on a cell phone while driving may limit his/their situational awareness.[27]

[26]Robert W Proctor, Trisha Van Zandt, (2018). *Human factors in Simple Complex systems.* CRC Press, Taylor & Francis Group, NW.

[27]Endsley, M. R., Jones, D. G. (2012). *Designing for situation awareness: An approach to human-centered design (2nd ed.).* London: Taylor & Francis.

The following is a good example to explain situational awareness and complexity.[28]

EXAMPLE 1.2

Analyze the situational complexity of the COVID-19 pandemic.

BACKGROUND

Starting in 2019, the world is engaged in a complex task environment – that is, fear and anxiety about a new infectious Coronavirus Disease (COVID-19). The COVID-19 pandemic is an example of complexity in action – creating complex humanitarian, economic, social, and health crises.

The world's scientists and global health professionals getting together to accelerate the innovative research to develop vaccines to control the spread of the COVID-19 pandemic and help care for those affected.

ANALYSIS

The spread of the disease is influenced by people's willingness to adopt preventative public health behaviors – such as social distancing and wearing masks. But, social distancing might make people feel isolated and can increase stress and anxiety. However, these actions are necessary to reduce the spread of COVID-19.

Human behavior is affected by people's knowledge and perceptions – depending on the individual judgmental decision, one person may think COVID-19 is basically like another flu or it only affects old people, thus he/she doesn't adopt preventative public health behaviors – their risk perception of COVID-19 is low. On the other hand, other people may perceive the risk of getting an infection with COVID-19 as relatively high: they adopt preventative public health behaviors and take extra precautions.

As we can see from this subjective situational complexity example, people's level to understand the risk perception on COVID-19 is different. This could be because of the individual judgmental decision, perception, or awareness of the situation.

Based on the information at this time, people with the following underlying medical conditions might be at an increased risk for severe illness from COVID-19: people 60 plus years old or with health conditions like lung or heart disease, diabetes, or conditions that affect their immune system – if we assume that those are facts then we call this objective situational complexity.

[28] Scharfe, M., Zeeb, K., Nele Russwinkel, N. (2020). The Impact of Situational Complexity and Familiarity on Takeover Quality in Uncritical Highly Automated Driving Scenarios. *Information*, Vol. 11, Issue 2, 10.3390/info11020115.

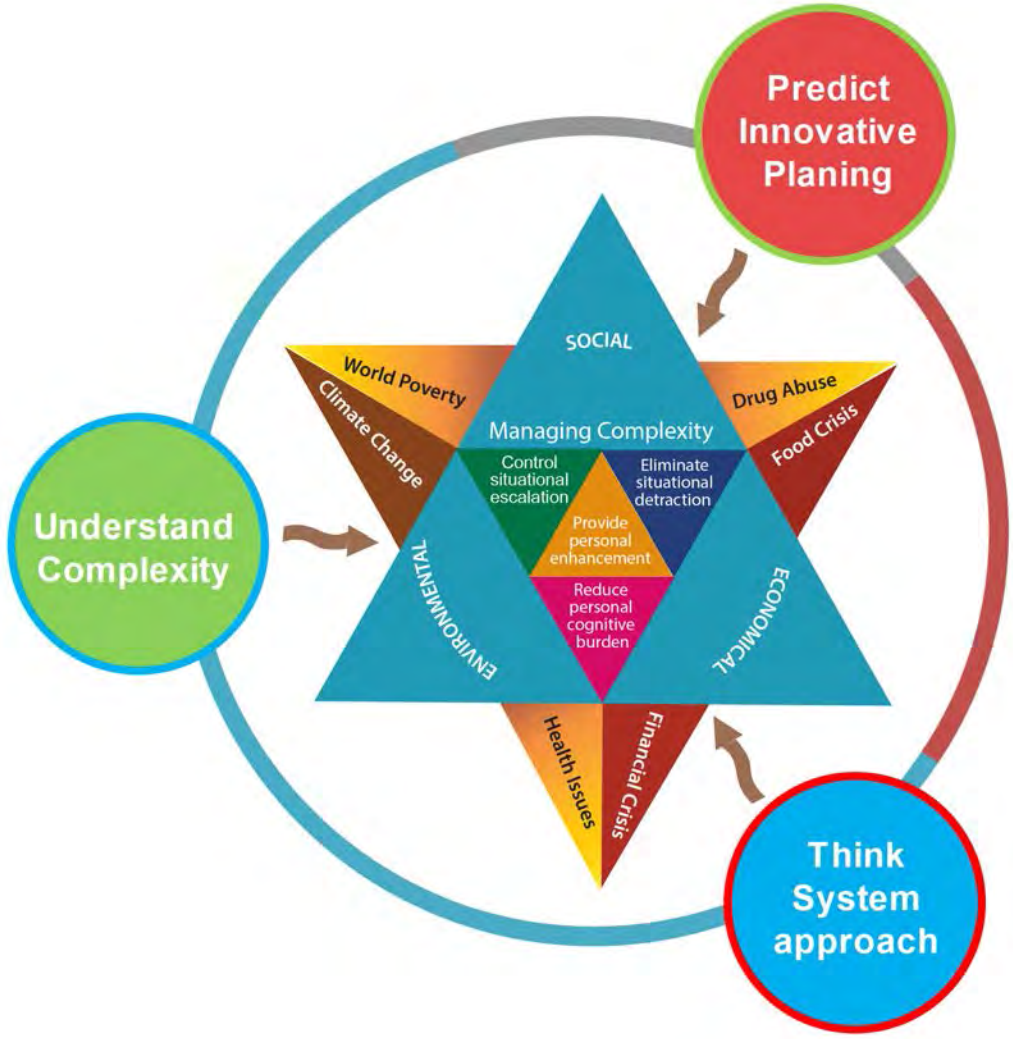


Figure 1.2: Managing Complexity.

1.4 Managing Complexity

It is important to understand the complexity of an issue and how it affects the understanding and projection of the solution. It is also crucial to managing complexity so that it does not overwhelm the design effort and prevent the development of effective solutions. In this regard, understanding of the complexity and the principal aspects of the path to the management of complexity shown in Figure 1.2 will be very briefly covered in this section.[29] Figure 1.2

[29]Ertas, A., *Transdisciplinary Engineering Design Process.* John Wiley & Sons, Inc., NJ, USA, 2018.



Figure 1.3: Managing Complexity.

shows some of the complex issues that impact directly on individuals, families, and communities and have effects on the lives of people – as shown in this figure, complex issues can be environmental, social, or economic.

TD program planning is an innovative process requiring broad comprehension along with a goal-oriented transdisciplinary approach. It is a challenging TD activity – Since more resources are involved, more innovation, creativity, and care must go into the program planning. The plan must identify the specific activities required to predict feasible solutions.

Systems thinking is the process of understanding how the elements of a system interact with one another and the ability or skill to perform problem-solving associated with them. For example, in nature, ecosystems are a complex set of interacting system-of-systems (SoS) – various elements such as air, water, movement, plants, animals, and as whole earth work together to survive or perish. This subject will be covered with applications in the proceeding sections.

1.4.1 Required Conditions for Managing Complexity

Although it may not be possible to identify required conditions for managing complexity, as shown in Figure 1.3, the following four necessary and sufficient conditions will be discussed in this section.[16]

1. *Controlling Situational Escalation*: Situational escalation may occur because of the following factors: (a) when analyzing complex problem-solving in teams, varying perceptions among the team members, (b) difficulty in managing group of professionals working together to solve a complex problem, (c) the existence of organizational or cultural constraints that hold back the valuable contribution to problem-solving, (d) difficulty of communication issues and implementation of problem solutions with customers, (e)

change in the problem situation and decision making with time, and (f) lack of participants to fill new, needed responsibilities. Overcoming these issues may be possible if the team's sense of coherence exists. It is important to note that resolutions to one factor don't necessarily resolution of others, and may even escalate them.

2. *Reduce Personal Cognitive Burden*: Let's consider a group of researchers (problem-solving team) working together to solve a complex issue. If one of the group members is in the position of trying to be part of the research activity to provide opinions and decisions for which the group member is not cognitively prepared then escalation of complexity will start – this situation is one of the evidence of mismanagement of complexity and creates a personal cognitive burden on the individual. Instructional design can be used to reduce the cognitive burden on learners.[30]
3. *Eliminating Situational Detraction*: Besides the factors affecting complex issues, there are many other situational factors that often exist which detract from problem-solving activity. Some of such factors are: (a) intrinsic (bounded rationality, imbalanced perception of problem factors, false saliency); (b) Cultural (narrow-mindedness, myopic vision); (c) Extrinsic (consuming egotism, arrogant abuse of power, knowledge disavowal).
4. *Providing Personal Enhancement*: The last of the necessary conditions for managing complexity is making available suitable conditions or entities or other means to enhance the capability of the individual to be effective in a problem-solving situation. For example, creating an effective group process, display of structured and unstructured information organized dialog, etc.

It is important to note that these four necessary conditions are not independent of one another.

1.4.2 Interactive Collective Intelligence Management

The concept of Interactive Management (IM) was developed at the University of Virginia in 1980. Since then, the practice of IM has spread to many places, and many applications have been implemented. IM is a system of management invented explicitly to apply to the management of complexity. IM was developed especially to apply management of complexity to cope with issues whose scope is beyond that of the normal type of problem that organizations can readily solve.[31]

IM has been renamed as Interactive Collective Intelligence Management (ICIM) to be the building block of the Transdisciplinary Design Process.[8]

As shown in Figure1.4, ICIM has three phases.[31]

Planning Phase: The aim of the planning phase is to make all the necessary preparations to accomplish the ICIM workshop. In this phase, the complex issues understudy will be clearly identified and knowledgeable experts in the field will be carefully selected and invited

[30]Paas, Fred; Sweller, John (2011). An Evolutionary Upgrade of Cognitive Load Theory: Using the Human Motor System and Collaboration to Support the Learning of Complex Cognitive Tasks. *Educational Psychology Review*. 24 (1): 27–45. doi:10.1007/s10648-011-9179-2.

[31]Warfield J. N., and Cardenas, A. R., A Handbook of Interactive Management, Iowa State University Press/AMES, 1994.

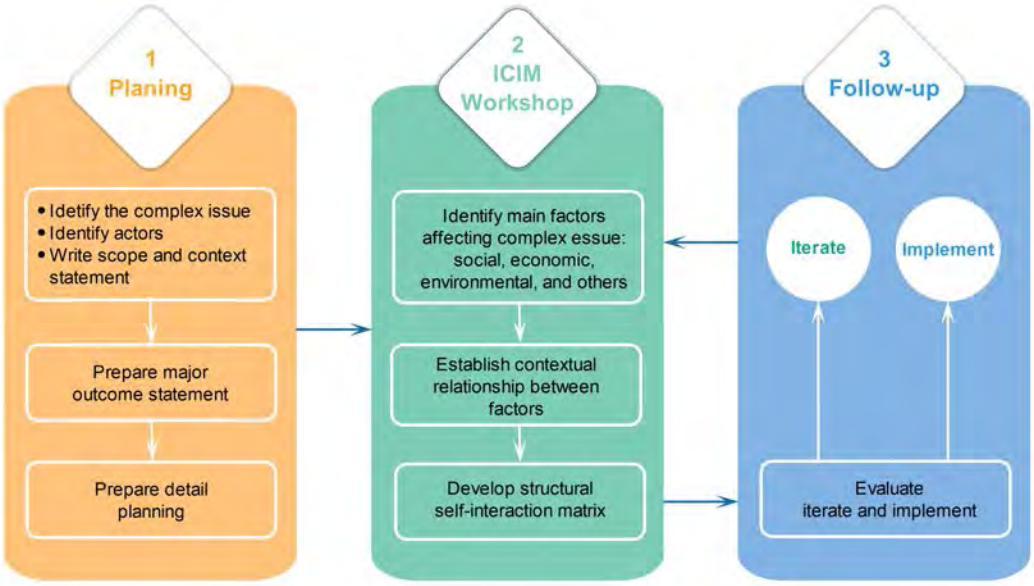


Figure 1.4: Three phases of Interactive Collective Intelligence Management (ICIM).

to participate. Once the scope of the issue is described, a context statement is written to focus on the ICIM workshop – the working environment of the ICIM workshop will be described.

Specific, measurable, and realistic major outcome statements will be planned and defined. Detail planning will be prepared on: methodologies to be used; triggering questions to be asked; generic questions to be used; types of field experts needed; the role of the participants during the ICIM workshop; schedule, place, and the budget of the ICIM workshop, etc. participants during the ICIM workshop; schedule, place and the budget of the ICIM workshop, etc.

ICIM Workshop Phase: The ICIM Workshop phase implements the plan that is developed in the planning phase. The workshop phase involves bringing a selective group of people together from expert domains who have knowledge about the issue under study to create extensive communication among the group members to discover the main factors affecting the complexity of an issue.

At the beginning of the workshop, the facilitator will make available flip charts to display the context statement of the workshop and a brief outline of the Nominal Group Technique (NGT). NGT is an efficient method for generating new ideas in groups, clarifying the generated ideas, editing and grouping the ideas, and developing an initial ranking of the set of ideas.[32]

The facilitator writes the problem or issue on a whiteboard to establish the factors affecting the complex issue. Using NGT, participants write down their ideas on the factors affecting complex issues in short sentences, one idea per sticky note until all their ideas are

[32]Delbecq A. L. and VandeVen A. H, (1971). A Group Process Model for Problem Identification and Program Planning. *Journal Of Applied Behavioral Science* 7, 466 -91, 1971.

exhausted. Then ideas on the factors proposed can be grouped together for open discussion by the participants. The facilitator asks each participant to prioritize the factors that have been discussed and tallies their votes.

Then, the working group continues to deliberate on establishing contextual relationships among the factors to develop a structural self – interaction matrix that required fundamental knowledge to decompose the complex issue into understandable and meaningful pieces.

Follow-up Phase: The follow-up phase includes iteration of the problem solution and its implementation. The outcomes obtained through this ICIM workshop process include:[31]

- **Learning.** Students who participated in the ICIM workshop process are exposed to a real sharing of ideas and information, and therefore are actively learning about the design research project at hand.
- **Commitment.** The final design project concept is created through the collaboration of students and instructors. Through this kind of approach, true commitment can be achieved.
- **Documentation.** During the ICIM workshop process, information, and decisions generated by research team members were documented and organized – providing the basis for broader dissemination of the outcomes.

1.4.3 Measuring Situational Complexity

The Situation Complexity Index (SCI) has been proposed as a combined single metric to compare complexity among a group of problematic situations. Situation Complexity Index is the product of the Miller Index, the Spreadthink Index, and the Demorgan Index. It is defined as:[33]

$$SCI = (\frac{N}{7})(\frac{V}{5})(\frac{K}{10}) \tag{1.1}$$

If SCI is over 100, then the situation is considered to be complex. In Equation 1.1, $(N/7)$ is identified as the *Miller Index*. George A. Miller discovered the famous "magical number seven, plus or minus two". If the number N happens to be 7, the value of the Miller Index will be 1.0 which can be taken as a reference point. For values less than this magical number of seven, it is assumed that human being is capable of functioning well. In Equation 1.1, $(V/5)$ is identified as the *Spreadthink Index*. The Spreadthink Index is a measure of the disagreement among the participant group on the relative importance of the N problems they have generated. In the above equation, V is chosen to be the "selected subset". The NGT voting system allows each voter to choose confidentially the 5 most important problems as he/she sees significant. If V=5, the spreadthink index will be the value of 1 which means that complete consensus. For values greater than 1, Spread Index indicates that the consensus is not achieved – it means that complexity is present. In Equation 1.1, the *De Morgan Index* is found from the simple formula $K/10$. When the De Morgan Index is 1, it indicates that the relationships among problem factors of an issue are acceptable and manageable with routine practices. For values exceeding 1, the De Morgan Index indicates that complexity is present.

[33]Warfield, N. J. Understanding Design Science, and its Implementation. First World Conference on Integrated Design & Process Technology, The University of Texas at Austin Texas, 1996.

EXAMPLE 1.3

Analyze the situational complexity of the refugee resettlement.

BACKGROUND

People are on the move for many reasons such as war and civil war, human rights, violation, economic, social, climate, environmental, political, and individual reasons that create these changing aspects. In such complex situations, the need to flee (forcibly displaced) versus the choice to leave (migration) can be difficult to determine. The issue of refugee resettlement is complex and includes many factors to consider.[34]

ANALYSIS

Transdisciplinary Collective Intelligence methodology implementation against this problem consisted of a group of 25 undergraduate students in senior design class, all pursuing Mechanical Engineering degree at Texas Tech University, two PhD students, one faculty member in design, four research engineers from different companies. This group recognized significant difficulties and challenges in carrying out successful refugee resettlement and sought to identify the main factors affecting the problem and how they were interrelated, with the goal of improving the rate of success for these displaced individuals.

The working group developed a set of factors affecting the complex issues of refugee settlement and they showed how the selected factors are related to each other. One of the Ph.D. students, who are familiar with the ICIM facilitated the workshop. The working group developed transdisciplinary collective intelligence using the Interactive Collective Intelligence Management workshop to investigate the issue. The Nominal Group Technique was used to develop and clarify a list of factors affecting the complex issue. 124 problems were identified and clarified. 20 problem categories are defined. 9 major problem areas were selected. Relationships among the major problem areas were 16. Table 1.1 shows the values of the Miller Index, the Spreadthink Index, and De Morgan Index from the ICIM workshop carried out in the 2020 Spring semester at the Mechanical Engineering Department. As shown in Table 1.1, since the value of SCI is larger than 100, it was concluded that the refugee resettlement issue is complex.

Table 1.1: Values of metrics of complexity.

Problems Identified **(N)**	Problems Selected **(V)**	Problems Structured	Number of Relationships **(K)**	Complexity Index **(SCI)**
124	20	9	16	113.34

$$SCI = (\frac{N}{7})(\frac{V}{5})(\frac{K}{10}) = (\frac{124}{7})(\frac{20}{5})(\frac{16}{10}) = 113.34$$

[34]Moran, D., Gulbulak, U., Ertas, A., and student group, (2020). Complexity of Global Refugee Crisis:Needs for Global TD Collaboration. *Transdisciplinary Journal of Engineering & Science*, Vol. 11, pp. 115-131.

1.5 Complex Societal Problems and Transdisciplinarity

Societal problems are real and people face them in their daily life. They are highly complex because of their dynamic character and impact on society.[35] Societal challenges are highly transdisciplinary, with social, cultural, economical, political, environmental, and emotional issues interconnected with technology.[8] They cannot be simply solved by experiment, and the implementation of an alteration to a problem changes the social system in a complex way.[36] Crucial societal problems, such as climate change, world poverty, health care, food crisis, and drug abuse, bring uncertain constraints with a high level of complexity for the people in dealing with them to solve. Cronin stated:[37]

> "There is a need for transdisciplinary research (TR) when knowledge about a societally relevant problem field is uncertain when the concrete nature of problems is disputed, and when there is a great deal at stake for those concerned by problems and involved in dealing with them. TR deals with problem fields in such a way that it can: a) grasp the complexity of problems, b) take into account the diversity of life world and scientific perceptions of problems, c) link abstract and case-specific knowledge and d) constitute knowledge and practices that promote what is conceived to be the common good."

Figure 1.5 shows the societal problem-solving process (SPSP). SPSP has three elements: Problem, Methodology, and Transdisciplinary Team. As shown in Figure 1.5, these three elements have connecting relationships – they are the major components of the exploration required to develop useful solutions.[38]

The generic tools for problem-solving may include communication tools, science tools, and technical tools. Problem solvers will select from those appropriate tools for societal problem-solving process structuring. It should be noticed that stakeholders involved with problem solutions may not be necessarily scientists. Content specialists are research participants who have acquired specialized knowledge that is relevant to an issue under study. Process modelers document a detailed description of the process that will be used for the problem solving and make sure that process rules and policies are followed. The research team evaluates each solution to select the one that shows the most potential to solve the problem, and then effectively implements the chosen solution. Management of the problem-solving process on social issues is crucial.

The societal problem-solving process requires a transdisciplinary team approach for the following reason:

- Values and subjective judgments play an important role in societal problems-solving. – requires consensus decision-making through deliberating among the transdisciplinary team.

[35] Dorien J. DeTombe, (2001). Compra, a Method for Handling Complex Societal Problems. *European Journal of Operational Research*, 128, 266–281, 2001.

[36] Warfield, N. J., *Societal Systems,* Intersystems Publications, USA, 1989.

[37] Cronin, K. Transdisciplinary research and sustainability. Environmental Science and Research (ESR), ltd., 2008.

[38] Warfield, N. J., Hill, J. D., (1973). An assault on complexity. A battelle Monograph, No:3, April 1973.

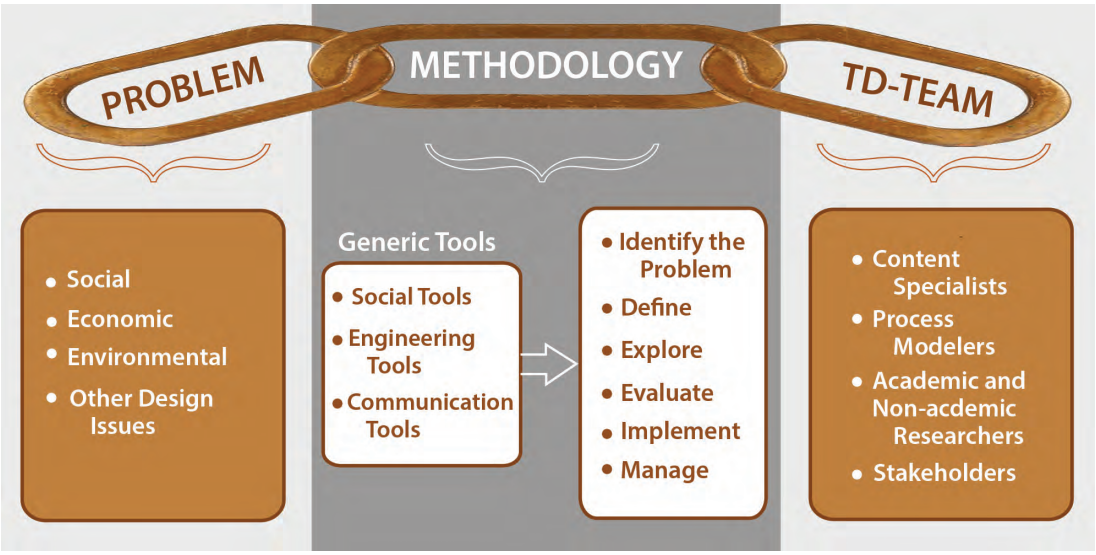


Figure 1.5: Societal problems solving process.

- The number of elements and their relations affecting the solution of the societal problem is large – tackling large-scale problems is not an easy task and requires a transdisciplinary team effort.

The large problems of growing society require collections of specialists using their specific knowledge in a common effort to the large scale societal problems solution – there is a need to encourage and promote transdisciplinary research.

1.6 Understanding Hierarchical Relationships and Complexity

The connection between hierarchies and complexity has been studied by Simon extensively.[14] He considers four aspects of complexity take the form of hierarchy. They are:

1. " The frequency with which complexity takes the form of hierarchy"
2. "The relation between the structure of complex systems and the time required for it to emerge through evolutionary process"
3. "The dynamic properties of hierarchically organized systems and... how they can be decomposed into subsystems in order to analyze the behavior"
4. "The relations between complex systems and their descriptions."

Walter Wallace emphasizes two distinct kinds of things to deal with when studying complexity. These are *elements* and *relations*.[39] Relationship states how two or more elements

[39]Wallace, W. L., (1969). *Sociological Theory*. Aldine Publishing Company, Chicago.

are related – defines the connection between two elements.

In working with complex problems and in working with systems, the study of hierarchies is essential. The three principal concepts of a hierarchy are:[40]

1. elements (factors) that are to be arranged in a hierarchy,
2. content and directions of any relations among any pair of these elements, and
3. subordinate relations.

The following is a good example to explain factors that are to be arranged in a hierarchy when studying sustainable self-sufficient ecovillage.

EXAMPLE 1.4

Analyze the factors affecting that are to be arranged in a hierarchy when studying performance of sustainable self-sufficient ecovillage.

BACKGROUND

Performance goals for the ecovillage may include: reduction of energy (using green buildings, wind, and solar energy), natural resource management, reduction of water use, waste treatment, recycling, and production of fruits and vegetables guided by intertwined with educational, economical, environmental, sustainable and social goals.[41]

ANALYSIS

Using the Nominal Group Technique, a group of ICIM workshop participants defined a set of factors affecting ecovillage performance and developed the hierarchy shown in Figure 1.6

As shown in Figure 1.6, the bottom three levels of the pyramid are called 'basic needs' because, in order to have healthy ecovillage, those basic needs must be met. If they do not exist, ecovillage becomes questionable. Thus, unity and strength through diversity; requirements of environmental issues such as nontoxic environment, recycling, air, water, and soil protection; renewable energy such as solar, wind, and hydro energies; green buildings such as the efficiency of buildings with respect to conservative water, energy, and materials use are basic needs and requirements of any ecovillage designed to be fully self-sufficient.

Once the basic needs of ecovillage have been met, our focus shifts to the highest level-IV of hierarchy – economic dimension and social issues. Top level-IV of the hierarchy of the pyramid is called 'sustainability needs'. To build a true ecovillage community for the positive transformation we should go beyond the basic needs.

[40] Warfiled, J. N., (1973). *An Assault on Complexity.* Battelle Memorial Institute.

EXAMPLE 1.4 (continued)

ANALYSIS

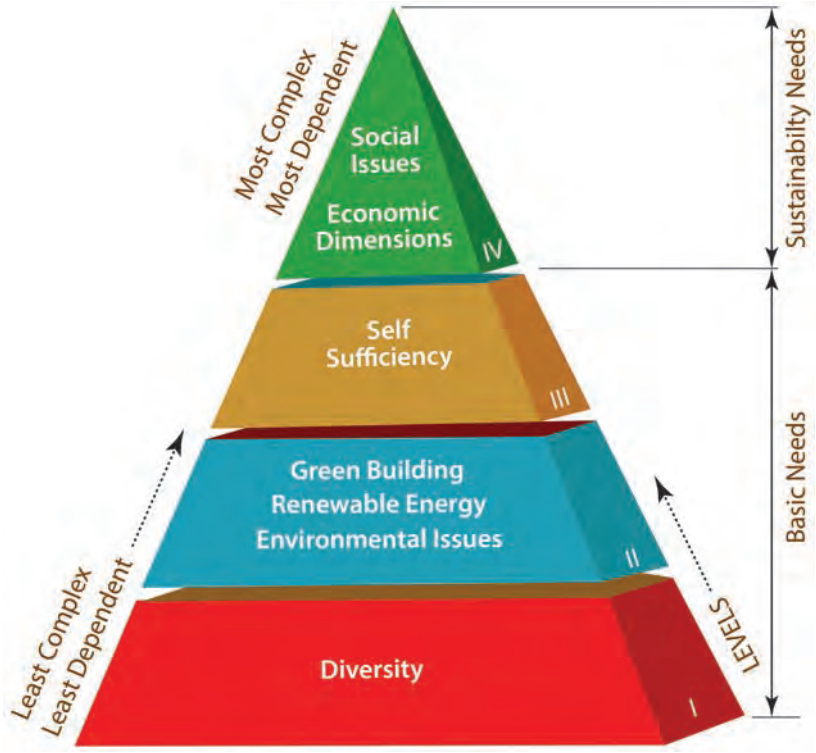


Figure 1.6: Hierarchy of factors affecting ecovillage performance.

Ecovillage's goal is to build economic practices and social systems – provide sustainable alternatives to the mainstream economy and develop a fair, effective, and accountable social community. Of course, the goal is to develop an ideal sustainable ecovillage. Unfortunately, development progress is often interrupted by a failure to meet lower-level needs because of the highly complex interrelated nature of the problem. Also, for example, the economic dimension is extremely dependent on all the factors in the lower hierarchy which creates high complexity for sustainable economic accomplishment. The same argument can be said for social issues. The factor of diversity is the independent key driver (all the other factors affected by this factor) for the ecovillage performance – as diversity has an impact on many factors with the least complexity, ecovillage participants have to pay maximum attention to establish a diverse but integrated community for a peaceful, healthy, and sustainable living so that related issues will not be out of control.

[41] Ertas, A., Rohman, J., Chillakanti, P., and Batuhan B. T., (2015). Transdisciplinary Collaboration as a Vehicle for Collective Intelligence: A Case Study of Engineering Design Education. *International Journal of Engineering Education*, Vol. 31, No. 6(A), pp. 1526–1536.

1.6.1 Forming Relationships Matrix

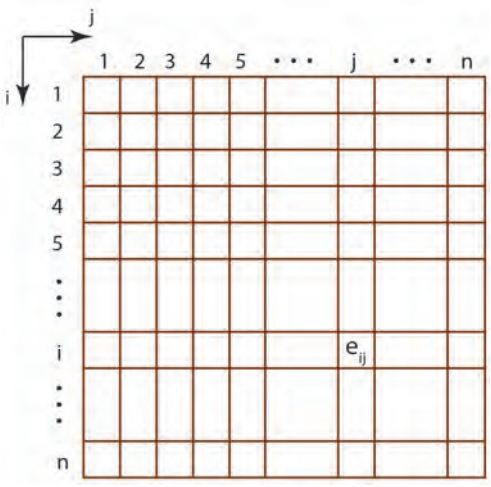


Figure 1.7: System elements relationships (dependency) matrix.

Three main tasks to form the relationships matrix are: 1) identify the relevant set of elements affecting the issue or problem, 2) determine the relationship among the elements, 3) translate the relationships in the form of *system matrix.*

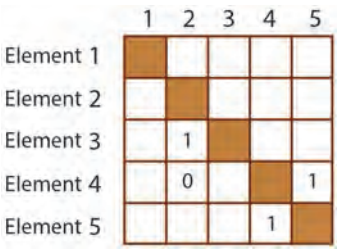


Figure 1.8: Relationships matrix.

System elements relationships matrix shown in Figure 1.7 is a square $n \times n$ matrix.The entries e_{ij} in the i^{th} row and j^{th} column indicates the relationships between elements i and j. If element i doesn't have relationship with element j, the entry e_{ij} will be zero. If element i is reaching (affecting) element j, enter a "1" in position e_{ij}. Since element j is not affecting element i, enter "0" in position e_{ji}. If elements i and j both reaching each other then the entry for both e_{ij} and e_{ji} will be "1".

For example, in Figure 1.8, element 3 is reaching element 2 but there are no relationships between elements 4 and 2. As seen from this figure, elements 4 and 5 are reaching each other, in other words, element 4 is affecting element 5, and element 5 is affecting element 4 – this is called *cycle.* The following example will show how to develop a relationship matrix.

EXAMPLE 1.5

Develop relationships matrix to reduce the cholesterol level considering below identified factors:

1. **to reduce cholesterol**
2. **to diet,**
3. **to exercise every day, and**
4. **to run every day.**

BACKGROUND

The American Heart Association (AHA) states that the above factors affect cholesterol levels by changing triglycerides, LDL, and HDL cholesterol levels. These changes may cause the risk for heart disease and stroke (adapted from reference 40).

ANALYSIS

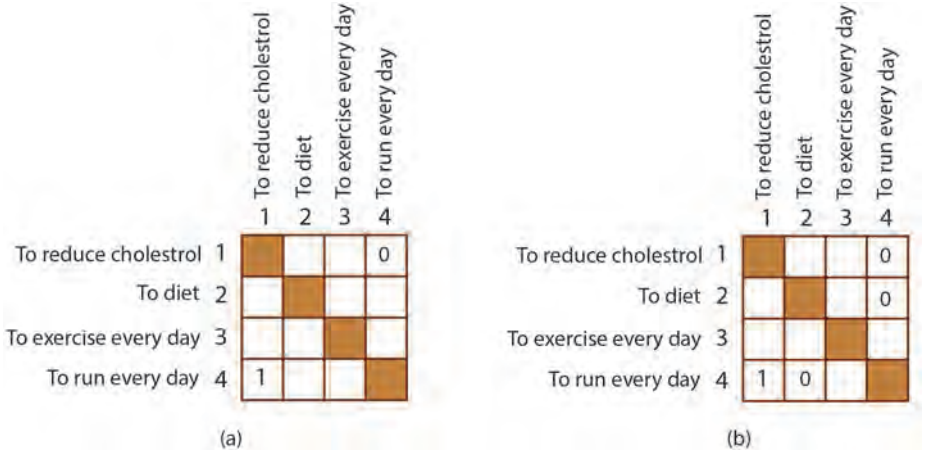


Figure 1.9: Partially completed matrix.

As shown in Figure 1.9(a), block all the entries on the matrix diagonal. In other words, set them to zero.

Referring to Figure 1.9(a), to run every day affects the reduce of cholesterol (set $e_{41} = 1$) but to reduce cholesterol doesn't affect to run every day (set $e_{14} = 0$). As shown in Figure 1.9(b), to run every day doesn't affect dieting (thus set $e_{42} = 0$) and to diet doesn't have relationships with running everyday (thus set $e_{24} = 0$).

EXAMPLE 1.5 (continued)

ANALYSIS

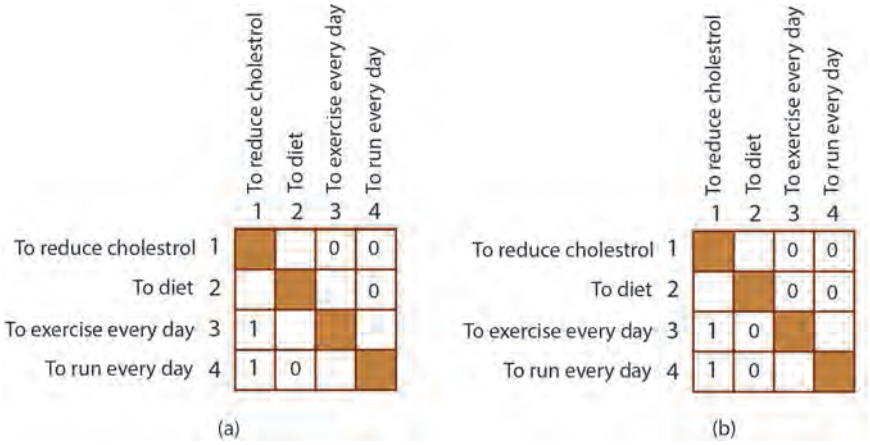


Figure 1.10: Partially completed matrix.

Figure 1.10(a): To exercise every day will reduce cholesterol level (thus set $e_{31} = 1$) however, to reduce cholesterol doesn't support the relationships with exercise everyday (thus set $e_{13} = 0$). Figure 1.10(b): to exercise doesn't contribute to diet (thus set $e_{32} = 0$). Dieting doesn't affect exercising (thus set $e_{23} = 0$).

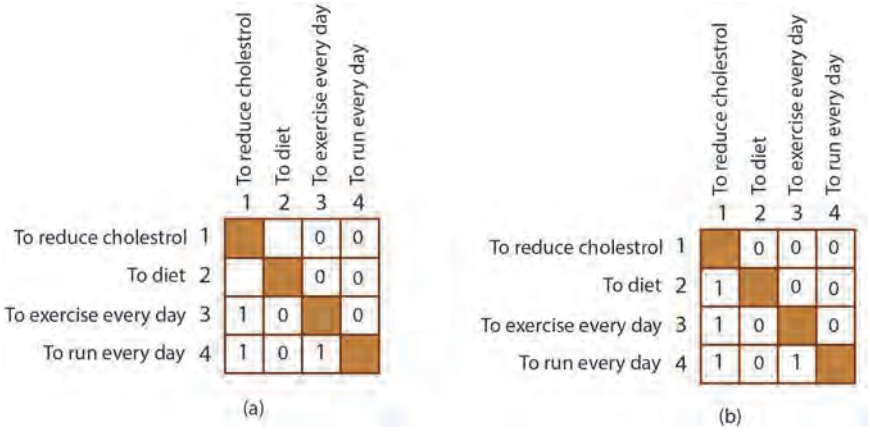


Figure 1.11: Figure 11(b) is completed matrix.

Figure 1.11(a): To run every day supports exercising (thus set $e_{43} = 1$), however, to exercise every day doesn't support the relationships with running everyday (thus set $e_{34} = 0$). Figure 1.11(b): to diet reduces cholesterol (thus set $e_{21} = 1$). To reduce cholesterol will not affect dieting (thus set $e_{12} = 0$).

EXAMPLE 1.5 (continued)

ANALYSIS

Finally, using the final relationship matrix shown in Figure 1.11(b), develop a digraph as shown in Figure 1.12. The matrix is shown in Figure 1.11(b) has four elements: therefore hierarchy will show these elements by numbers. Wherever there is a number 1 in the matrix, there will be a connection (relationship) between the associated elements. For example, since the matrix shown in Figure 1.11(b) has $e_{3,1}$, the direction of the link will go from 3 to 1 – using the same approach complete digraph can be developed as shown in Figure 1.12.

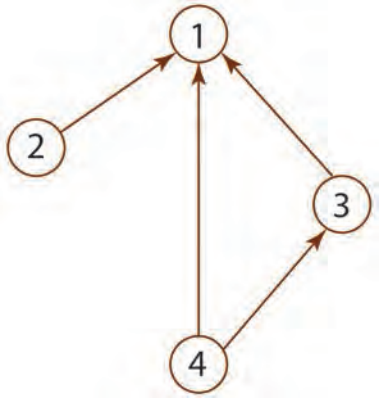


Figure 1.12: Digraph associated with Fig 1.11(b).

1.6.2 Graphical Representations

As Simon defined "complex systems," have a large number of elements that have many interactions.[14] Hierarchical systems consist of element relationships to each other and can be represented by a directed graph. A directed graph (digraph) shown in Figure 1.12, has a set of elements (in this case 4 elements) that are connected together, where all the links are directed from one node (element) to another.

When drawing a digraph, the links (edges) are drawn as arrows indicating the direction, as shown in Figure 1.13. The arrow shows the direction of the linkage. For example, in Figure 1.13(a), element 2 is reaching (affecting) element 3 and element 4 is reaching to element 2. Elements 1 and 4 are reaching each other and create a loop (cycle). The directed graph is shown in Figure 1.13(a) provides another important piece of information – since element 4 is related to element 2 and element 2 is related to element 3, then element 4 is related to element 3 through the intermediate element 2 (this is called *transitivity rule*). This is shown in Figure 1.13(b).

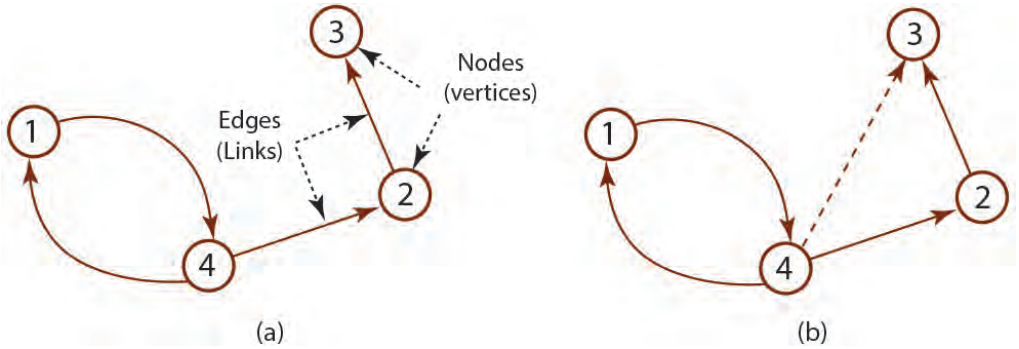


Figure 1.13: Directed graph (digraph).

1.6.3 Cycles in Digraph

A cycle in a digraph is a non-empty directed path in which the only repeated nodes are the first and last nodes – the first node of the path corresponds to the last. If a graph has a cycle it is a cyclic graph. A graph without cycles is called an acyclic graph.

As shown in Figure 1.14, node 2 and 3 makes a two-element cycle and nodes 1, 2, 4 make a three-element cycle, which means that these two and three elements are coupled, respectively. Figure 1.14 also shows the simplest possible cycle – a cycled called *self-loop*. In other words, element 1 is related to itself in some way.

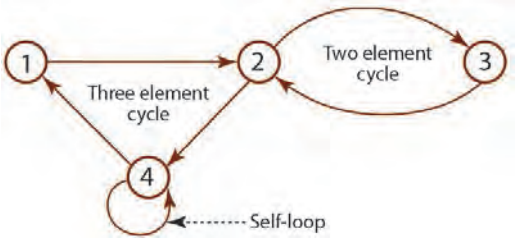


Figure 1.14: Cyclic graph.

EXAMPLE 1.6

Explaining cyclic situations with chicken or egg examples.

BACKGROUND

Chicken or egg situation is a good example to explain cyclic graph – it is impossible to make a decision which of two things existed first: chicken or egg?

EXAMPLES

For example, to get a job you need to have experience, but often without work experience, you cannot get a job. This is a chicken and egg situation – it is difficult to know if the cause of the problem is not having work experience or not having of job.

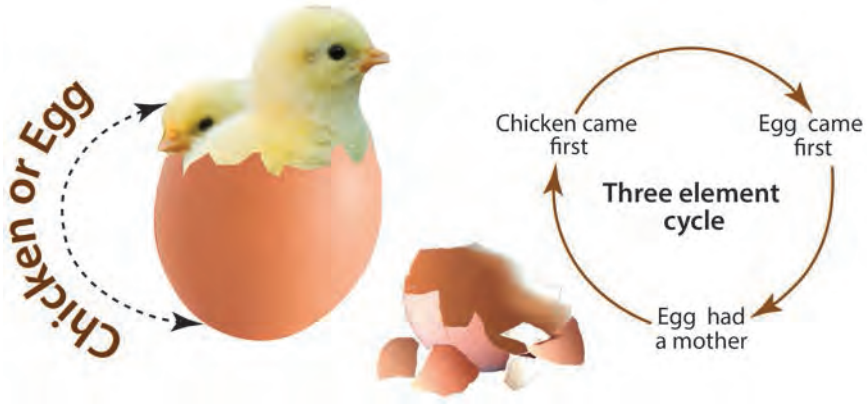


Figure 1.15: Chicken or egg situation.

More complex cycle involves of three elements is shown in Figure 1.15 – chicken or egg cycle. If the chicken came first, then it eventually had to hatch from an egg. If the egg came first, then it had to have a mother to create the egg. If the egg had to have a mother, then the mother should be the chicken – it is impossible to identify the starting point of a circular (cyclic) cause. This kind of situation may create uncertainty in design and makes the design effort complex.

1.6.4 Cyclomatic Complexity

Cyclomatic complexity is used to measure the complexity of a software program. Based on a control flow representation of a program, it was developed by Thomas J. McCabe in 1976. Control flow represents a program as a graph that contains nodes and edges – similar to digraph as shown in Figure 1.16. In this figure, nodes represent processing tasks while edges

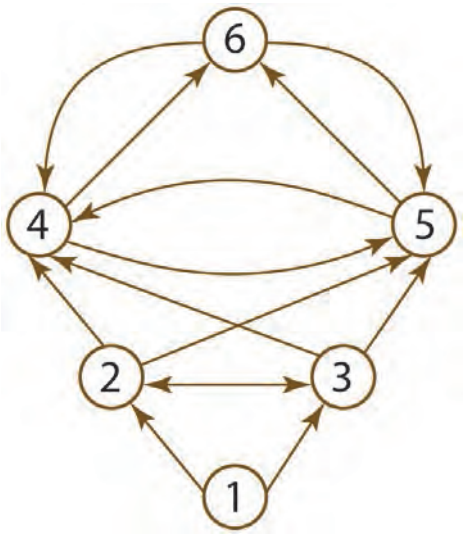


Figure 1.16: Digraph with six nodes.

represent control flow between the nodes. Mathematically, the Cyclomatic complexity, M is calculated by

$$M = E - N + 2P \tag{1.2}$$

where

E = the number of edges of the graph
N = the number of nodes of the graph
P = the number of connected components

The number of edges shown in Figure 1.16 is 13, the number of nodes is 6, and the number of connected components, P is equal to 1. Then, the Cyclomatic complexity M of the digraph given in Figure 1.16 is

$$M = 13 - 6 + 2 \times 1 = 9$$

We may conclude that the system represented by Figure 1.16 is considered very close to the limit to be complex suggested by McCabe.

The complexity of an issue will be difficult to understand when the Cyclomatic complexity number is high. The threshold limit value of Cyclomatic complexity was suggested by McCabe – "the particular upper bound that has been used for Cyclomatic complexity is 10 which seems like a reasonable, but not magical, upper limit."[42]

Profound measurement of complexity can help to improve our understanding and ability to work with complex systems. With the help of the Cyclomatic complexity measure, it will

[42]McCabe, T. J., "Describing Cyclomatic Complexity," *IEEE Transactions on Software Engineering,* Vol. 2, No. 4, p. 308, 1976.

be possible to track complexity changes over several product generations. It is also possible to benchmark one company's product or process complexity concerning its competitors.

Although a general complexity measure has remained abstract, the following factors can be considered for complexity measures:

- The number of decomposed elements (components, tasks, or teams)
- The number of interactions to be managed across the elements
- The uncertainty of the elements and their interfaces
- The patterns of the interactions across the elements (density, scatter, clustering, etc.)
- The alignment of the interaction patterns from one domain to another

1.7 Transdisciplinary Research Process

The key characteristics of transdisciplinary research distinguishing from other related research approaches are:

- Related to real-life complex problems and specific problem solving
- Eliminate disciplinary boundaries for strong collaboration
- Participation of (non-academic) stakeholders
- Acceptance of diverse perspectives, problem framing, and interpretations
- Holistic (non-reductionist) approach to produce new knowledge for solving specific problems (transformative knowledge)

Figure 1.17 shows the proposed TD research process model, which is hypothesized in three phases: 1) team-building and collaboratively understanding of the research problem to develop collective intelligence, 2) Decomposing complex issues, 3) Transdisciplinary assessment and knowledge integration.[43]

1.7.1 Team Building and Collaboratively Understanding of the Research Problem

Transdisciplinary teams can be created with distributed leadership – research team leadership can be altered by the specific expertise required for the project in question. Often, developing and understanding a complex problem may become difficult – collaborating team members may not even agree on what the problem is and no solution can make everyone happy.[44]

Interactive Collective Intelligence Management Workshop: Using any communication platform, an ICIM workshop can be organized where research teams will introduce the project proposals (concepts) about the complex problem being investigated. Using expert

[43]Ertas, A., Rohman, J., Chillakanti, P., Baturalp, T. B. Transdisciplinary collaboration as a vehicle for collective Intelligence: a case study of engineering design education. *International Journal of Engineering Education*, Vol. 31 No.6(A), pp. 1526-1536, 2015.

[44]Denning, P. J. Mastering the Mess. *Communications of the ACM*, Vol. 50, No. 4, pp. 21–25, 2007.

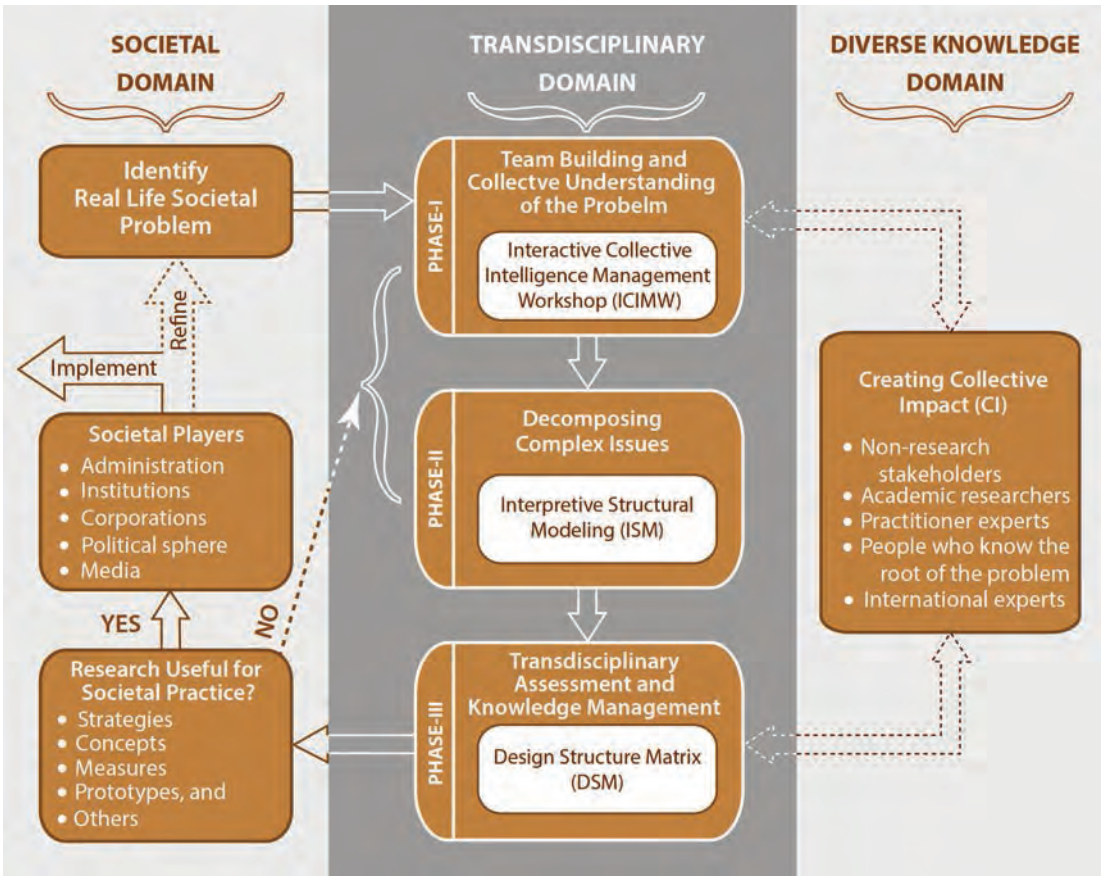


Figure 1.17: Transdisciplinary research process (adapted from [11]).

guidance from diverse knowledge domains, through dialog, the collective best ideas of research teams will come out, and the incorrect or vague ideas that the research team held at the outset will be recognized as wrong or will be sharpened to make them useful.

1.7.2 Decomposing Complex Issues

Through the ICIM workshop process,[45] ideas with high interaction will be grouped into clusters. Thus, research team members can identify and examine cluster interactions internally and interactions between clusters. Decomposed complex problem clustering will be placed in a sequence by using a transdisciplinary tool called Interpretive Structural Modeling (ISM).[46]

[45] Warfield, J. N., and Cardenas, A. R. *A handbook of interactive management.* Iowa State University Press/AMES, 1994.

[46] Rittel, H. W. J., & Webber, M. M. Dilemmas in a general theory of planning. *Policy Sciences*, 4, 155-169, 1973.

1.7.3 Transdisciplinary Assessment and Knowledge Integration.

Transdisciplinary Assessment (TA) embraces integrating people (social), artifacts (technical), and knowledge (cognitive) related to different technical and non-technical knowledge domains[47] into an appropriate methodology.[48] Societal players who are involved with the problem must be included in the research process to effect scientifically valid research (see Figure 1.17).

Data will be collected using the Design Structure Matrix (DSM). Team-based DSM is used for information flow between team members or teams.[49] The following possible ways of information flow will be obtained [15]:

- Level of Detail – Sparse (Documents, e-mail) to rich (models, face-to-face)
- Frequency – Low (batch, on-time) to high (on-line, real)
- Direction – One-way to two-way
- Timing – Early (preliminary, incomplete, partial) to late (final)

If the results of the transdisciplinary assessment provide useful research for societal practice then the research outcome will be implemented otherwise TD process will repeat itself as shown in Figure 1.17.

1.7.4 Creating Collective Impact

The diverse knowledge domain shown in Figure 1.17 is the guidance of subject matter experts to create collective impact (CI) to solving social problems. Collective Impact is the commitment of cross-sector collaboration from different sectors (see Figure 1.17). It is an innovative TD approach to tackle unstructured problems by crossing professional and societal domains.

Utilizing TD methods and tools, research team members will learn: how to become more creative and discover new innovation methodologies; how to decompose unstructured complex problems to understand how various parameters relevant to the problem are interrelated; how to collaborate on achieving collective results; how to hold each other accountable for delivery according to their plans; how to candidly discuss conflicting ideas; how to accept critical dialogue and debate; and how to trust each other.

Through the following chapters of this book, we will introduce TD tools to design, manage or organize projects spanning diverse disciplines. Tools that will be covered are:

- Interactive Collective Intelligence Management (ICIM)
- Kano analysis

[47] Blomberg, K-L, Eriksson, J., Svensson, J. Mapping of relations and dependencies using DSM/DMM-analysis. *Internationel la Handelshogskolan*, Hogskolan I Jonkoping, 2005.

[48] Hinkel, J. *Transdisciplinary knowledge integration: Cases from integrated assessment and vulnerability assessment*, Ph.D. thesis, Wageningen University, Wageningen, The Netherlands, 2008. ISBN 978-90-8504-825-1.

[49] Tyson R. B., (2001). Applying the design structure matrix to system decomposition and integration problems: a review and new directions. *IEEE Transactions on Engineering Management*, Vol. 48, No. 3, pp. pp. 292 - 306, 2001.

- KJ diagram
- Critical to Quality (CTQ)
- Quality Function Deployement (QFD) & House of Quality (HOQ)
- Theory of Inventive Problem Solving (TRIZ)
- Axiomatic Design (AD)
- Interpretive Structural Modeling (ISM)
- Design Structure Matrix (DSM)
- Risk Management Standard Tools

The integration of transdisciplinary tools used to solve cross-disciplinary unstructured problems is shown in Figure 1.18. Traditional design process approaches are inadequate to solve complex issues affecting the world today. In the proceeding modules, we will discuss some of the TD tools and their integration for the solution of complex problems.

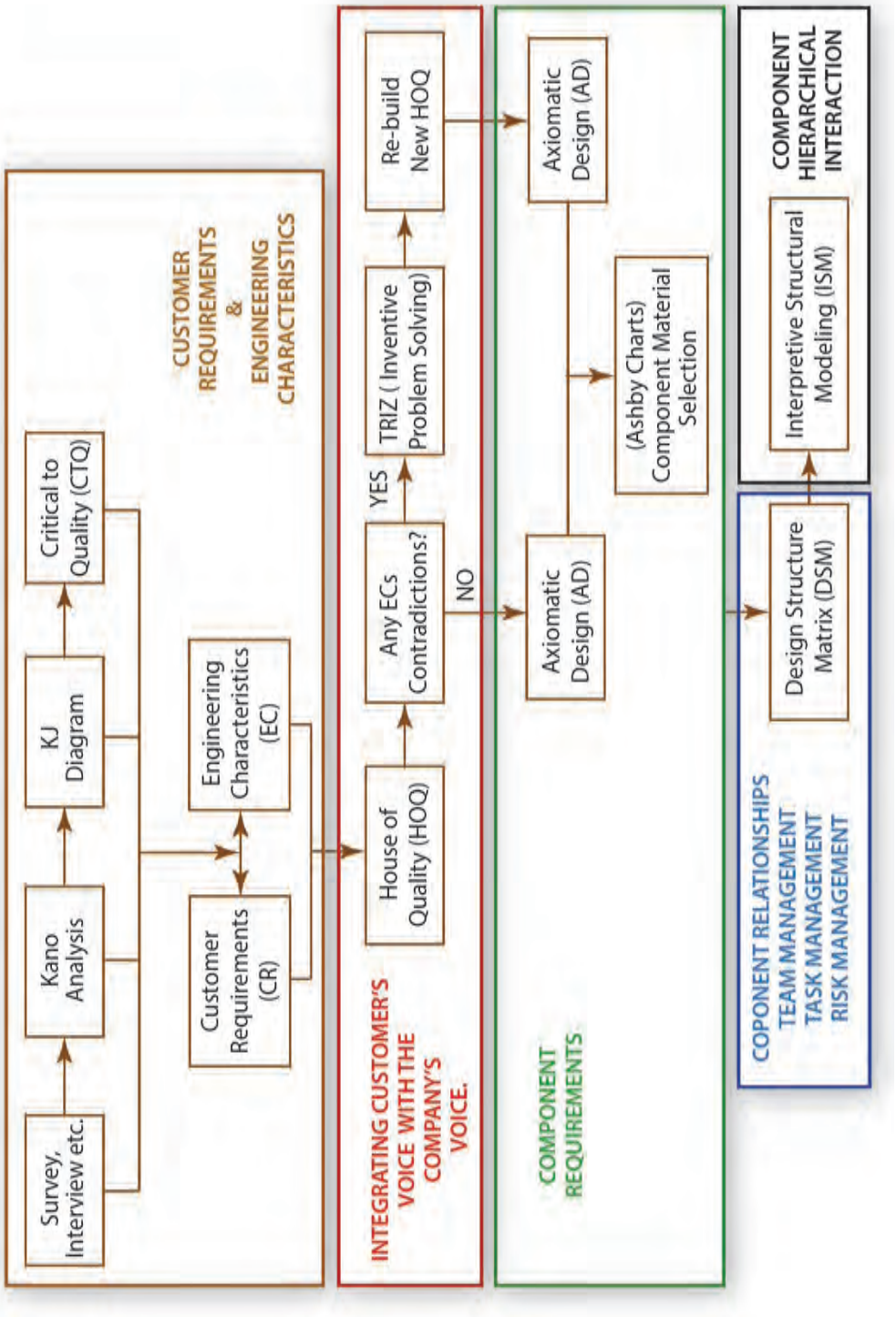


Figure 1.18: Tools for project development structure.

CHAPTER 2

Requirements Development

The most difficult part of requirements gathering is not the act of recording what the user wants, it is the exploratory development activity of helping users figure out what they want.

Steve McConnell

When you are out to describe the truth, leave elegance to the tailor.

Albert Einstein

2.1 Introduction

The requirement is specific documented physical and functional capabilities and attributes that a particular design, product, or process must be able to perform. The process of developing correct requirements is not an easy issue–it is a comprehensive, iterative, and recursive process. It is important to note that the fundamentals of well-defined requirements are clarity, brevity, and simplicity. The elegant and entertaining requirement writing style is not necessary. This is a task that will be accomplished after the concept has been selected. Requirements are used throughout the system development lifecycle activities – from beginning to completion.

2.2 Requirements Development Steps

As shown in Figure 2.1, the following six steps are used for developing requirements:[1]

1. **Develop High-Level Requirements** – Before the six steps requirement development starts, as seen from Figure 2.1, customer needs should be defined through the general process shown in Figure 2.2. After operational needs are evaluated and the design concept is completed, the next step is to develop high-level requirements. The customer needs

[1]Requirements Development Steps. http://acqnotes.com/acqnote/tasks/requirements-development-steps. Accessed January 11, 2020.

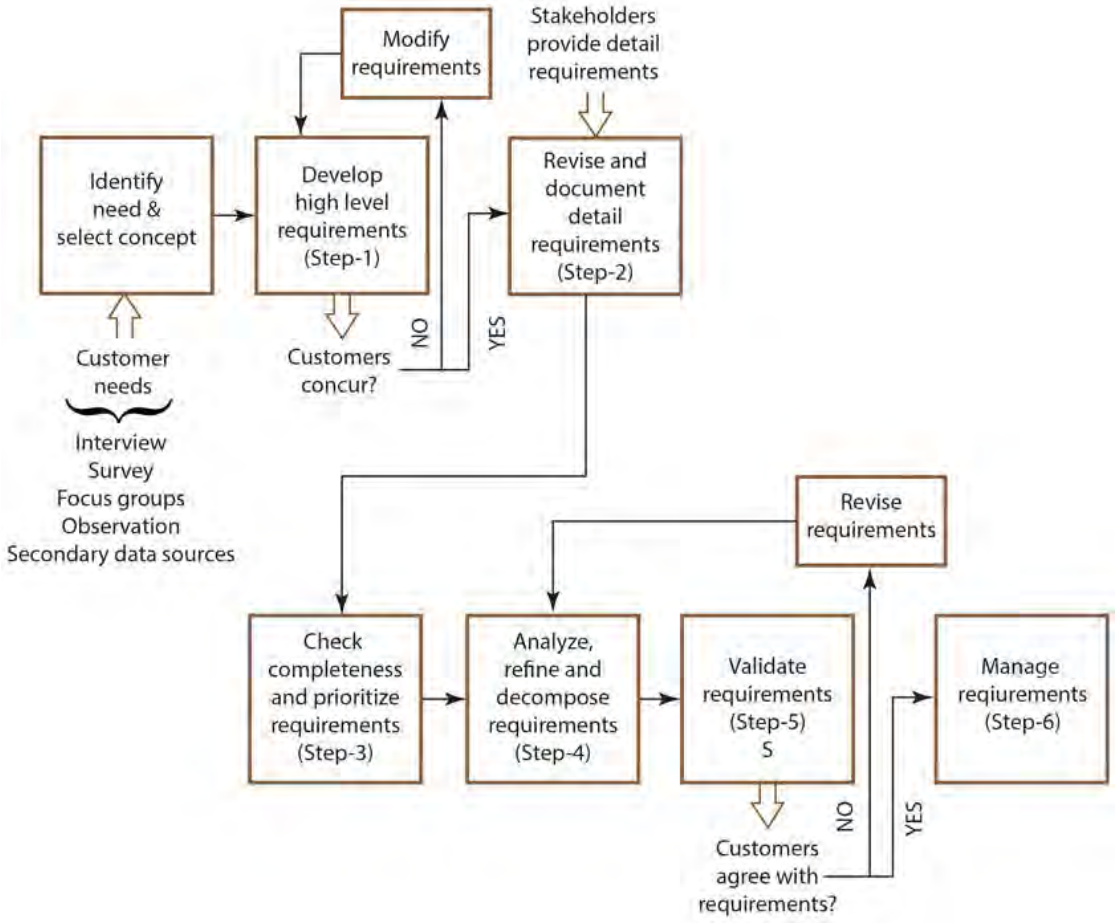


Figure 2.1: Requirements development process.

data collection is performed through interviews, surveys, focus group discussions, secondary data sources, and observation of lectures, seminars, or lab classes. The project's purpose and important details of the project must be understood through customer communication.

2. **Revise and Document Detail Requirements** – After all the characteristics (functional, physical, and performance) desired by the customer are defined, detailed requirements should be documented. For each characteristic (attributes) constraints should also be determined during this step.

3. **Check Completeness** – The next step is toward developing and checking accurate and complete requirements that capture the essence of a concept.

4. **Analyze, Refine, and Decompose Requirements** – This step assesses each requirement to see if it meets the physical and functional characteristics of the project. Since not all requirements are equally important, they can be arranged hierarchically. Higher-level requirements could be unclear and should be decomposed into a more refined set of sub-requirements. Decomposition of the requirements should be carried out to a *simple* level so that the requirement is *self-evident* at the lowest level. As a general rule, decomposition should be done from the highest level (most abstract, least concrete) to the lowest (least abstract, most concrete) level.
5. **Validate Requirements** – In this step, each requirement must be verified and validated to ensure that they are consistent, complete, understood, not vague, and reflect the actual needs and expectations of the customers.
6. **Manage Requirements** – In step six, ensure that a common understanding of the requirements exists, the requirements have been approved, and a baseline is recognized by the customer. Any changes to the requirements are tested regularly to determine if the customer will be satisfied with the changes. During this step, some sort of transdisciplinary coordination group needs to be established to discuss the design effort ongoing in each discipline and how the design requirements are being interpreted and applied. This process will force the transdisciplinary coordination to focus on a task that ensures proper subsystem integration and a uniform understanding of design requirements.

It is important to have well-defined and well-controlled requirements, but, it is also crucial to minimize requirement changes as the systems are implemented. Changes to the requirements during the design process can have a profound and negative impact on the final quality of the design project. In many high-tech companies, requirement changes may cause long lead times for the design effort. On large-scale complex systems, it is normal to experience requirements problems late in the design process.

2.3 Process of Defining Customer Needs/Requirements

Figure 2.2 shows a generic process of defining customer needs (requirements). Customer needs project (product) characteristics desired or needed by the customer. Just asking the question of what is important to them may not give you enough information to decide on the requirements. Customers may deliver you with poor and misleading a lot of unrealistic information because they may struggle to articulate their needs or they may change the project needs over time.

2.3.1 Customer Data Collection and Analysis

The following qualitative and quantitative data collection methodologies can be used to gather data for customers' needs.

2.3.1.1 Interviews

Interviews are a key qualitative data collection method one-on-one between an interviewer and an individual to gather information on a specific set of project topics. Interviews can be

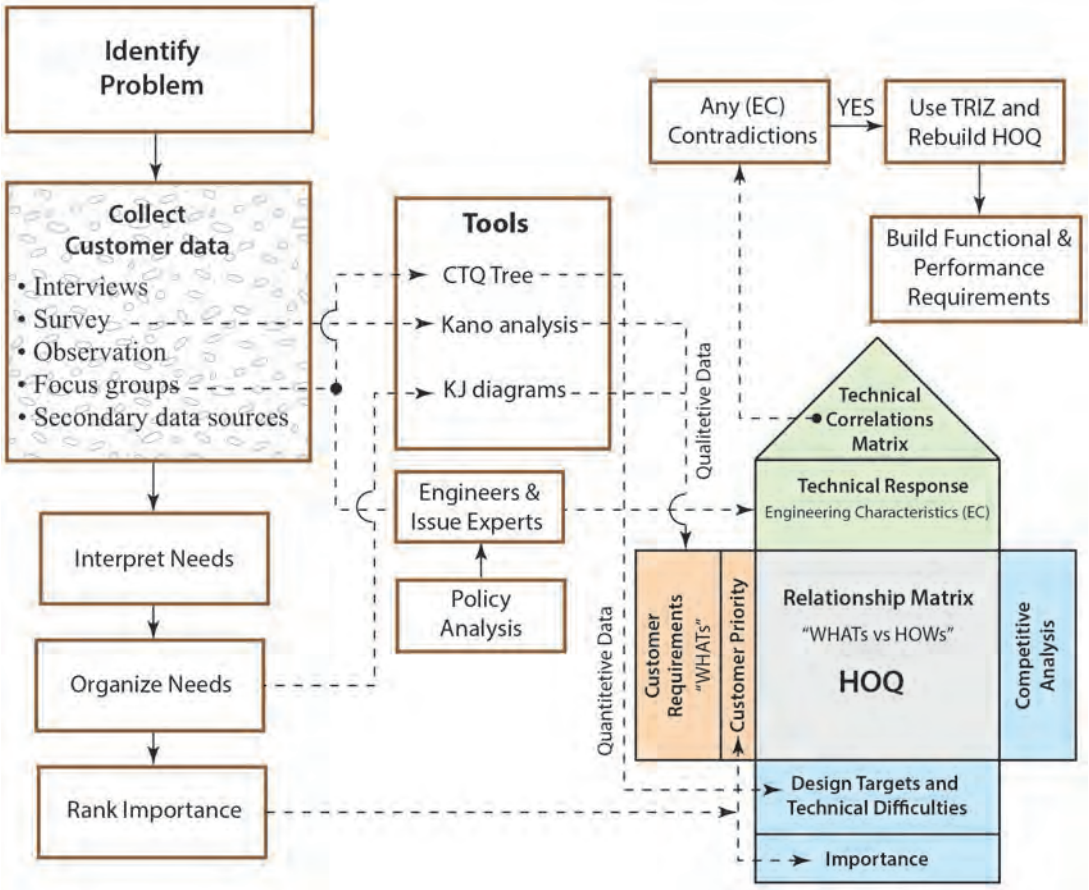


Figure 2.2: Process of defining customer needs/requirements.

conducted in person, over the phone, or by submitting a proposal.

2.3.1.2 Observation

Observation is s systematic data collection method by observing people in which the researcher does not participate in the communications, for example, observing learning and teaching activities (lectures, seminars, lab classes).

2.3.1.3 Focus Groups

A *Focus groups* is a qualitative data collection method as opposed to quantitative data collection that involves numerical-based data collection. This is a dynamic group discussion of approximately six to twelve participants engaged to share similar common interests. A moderator leads the group based on a prearranged set of topics.

2.3.1.4 Secondary Data Sources

Secondary data sources are public information in the open literature that is collected by others. It is usually free or low-cost to obtain and can support as a strong foundation for any research project.

2.3.1.5 Surveys

Surveys are important qualitative or quantitative data collection methods that are usually used with customers to discover customer needs. It includes a structured questionnaire that can be administered by paper and pencil, as a Web form, or by an interviewer who follows a strict script.

As shown in Figure 2.3, Griffin et al. handled a survey interviewing 30 customers to find out 220 needs.[2] It is evident from this figure that 15-20 respondents should be enough to get a reasonably good understanding of their customers' needs. Details for surveys will be discussed in the following section.

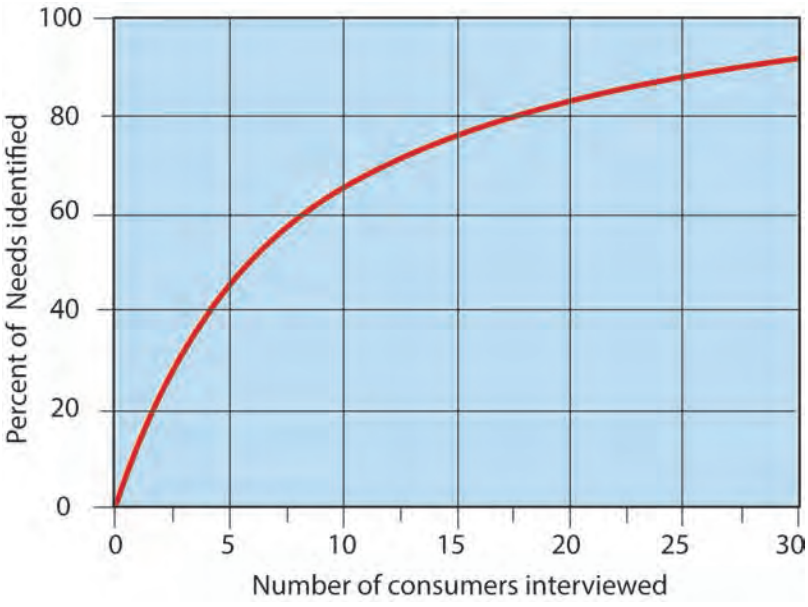


Figure 2.3: Survey result for customer need (Griffin, Abbie and John R. Hauser, 1993).

2.3.2 Kano Model – Understanding Customer Needs

Think about your new startup company design team that is trying to come up with something that no one has ever done before–a new invention. The design team is very excited about this discovery–the goal is to create the best-selling product of the year. However, the project

[2]Griffin, Abbie, and John R. Hauser, 1993. The Voice of the Customer. Marketing Science, Vol 12, No. 1.

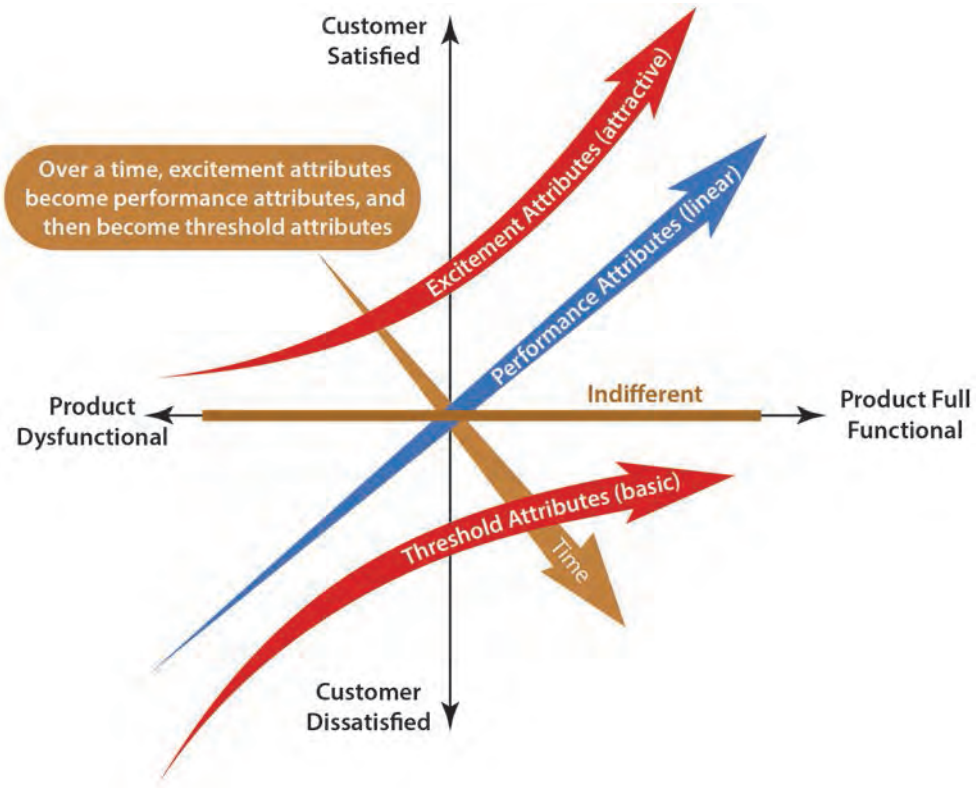


Figure 2.4: Kano model.

director has some doubts about the extra features that will increase the cost of the product, thus not maintaining a good profit margin and also keeping up with the competition. The project director wants to create a vision and direction for the product offering over time with the right features. There could be many reasons why the design team might need to include a given feature, but they have to decide which feature will make their customers happy and prefer it over others. There is no easy answer to this question, but luckily there is a very effective tool to guide the design team in deciding which features should be included in the product development: the Kano Model as shown in Figure 2.4.

2.3.2.1 Kano Model: Prioritizing Customer Satisfaction

The *Kano Model* is a method for product development and customer satisfaction that was proposed in the 1980s by Professor Noriaki Kano. As shown in Figure 2.4, the Kano Model considers three types of product/service attributes:

1. **Threshold Attributes (Basic Requirements)**.

   These are necessary product/service attributes that are expected by the customers. A

competitive product must meet basic attributes. For example, when you book into a hotel you would expect a shower with hot water as a minimum feature – no hot water makes customers unhappy.

2. **Performance Attributes (Linear Requirements)**. These attributes are not necessary, but they improve customer satisfaction. For example, you would be happy to have a free internet connection, when you would normally expect to pay.

3. **Excitement Attributes (Attractive Requirements)**. These are the unexpected attributes (delighted) of a product or service that can result in high levels of customer satisfaction. They are the features that customers are not aware of, but are delighted with when they see them. For example, in your hotel room, you notice a delicious selection of goodies and a wonderful relaxing glass of wine to enjoy during your stay when you wouldn't normally expect to see such a welcome gift.

As seen from Figure 2.4, if a product's features don't meet a customer's threshold attributes, it will cause extreme customer dissatisfaction. However, even if you fully deliver on these features, it will not excite customers so much. Note that, over time, excitement attributes become performance attributes, and then become threshold attributes (see Figure 2.4). For example, an iPhone touchscreen caused such admiration back in 2007 and is now just an expectation when purchasing a phone – the steady advancement of technology and emergence of competitors cause this decay in delight.

Most products compete on performance attributes, where a customer compares one product against another and makes a decision on satisfaction by the presence of different features. For example, a family with five children would be willing to pay more for a minivan that provides them comfort with better fuel economy. Reverse features may cause dissatisfaction to some customers. For example, providing fully automated high-tech cars with many features may cause dissatisfaction. Some customers prefer the basic model of a car without having too many extra features. if these features are present, customers' dissatisfaction will grow and they will actively reject these futures. The summary of the Kano model to help design teams to classify customer needs and attributes into a five-step guide is shown in Table 2.1.[3]

[3]Ertas, A. *Transdisciplinary Engineering Design Process*, John Wiley & Sons Inc., 2018.

Table 2.1: Classification of customer needs and attributes.

Requirement Type	Definition
Must be (threshold attributes)	These are the basic (must be) features of a product or service – customers expect these requirements that are fulfilled.
One-Dimensional/Linear (performance quality)	These qualities are not absolutely necessary, but they increase a customer's satisfaction.
Excited attractive quality	These are the surprise qualities of a product or service. If these qualities are absent, it does not cause customer dissatisfaction.
Indifferent quality	Customers don't care if these features are provided or not provided.
Reverse quality	Providing more features may cause dissatisfaction.

2.3.2.2 Kano Model Analysis

A rather easy approach to applying the Kano Model analysis is to develop a set of survey questionnaires. To eliminate inconsistency each set of questions will have a positive statement/question and a negative statement/question about each requirement. Then the questionnaire is sent to a group of prospective customers. As shown in Table 2.2, the question can be phrased in two ways and then can be allowed for multiple-choice answers to the question.

Table 2.2: Example of Kano questionnaire.

If gym memberships & fitness programs is free, how do you feel? (positive question)	(a) I like it (b) It must be that way (c) I am neutral (d) I can live with it (e) I dislike it
If gym memberships & fitness programs is not free, how do you feel? (negative question)	(a) I like it (b) It must be that way (c) I am neutral (d) I can live with it (e) I dislike it

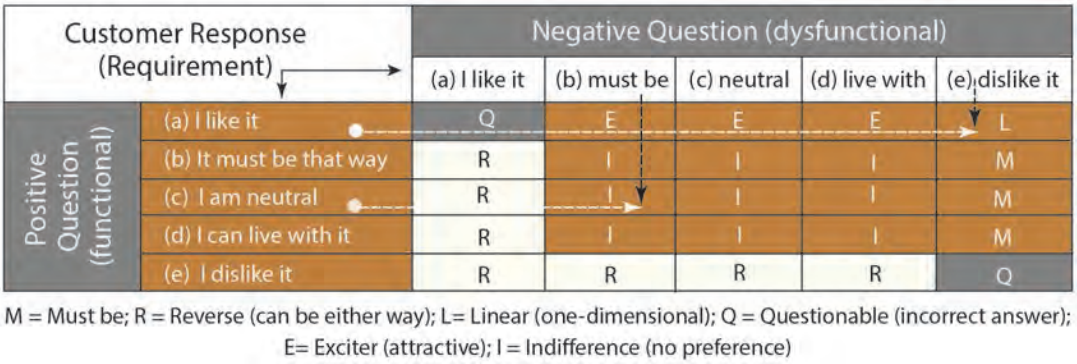


Figure 2.5: Kano model questionnaire evaluation.

2.3.2.3 Evaluating Kano Questionnaire

To translate the survey results, the category of each attribute can be classified through Kano's paired functional/dysfunctional questionnaire as shown in Figure 2.5. As indicated in this figure, the rows of the Kano matrix correspond to the answers to the functional question, the columns correspond to the answers to the dysfunctional question. As an example, suppose a customer likes free gym membership and fitness program (see Table 2.2), he/she would likely give an answer (a) to the positive question and (e) to the negative question. Following the evaluation matrix given in Figure 2.5, this option will fall into the "Linear" attribute 'L'.

2.3.2.4 Kano Analysis of Results

Let's consider a gym with features evaluated by customers shown in Table 2.3. A questionnaire should be sent to enough customers to have realistic results that represent the majority of customers' requirements. Let's assume that we have 45 customers. After the survey results through the Kano evaluation chart shown in Figure 2.5 is completed. The next stage of the analysis is assigning a letter score to every attribute as shown in Table 2.3.

In this example, the main aim is to identify and evaluate the attributes of *gym* service which affect its quality from the point of view of customers. More than %60 of the customers required performance future (linear): customers' satisfaction increased proportionally when they saw the acceptable price range. The following are identified among the "must be" category: offering a variety of exercise equipment as well as pleasant personal trainers. Poor quality of exercise equipment results in customer dissatisfaction and eventually loss of business. As shown in this table, almost %50 of the customers are excited when they see a clean and pleasant atmosphere: this is a feature that customers didn't expect.

The results of the analysis should show us which features are considered important by the customers and how the implementation of those features affects the customers' satisfaction. This allows the designers to prioritize the accepted feature list of products/services during the product/service development. Note that "must-be" and "performance" features should be implemented at as high of a rating as possible. Designers should reserve a room for delighters during the product development process: attractive attributes give the competitive

Table 2.3: Results of Kano Analysis for 45 responses.

Gym Features	Exciter	Linear	Must be	Indifferent	Reserve	Questionable
Acceptable price range	1	(29)	11	3	1	0
Variety of exercise equipment	4	(17)	(21)	1	1	1
Pleasant Personal Trainers	5	15	(21)	2	1	1
Pleasant atmosphere	(22)	8	7	6	1	1

advantage that allows a company to outperform compared with competitors. Because most customers simply don't care about whether indifferent features are present or absent, it will not affect their satisfaction. Therefore, indifferent features can be carefully evaluated or avoided because they are essentially money sinks. The reverse or questionable results would need to be further analyzed to properly determine their place or they should be excluded from further considerations.

The Kano model is a tool that can be used for KJ-Method to organize data collected from customers and prioritize the Critical to Quality (CTQ) characteristics.

2.3.3 KJ Method

The KJ-Method, named after its inventor Kawakita Jiro, is a useful tool used to organize data and ideas. KJ method allows the research team to reach a quick and effective way to get team consensus on priorities of qualitative data collected from customers and develop a set of customer requirements. The following simple steps can be used for the KJ analysis:[3]

- Collect all ideas without considering their reasons
- Cluster (group) the ideas that seem to be related
- Develop hierarchies of groups and subgroups

2.3.4 Critical to Quality Characteristics

Once the customer needs are recognized, an effort can be made to translate them into quantitative terms known as Critical to Quality (CTQ) characteristics. CTQs are the key measurable characteristics of a product or process that help a company translate the most important needs of products/services into requirements to ensure their quality. These requirements include the upper and lower specification limits or any other factors related to the product/service defined by the customer. In general, a CTQ is translated from a qualitative customer statement to a quantitative product specification. Below are some examples of the translation that needs to be made to define quantitative product specifications. Let's consider the CTQ of a minivan.

- Customer requirement – an SUV with good fuel mileage.

  CTQ – a quantitative specification could be 27 miles per gallon.
- Customer requirement – a fast acceleration.

  CTQ – a quantitative specification could be 3.7 seconds from 0 to 60 mph.
- Customer requirement – an acceptable price range.

  CTQ – a quantitative specification could be priceless than $40K.
- Customer requirement – powered by the strong engine.

  CTQ – a quantitative specification could be: the engine has 300 hp.
- Customer requirement – safety.

  CTQ – a quantitative specification could be a 5-star National Highway Traffic Safety Administration (NHTSA) safety rating.

2.3.4.1 Critical to Quality Characteristics Tree

The next step is for the project team to brainstorm customer requirements with the people who investigated the customer needs to identify the specific features (*drivers*) that have to be decided to meet the needs that were identified: the minimum performance requirements that are to be satisfied for each driver. A CTQ tree is a form of a simple effective diagram that helps design teams identify and list what the customer wants and helps the designers to ensure that customers get what they want. Now, consider the CTQ tree to get the most out of your trip with the cruise. Although most people can identify dozens of things they love about cruising, as shown in Figure 2.6, in this example, we have included some main drivers of cruise travel that will appeal to almost everyone: food, acceptable price, service, convenience, and emergencies.

For this example, the following are some of the simple questions you'll want to ask before booking a cruise: How cruise line handle food allergies and emergencies? When is the best time to sign up for a shore excursion? How do we prevent getting motion sickness? How big is the cruise ship? How many passengers can it hold? Is the cruise line reputable? and more. CTQ tree consists of four elements as shown in Figure 2.6: need, drivers, requirements, and convert requirements into CTQs.

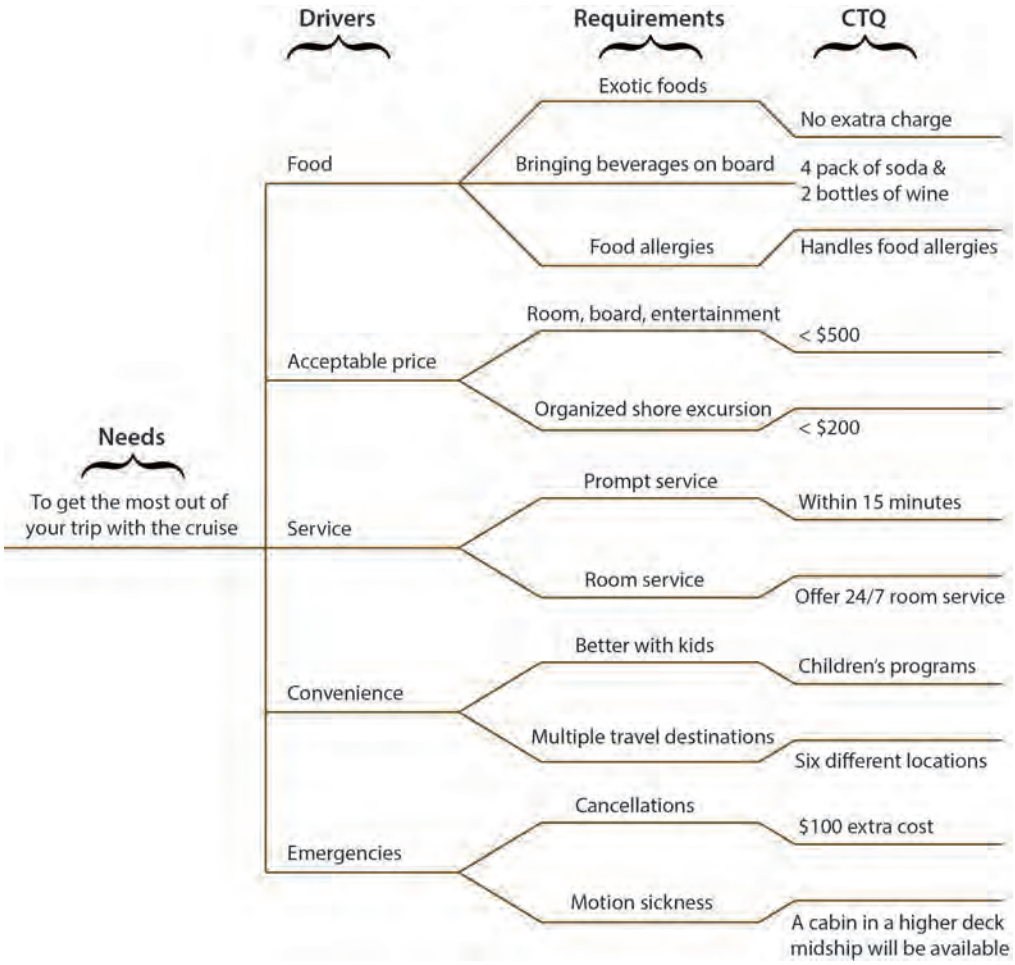


Figure 2.6: CTQ tree.

EXAMPLE 2.1

Process of defining customer needs a finger rehab device: Stroke is one of the reasons that can cause fingers to malfunction or patients that break or suffer ligament damage to their joints, particularly in the index finger, need rehabilitation for recovery. There is a need to design and develop a home-based finger rehabilitation device to support the rehabilitation process. Consider redesigning a new finger rehab device that would rehabilitate the proper motion of the finger safely and passively.

BACKGROUND

To design a new finger rehab device (see Figure 2.7), the following positive and negative survey questions were sent to a group of customers to define their needs. The survey questions were as follows:[a]



Figure 2.7: Finger rehab device.

Positive Questions (functional):

1. How would you feel if the rehabilitation device function (flexion & extension) is automated?
2. How would you feel if the rehabilitation device is designed for patient comfort?
3. How would you feel if the rehabilitation device is lightweight?
4. How would you feel about the rehabilitation device's low cost?
5. How do you feel about the rehabilitation device being controlled by an app?
6. How do you feel about the battery being rechargeable?
7. How do you feel about the rehabilitation device with concealed wires?
8. How do you feel about the rehabilitation device being portable/robust?
9. How do you feel if the product prevents swelling?
10. How do you feel if the device has continuous passive motion?
11. How do you feel if the device meets the medical device regulations.
12. How do you feel if the device supports user activity.

EXAMPLE 2.1 (continued)

Negative Questions (dysfunctional):

1. How would you feel if the rehabilitation device (flexion & extension) is not automated?
2. How would you feel if the rehabilitation device is not designed for patient comfort?
3. How would you feel if the rehabilitation device is not lightweight?
4. How would you feel about the rehabilitation device is not low cost?
5. How do you feel about the rehabilitation device is not controlled by an app?
6. How do you feel about the battery not being rechargeable?
7. How do you feel if the rehabilitation device has exposed wires?
8. How do you feel about the rehabilitation device is not portable/robust?
9. How do you feel if the rehabilitation device doesn't prevent swelling?
10. How do you feel if the device doesn't have continuous passive motion.
11. How do you feel if the device doesn't meet the medical device regulations.
12. How do you feel if the device doesn't support user activity.

KANO ANALYSIS

The survey was sent to approximately 40 people and 30 responses were received. Raw data from customer responses were analyzed and customers' need statements were extracted from each response. Using survey results and Figure 2.5, each positive question was compared against each negative question for every respondent to determine appropriate letters shown in Table 2.4.

Table 2.4: Kano analysis results for 30 responses.

Features ↓	**E**	**L**	**M**	**I**	**R**	**Q**
Automated	10	6	7	3	0	4
Comfort	14	8	4	3	0	1
Light weight	9	9	9	0	0	0
Low cost	4	10	8	4	0	4
Device controlled by an app	13	5	5	4	0	3
Device with rechargeable battery	5	10	9	4	0	2
Device with concealed wires	6	6	14	2	1	1
Portable/robust	5	12	6	4	0	3
Device prevents swelling	6	6	14	2	0	2
Device has continuous passive motion	4	9	10	4	0	3
Meets regulations	2	9	12	4	0	3
Support user activity	4	8	11	4	0	3

EXAMPLE 2.1 (continued)

From the Kano analysis results, we can define the most important design categories to include in the final customer needs and engineering characteristics (requirements). To develop a set of customer requirements, qualitative data collected from customers is used to build the KJ diagram shown in Figure 2.8.

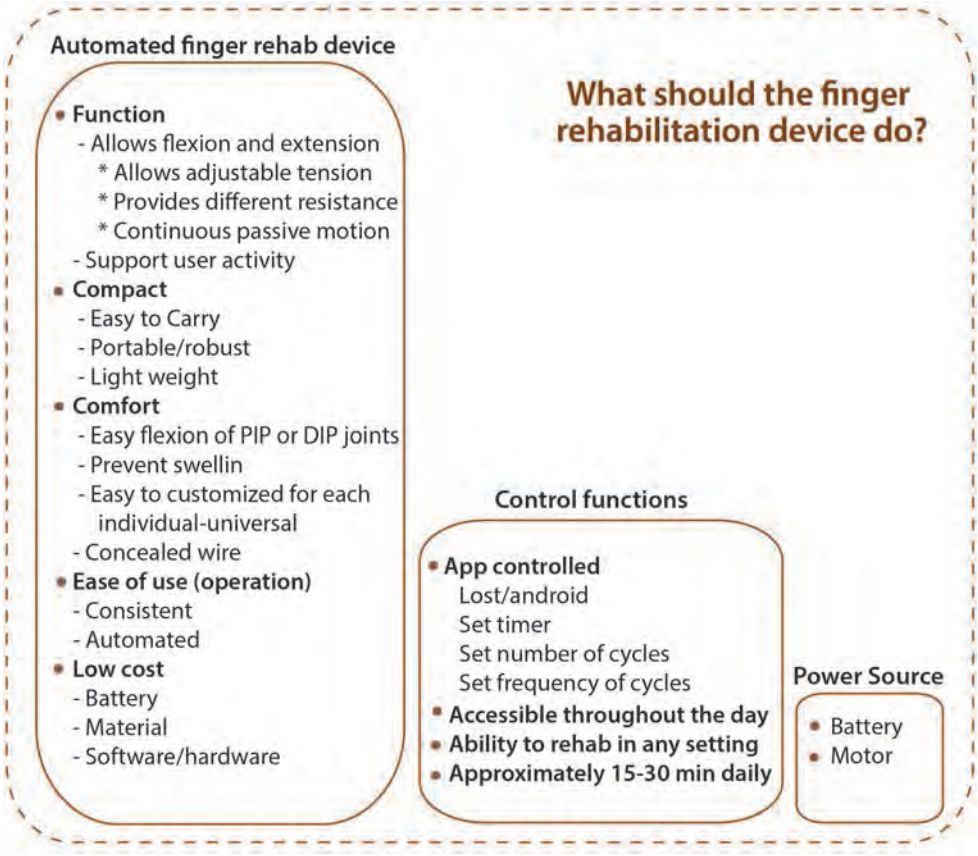


Figure 2.8: KJ diagram of finger rehabilitation device.

After forming the KJ diagram, customer data can easily be translated into quantitative terms to develop the CTQ tree, shown in Figure 2.9. In Figure 2.9, the driving design categories are expanded more in a rehab device CTQ tree to allow a more specific idea of what is needed for the design requirements to be developed.

[a] This example problem was adapted from the design class project. Raymon Garza Isaiah Marquez, Abdul Hamed, Alejandro Procel, Jesus Rongel, Yeung Hun Choi, (May 2020). "Automated Rehab Finger."

EXAMPLE 2.1 (continued)

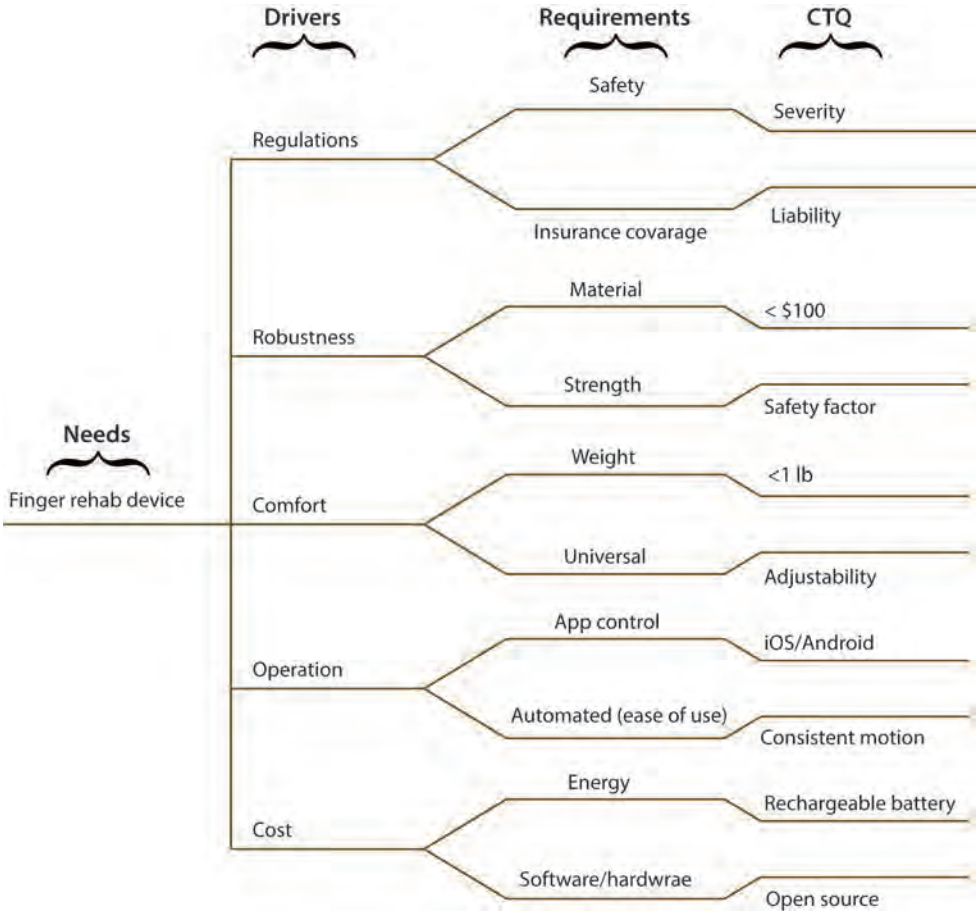


Figure 2.9: CTQ tree for finger rehabilitation device.

2.4 Quality Function Deployment: Requirement Prioritization Method

Quality Function Deployment (QFD) was developed in Japan in the early 1970s and has been effectively used in the United States since the 1980s. QFD is a planning process and management approach for product and service development to reflect the voice of the customer – to weigh or prioritize customer requirements and correlate customer desires (WHATs) to system features (HOWs). It is a method for identifying customer needs and making sure that the voice

of the customer is included in a design process for product/service development. QFD provides a systematic design process that allows an enterprise to go beyond CTQ characteristics.

The five stages of the QFD chart are shown in Figure 2.10. The steps for documenting information in this chart is as follows:

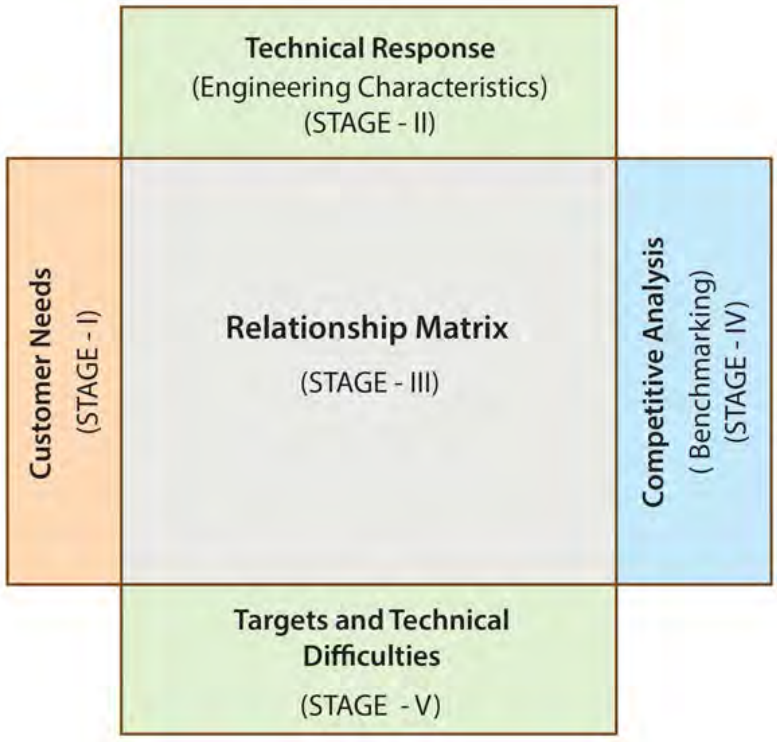


Figure 2.10: QFD matrix.

- *Stage 1*: includes customer needs. Customer needs are product characteristics desired or needed by the customer. However, understanding poor and incomplete information on customer needs is not an easy task. Five important concerns to understanding customer needs are:

  1. Customer may have unknown needs that they don't even know they have,
  2. Customers may have a hard time expressing their needs,
  3. Customers' needs may change in time,
  4. Customers may not realize what they want until they see it, and
  5. It is difficult to know all of the customers' needs.

  Note that, after filtering and translating customer needs into engineering terms, customer needs become customer requirements. The practice of collecting the voices of customers

and converting them into engineering characteristics is an important initial part of the project execution.

- *Stage 2*: includes the list of engineering characteristics. The customer's subjective and non-technical requirements are translated into measurable engineering language. These requirements are developed by design engineers to satisfy the customer's needs.

  The customer needs to tell us what to do and the engineering characteristics tell us how to do what customers want.

- *Stage 3*: involves developing matrix relationships between engineering design characteristics and customer needs. This relationship matrix is used to verify and improve the dependability of the translation of customer needs into measurable engineering characteristics. By ranking the relationship between customer needs and engineering characteristics as strong, medium, or weak, the requirements are identified in quantifiable terms.

- *Stage 4*: the product design is compared with competitors' products through what is referred to as competition benchmarking. Other product design attributes are compared with the list of customer needs to identify the best optimal design solution. The process of benchmarking provides the following benefits[4]:

  1. eliminating the trial and error process,
  2. stimulation the improvements process,
  3. improving the efficiency of the company in developing innovative ideas.

  It is important to note that the selected benchmarking products should have similar functions and applications to be comparable. Benchmarking can be scaled between 1 and 5, with 1 being not satisfied and 5 being completely satisfied.

- *Stage 5*: In this stage, the technical difficulty of each engineering design characteristic is scaled between 1 and 5, with 1 being easy and 5 being most difficult to achieve. Also, the target values of each engineering characteristic are set.

[4]C. E. Bogan and M. J. English, (1994).*Benchmarking for best practices: winning through innovative adaptation,* vol. 1. McGraw-Hill New York.

EXAMPLE 2.2

Using Kano analysis results, KJ (given in Figure 2.8), and CTQ diagram (given in Figure 2.9), develop Quality Function Deployment for the finger rehab device.

The purpose of the Kano, KJ, and CTQ analysis is to help construct and define engineering characteristics to better achieve customer needs. Using the results of Kano, KJ, and CTQ, the student research team developed the following customer needs.

Universal: The design of the finger rehab device will be usable by all people, to the greatest extent possible.

Portable: The next customer need is " the device must be portable" - lightweight, compact, and small enough to fit on a finger.

Automated: Automation is an important aspect of this design. The purpose of designing an automated device is to mobilize the finger safely and repetitively so that users achieve their highest level of recovery.

Controlled by app: One of the most unique features of this design is providing users with a programmed mobile application that allows users to control the device to their convenience. The application will provide users with a variety of options to better control the motion of the finger. These features include speed, deflection, timing, and sensitivity.

Concealed Wires: As opposed to the previously described requirements, customers were not satisfied with having exposed wires.

Rechargeable Battery: A rechargeable battery will provide a variety of benefits to users which include convenience, battery efficiency, performance, earth-friendly, and money-saving.

Inexpensive: Customers would like to have a good quality product at an affordable price. Cost is one of the driving factors for this product.

Light weight: Customers would like to have a device lightweight.

Figure 2.11 shows simplified eight customer requirements developed by the design team used for the Quality Function Deployment to provide a structured way of designing quality into the finger rehab device while establishing engineering characteristics – thus integrating the voice of the customer into the design process.

EXAMPLE 2.2 (continued)

Ranking Key		
Strong Relationship	◉	9
Medium Relationship	○	3
Weak Relationship	△	1

Customer Requirements (What?)	Engineering Characteristics (EC) (How?): Minimum cost	Weight	Strength	Support user activity	Reliability	Power & energy	Flexion & extension	Customer Score	Benchmarks (1-low, 5 high): Proposed Product	Competitor 1	Competitor 2
Universal	◉	○					△	13	3	1	2
Portable	△	◉	○			△	○	17	5	2	4
Automated	◉	△		◉	◉	◉	○	40	5	4	3
Controlled by app	◉			◉				18	5	3	4
Concealed wires		△			△			2	5	4	4
Rechargeable battery	○				○	◉		15	5	5	5
Inexpensive	◉	◉	○	○	○	△	△	29	5	4	3
Light weight	○	◉	○		○	△	△	20	4	3	3
(EC) Score	43	32	9	21	19	21	9				
Unit	$	lb	psi		%						
Target Value	<90	<1	400		99%						
Technical Difficulty (1-Easy, 5-Most Difficult)	3	3	4	4	4	2	3				

Product Targets and Benchmarks

Figure 2.11: Quality Function Deployment (QFD).

As shown in Figure 2.11, the customer's requirements are listed as the row of the matrix, and the engineering characteristics are listed as the columns of the matrix. Engineering characteristics are what you control, performance criteria are what your customer cares about. A 'target value" refers to the planned value for an "engineering characteristic" in the final design that you have certain control over. For example, weight, size, shape, speed, cost, etc. Engineering characteristics may have an effect on certain performance criteria – for example, the engineering characteristics of the weight of a system may affect the performance criteria of cost. By grading the relationships as strong, medium, and weak between the customer's requirements and engineering characteristics we identify those areas in need of improvement and focus. If the relation cells are blank, that indicates there is no correlation between customer requirements and engineering characteristics.

EXAMPLE 2.2 (continued)

As shown in Figure 2.11, automation (40), inexpensive (29), and lightweight (20) scored the highest for the customer's requirements. Minimum cost (49) and weight (32) scored the highest for the engineering characteristics. For customer satisfaction, design efforts will focus on improvement in those areas that were scored high. The cost of the finger rehab device production is the driving factor for this product to survive in the market.

To understand the market position of the finger rehab device benchmarks for each competitor's values are also shown in Figure 2.11. The degree to which competitors satisfy the requirements was evaluated by rating them on a 3-point scale. Finally, the target value of each engineering characteristic is defined and target difficulties are shown in the figure. Each engineering characteristic was evaluated for satisfaction criteria. If the criteria could be measured, a unit of measure was defined and a target value was specified. For example, the target cost of production was determined to be less than $90.

From this QFD analysis, designers can make a decision on the critical areas and potential failure points for the final product design.

Bridging customer needs, engineering characteristics, and design requirements is an important step in developing design requirements. Normally, we collect our customer needs first, then filter and translate those into engineering terms as long as we are getting those needs from actual users. Then, we carefully decide on engineering characteristics to meet the customer's requirements. This will allow us to develop a QFD to understand how customer requirements and engineering characteristics are correlated. These customer requirements and engineering characteristics become parts of the design requirements for the product (see Figure 2.12).

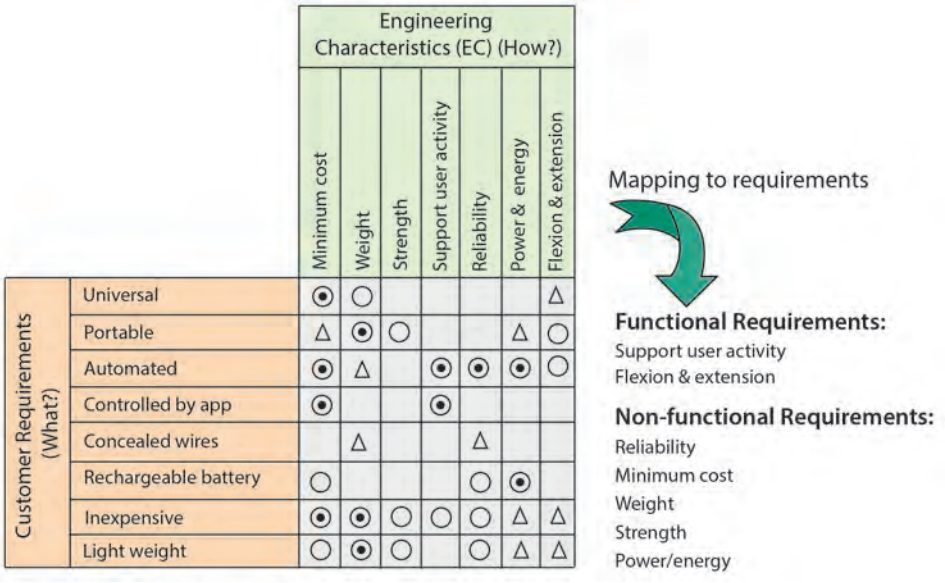


Figure 2.12: Mapping to requirements.

2.4.1 Design Requirement Categories

There are three main requirement categories.

a) **Functional/Non-functional Requirements.** A functional requirement (FR) describes ***"what"*** the system/product must do without describing them in quantitative terms. For example, "the finger rehab device shall be capable of flexing and extending the hand fingers, repetitively." Non-functional requirements (NFR) serve as constraints or restrictions on the design of a system. For example, security, reliability, maintainability, weight, strength, etc.

b) **Performance Requirements.**

Performance requirements describe ***"how well"*** the system/product must perform certain functions under specific conditions. They are quantitative requirements and are verifiable. For example, "the finger rehab device shall be capable of exerting 3-axis forces at each fingertip with output force ranges up to 3.5 N, having 0.5 second response time during each cycle, to open the fingers." As seen from this example, there is more than one performance requirement associated with a single functional requirement.

c) **Design Constraints.** Constraints determine the performance limits of the system/product such as acceptable range of frequency, temperature range, operation range, weight, size, etc. – what is expected of the product. For example, "the finger rehab device weight shall not exceed 0.5 lb". Categories of some examples of constraints are shown in Table 2.5.

Table 2.5: Categories of some examples of constraints.

Technical	**Social**	**Environmental**	**Economical**
Physical	Legal/Ethical	Ecological	Ergonomic design
Functional/performance	Political	Operational	Cybernetic design
Laws and regulations	Health	Regulations	Microeconomic factors
Standards and guidelines	Security	Storage	Affordability constraints
Policies and procedures	Public and & international laws	Reuse and reusability	Budget
Codes	Safety		

2.4.1.1 How to Write Good Requirement

As mentioned before, writing good requirements is not an easy task.

As mentioned by Albert Einstein, *"When you are out to describe the truth, leave elegance to the tailor."* This quote tells us that an elegant and entertaining requirement writing style is not necessary – don't use buzzwords.

The followings are the summary of essential points to write a good requirements:[3]

- Define requirements as clear as possible – uncertainty leads to confusion and unhappiness.
- Define one requirement one at a time - each requirement should be short. To avoid confusion try not to use conjunctions like and, or, also, with, and the like.
- If extensive conjunctions are necessary for clarity, the sentence should be decomposed to a shorter sentence.
- Each requirement should have a complete sentence with no buzzwords or acronyms.
- Don't use vague and unverifiable terms. For example user-friendly, versatile, robust, approximately, minimal impact, easy, sufficient, flexible, adequate, fast, large, small, etc. This will cause difficulties in defining their test cases.
- Each statement that defines a requirement must contain the word "SHALL". Use positive statements such as "the system shall...", instead of "the system shall not..."
  - Examples using correct terms:
    - The finger rehab device shall be capable of exerting 3-axis forces at each fingertip with output force ranges up to 3.5 N.
    - The buildings shall withstand wind loads of 150 mph.
    - The scooter shall have a maximum speed of 10 mph.
- "Will" should be used only for statements that provide information, and "Should" be used to represent a goal to be achieved.
- Requirements must be realistic and allow acceptable solutions (what not how). Requirements should state WHAT is needed, not HOW to provide it.
- Requirements must be quantifiable, testable, and verifiable.
- Do not use "To Be Determined" (TBD) and "To Be Resolved" (TBR). Use the current best estimate within brackets [value] in the requirement and state your basis for why the value is still an estimate.
- State tolerances for qualitative values. For example, less than; greater than or equal to; plus or minus; root mean squares.

2.4.1.2 Check Requirements Reliability & Correctness

- Is each requirement correct and as clear as possible?
- Are the requirements technically feasible and realistic?
- Are the requirements measurable, testable, and verifiable?
- Are the reliability requirements specified?

Rationale statements are useful for reducing ambiguity in the requirements documents. It is an additional statement to simplify and support design requirements. For example, consider NASA's ISS Crew Transportation and Services Requirement Document. 3.8.5.1.5 Operable by

Single Crewmember. The spacecraft shall be operable by a single crew member for operations that require crew control [R.CTS.135].

Rationale: "...The vehicle must be designed so that mission events can be completed by a single crew member. In addition, vehicle design for single crew member operations drives operations simplicity and contributes to operations affordability. This requirement results from lessons learned from the Shuttle cockpit, which had critical switches that are out of the operator's reach zone and software that requires more than one crew member to perform a nominal operation..."[5]

2.4.1.3 Requirement Decomposition

Requirement decomposition is a complex system engineering task. When developing large systems, it is important that the requirement decomposition process is performed. Because not all requirements of the system are equally important they can be arranged hierarchically. Higher-level requirements may be abstract and should be decomposed into a number of sub-requirements. Figure 2.13 shows a requirement decomposition of a new start-up company.

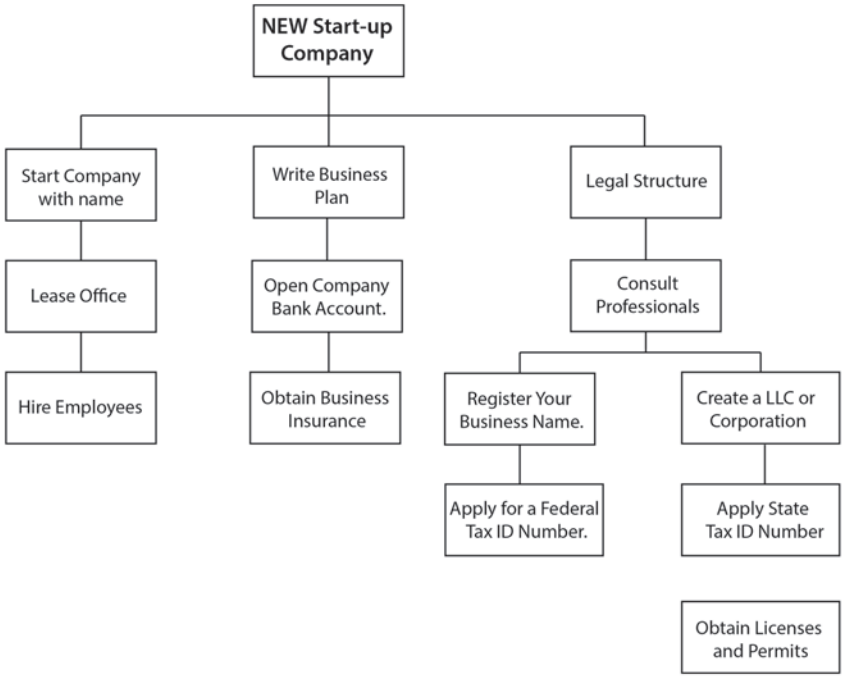


Figure 2.13: Requirement decomposition of a new start-up company.

[5]Source: https://qracorp.com/write-clear-requirements-document/

2.4.2 House of Quality

Afterward, Toyota improved the QFD and introduced the House of Quality (HOQ). The house of quality is a transdisciplinary design tool that has been used successfully by Japanese manufacturers of consumer electronics, home appliances, clothing, integrated circuits, synthetic rubber, construction equipment, agricultural engines, etc.

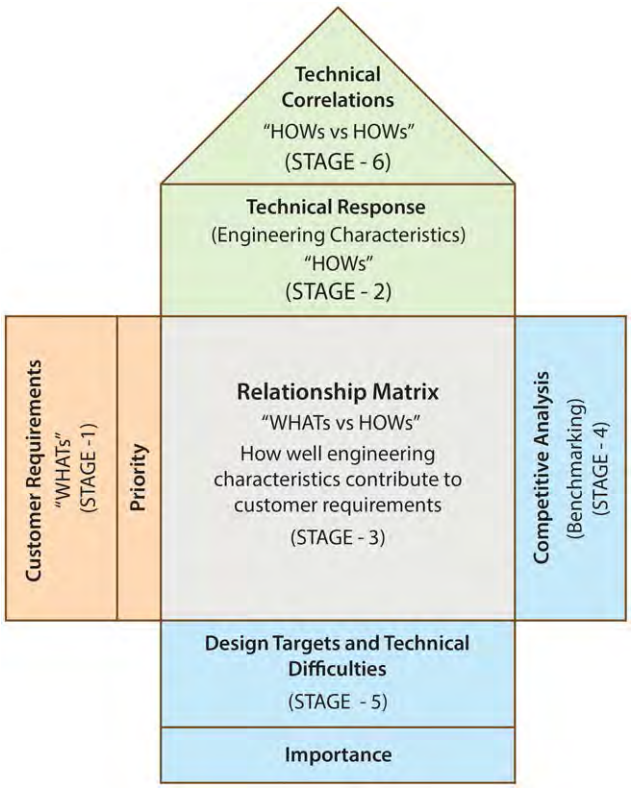


Figure 2.14: *textnormalHouse of Quality (HOQ).*

As shown in Figure 2.14, the HOQ matrix has the shape of a house with a *correlation matrix* as its roof – Like the QFD, it uses a relationship matrix to relate what the customer wants to how a production company is going to meet those wants. There are several advantages of HOQ: (a) reduces the time involved in planning, (b) reduces design changes, (c) improves quality, (d) reduces design and manufacture costs, (e) reduces time to market, (f) helps in prioritizing different design parameters, (g) improves customer satisfaction.

The finger rehab HOQ example shown in Figure 2.15 gives a straightforward overview of the intended use of an HOQ.

EXAMPLE 2.2

HOQ example for the finger rehab device.

Design team prepared an orthogonal array (House of Quality) for the finger rehab device design as shown in Figure 2.15.

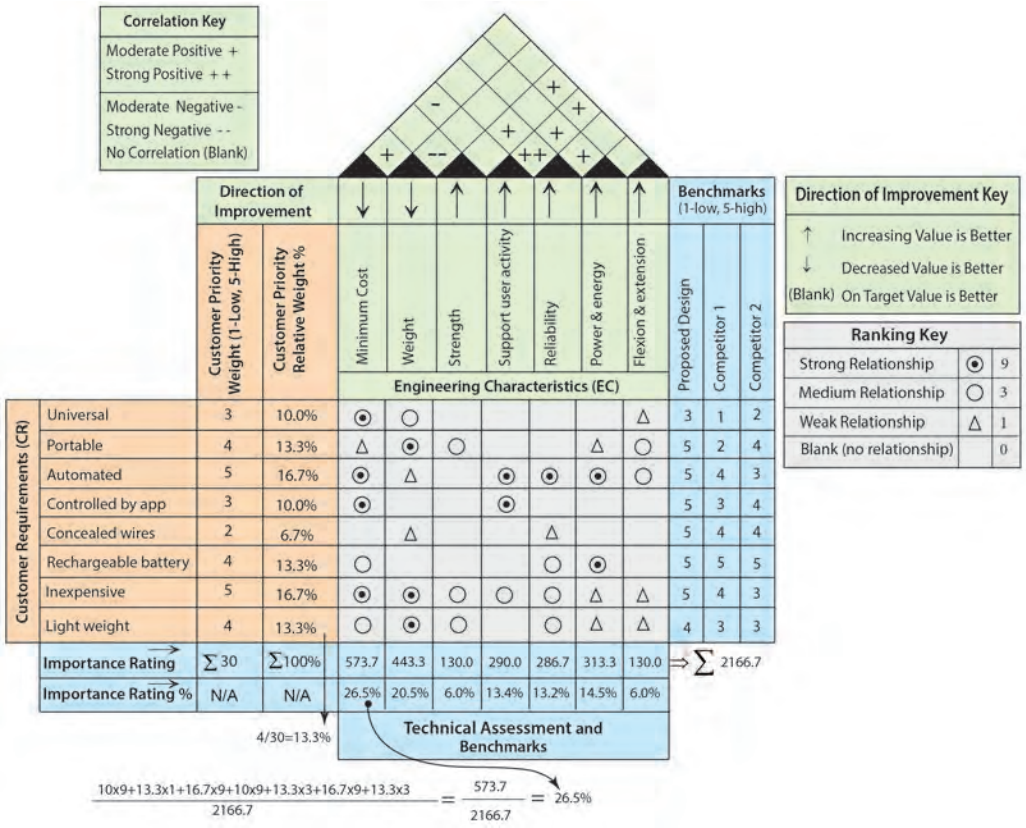


Figure 2.15: HOQ for the finger rehab device.

EXAMPLE 2.3 (continued)

$$\begin{aligned}\text{Importance Rating} &= \sum \text{Priority relative weight } \% \times \text{Relationship ranking} \\ &= +10 \times 9 + 13.3 \times 1 + 16.7 \times 9 + 10 \times 9 + \\ &\quad +13.3 \times 3 + 16.7 \times 9 + 13.3 \times 3 \\ &= 573.7\end{aligned}$$

Importance rating % row is completed by dividing individual importance rating by the total importance rating of 2166.7. For the "minimum cost" requirement, this number is 573.7/2166.7= 26.5 % (note that, since it is rounded to one decimal place, you may have a round of error).

The proposed finger rehab device design is compared with two other competitors' similar product designs through what is referred to as competition benchmarking. Benchmark design features are compared with the list of customer requirements scaled between 1 and 5, with 1 being not satisfied and 5 being completely satisfied.

The direction of Improvement is shown in Figure 2.15. For example, if we keep all the other engineering characteristics constant, lower weight is better for the finger rehab device design. From the HOQ analysis, it is clear that weight and the cost of production have the highest importance rating. These critical design points should receive concentrated effort in the design process.

The engineering characteristics may often conflict with each other. As shown in Figure 2.15, the correlation matrix is used to identify where engineering characteristics support or conflict with each other in the design of the finger rehab device. For example, Figure 2.15 shows that a finger rehab device with lightweight requires lower-cost production – affects each other positively. Similarly, support user activity and reliability affect each other strongly and positively. But lightweight and strength have a strongly negative impact on them – the finger rehab device gets stronger (improvement: good), but the weight increases (worsening: bad). This situation involves a trade-off between different engineering characteristics (parameters) – how much one design parameter can be optimized without sacrificing other parameters. Or, the design must be repeated or discussed with the customer until the negative impact can be designed out. Another option to eliminate the conflict is the use of "Theory of Inventive Problem Solving (TRIZ)". This subject will be covered in Chapter 3.

2.4.3 Concept Development

The importance rating of engineering characteristics from HOQ analysis can be used for concept development. If the importance ratings are not available then engineering judgment can be used for the importance ratings.

For example, consider that we have two-finger rehab design concepts and one of them will be selected for further analysis. For the selection process, the concept selection matrix shown in Figure 2.16 can be used to quantitatively decide which conceptual design would be a better option. The following engineering characteristics from HOQ are used to measure the effectiveness of each concept: Cost of Production, Weight, Strength, Software, Reliability, and Power & Energy.

Criteria (Engineering Characteristics)	Importance Rating, % (IR)	Concept A (IR)x(R)	Concept B (IR)x(R)
Minimum cost	26.5	⊙ = 132.5	◯ = 79.5
Weight	20.5	◯ = 61.5	⊙ = 102.5
Streght	6.00	⊙ = 30.0	◯ = 18.0
Support User Activity	13.4	◯ = 40.2	▲ = 13.4
Reliability	13.2	▲ = 13.2	◯ = 39.6
Power & Energy	14.5	◯ = 43.5	◯ = 43.5
Flexion & extension	6.0	◯ = 18.0	◯ = 18.0
		338.9	314.5

Ranking (R)		
Strong Relationship	⊙	5
Medium Relationship	◯	3
Weak Relationship	▲	1

Figure 2.16: Concept selection matrix.

As shown in Figure 2.16, importance ratings of each engineering characteristic were determined and used in the concept selection matrix. As shown in this figure, a three-point ranking is used for the relationships between the engineering characteristics and each concept. Related ranking numbers for each concept and importance ratings are multiplied together to determine the concept score.

In Figure 2.16, results show that concept A has the higher total sum of 338.46. Thus, Concept A will be chosen as a basis for the final design analysis.

2.4.4 Cascading QFD Analysis

Usually, one QFD may not be sufficient to explain the customer requirements down to actual production. As shown in Figure 2.17 there are four phase processes to develop a product which includes four cascaded House of Qualities (HoQ). This figure shows that QFD is an integrative process for connecting customer requirements to production – HOWs are refined until the detailed level of production requirements is reached. As seen from this figure, the HOWs

of phase I become the WHATs of phase II. For example, in phase I, taking the customer requirements and defining engineering characteristics that are carried on to phase II to establish the basis for the component requirements. This process will continue until the manufacturing operations are defined. The cascaded HOQ phases translate the customer requirements to a set of process parameters to be controlled.

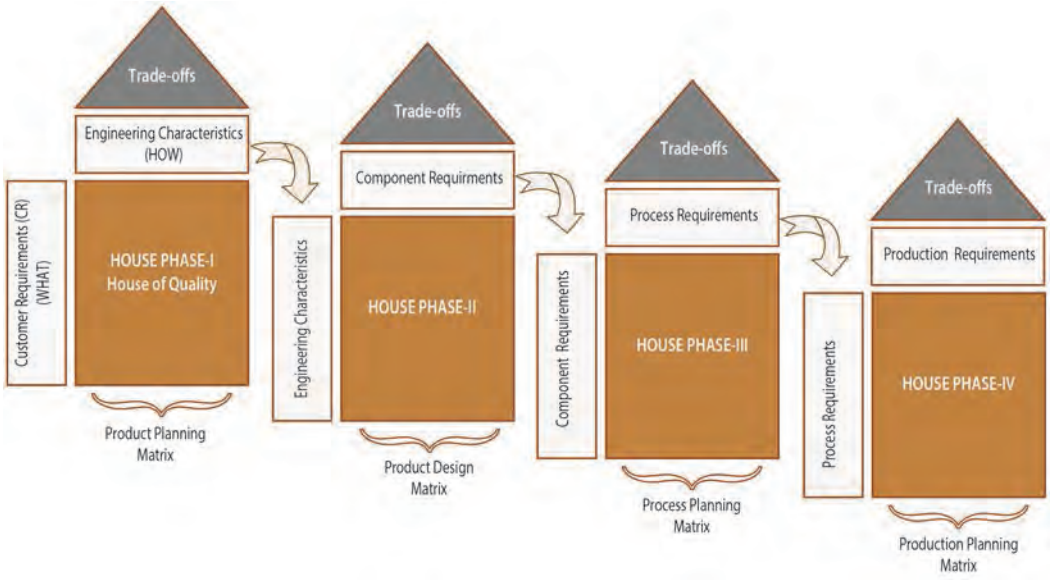


Figure 2.17: Connecting customer requirements to production.

CHAPTER 3

Theory of Inventive Problem Solving (TRIZ)

Inventing is the resolution of technical contradictions.

Genrich Altshuller

3.1 Introduction

Theory of Inventive Problem Solving (TRIZ) developed by G.S. Altshuller and his colleagues in Russia between 1946 and 1985 is a well-known effective methodology to solve complex problems. It is a problem-solving methodology developed on the assessment of the repetitions of problems and solutions using logic, data, and research. TRIZ represents the output of over 2000 person-years worth of research into not just patents, but well-defined successful problem solutions from all areas of human work.[1] The number of Triz practitioners has grown 40% per year since 2007. Today many Fortune 500 companies successfully use TRIZ methodology in at least 50 countries.[2]

"The Russian engineer and scientist Genrikh Altshuller studied thousands of patents and noticed certain patterns. From these patterns, he discovered that the evolution of a technical system is not a random process, but is governed by certain objective laws. These laws can be used to consciously develop a system along its path of technical evolution - by determining and implementing innovations."[2]

After Altshuller evaluated hundreds of thousands of patents to determine the patterns that predict innovative solutions to problems, he found that:[3]

(a) 99.7 percent of inventions were made using known methods of solution,

(b) only 0.3 percent of solutions were disruptive, and

(d) the innovation process can be systematically organized.

[1]Salamatov, Y., (1999). TRIZ: The Right Solution At The Right Time. Insytec BV, The Netherlands, 1999.

[2]The Altshuller Institutefor TRIZ Studies. https://www.aitriz.org/triz, accessed July 20, 2020.

[3]Valeri Souchkov, (2017). Accelerate Innovation with TRIZ, http://www.xtriz.com/publications/AccelerateInnovationWithTRIZ.pdf, accessed July 15, 2020.

The main findings of systematic innovation are:[4]

1. "that the same problems and solutions appear again and again across different industries, but that most organizations tend to reinvent the wheel rather than look outside their own experiences or the experiences of their direct competitors.
2. that the most powerful solutions are the ones that successfully eliminate the compromises and trade-offs conventionally viewed as inherent in systems.
3. that there are only a small number of possible strategies for overcoming such contradictions.
4. that the most powerful solutions also make maximum use of resources. Most organizations are highly inclined to solve problems by adding things rather than making the current things work more effectively or transforming the things viewed as harmful into something useful.
5. that technology evolution trends follow highly predictable paths."

TRIZ transforms problems from the specific to the generic by assessing the current challenges with 40 different inventive principles. Altshuller and his colleagues who developed TRIZ found that:[5]

- Problems and solutions repeat across industries and sciences.
- Patterns of technical evolution repeat across industries and sciences.
- Innovations used scientific effects outside the field where they were developed.

Jumping to a solution for problem-solving is easy and often necessary. However, it just happens to be bad for product development. Even though we are aware that designers should avoid jumping to a problem solution, we still find it very hard to stop that very human desire to try to figure out a solution as soon as possible. One of the important principles of TRIZ is, that instead of quickly jumping to a solution, TRIZ proposes to analyze a problem, build its model, and apply a relevant pattern of a solution from the TRIZ databases to discover possible solution directions.

Benefits of TRIZ are:[6]

- TRIZ problem-solving based on a fixed repeatable algorithm
- TRIZ accelerates the speed of system development and evolution.
- TRIZ reduces the number of trials and errors to save money
- TRIZ helps model problems that are not well defined into a specific problem that can be solved by any engineer.
- TRIZ allows design teams to find examples of how people have solved similar problems in the past. In other words, somebody, somewhere, has already solved your problem or one related to it. Creativity means finding that solution and altering it to your problem.

[4]TRIZ Journal. https://triz-journal.com/what-is-triz/, accessed July 17, 2020.

[5]http//www.triz-journal.com/whatistriz.htm, accessed August 20, 2015.

[6]The Altshuller Institute for TRIZ Studies. https://www.aitriz.org/triz/14-triz/triz/610-benefits#: :text= TRIZ%20increases%20the%20speed%20of,be%20solved%20by%20any%20engineer, accessed July 18, 2020.

As seen from Figure 3.1,[7] TRIZ not only reduces the number of trial and error iterations by avoiding much of the solution set and getting to the solution faster but also provides an exhaustive set of potential solution concepts compared with the conventional methods.

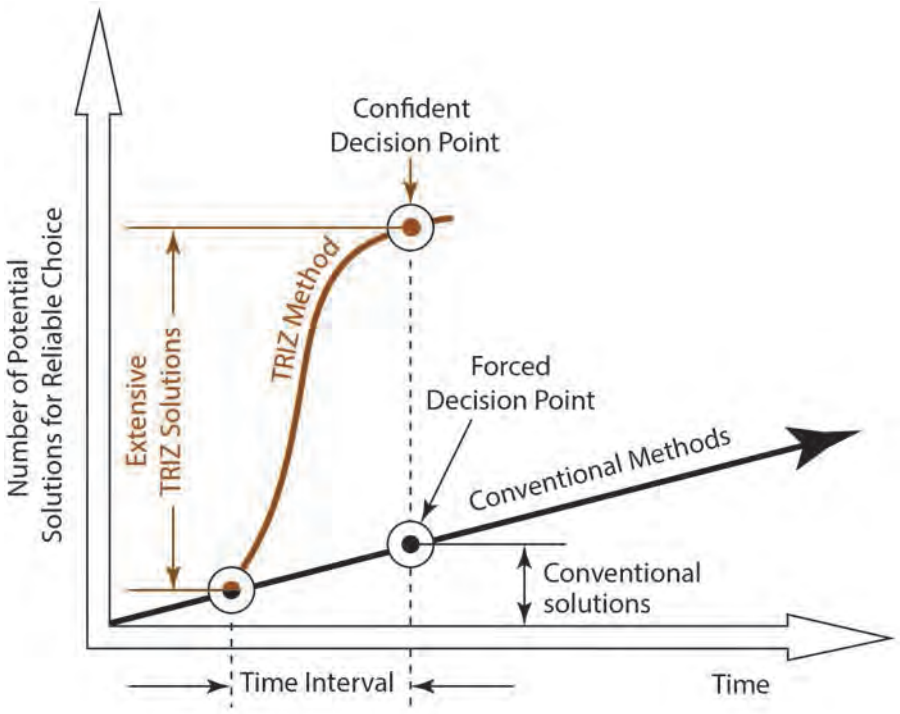


Figure 3.1: Impact of TRIZ on an organization (adapted from reference 7).

3.2 TRIZ Problem Solving Process

Figure 3.2 shows the process of TRIZ problem-solving.[8] A conventional approach for solving problems is to consider directly a specific problem to find a specific solution. However, in some cases, this approach may not work due to contradictions or conflicts among the characteristics of the problem which prevent the appropriate solution from being generated. TRIZ's problem-solving process is different from the conventional methods of problem-solving. The basic approach of TRIZ is that in most cases the problem we are trying to solve now has already been solved by somebody in a different situation.

As seen from Figure 3.2, the TRIZ problem-solving process starts with identifying a specific problem with main functions such as the main functions of an aircraft including power, speed, weight, drag force, etc. that the problem in hand is seeking to achieve.

[7]Recreated from Glenn Research Center at Lewis Field, NASA
[8]Ertas, A. (2018). Transdisciplinary Engineering Design Process. John Wiley and Sons, Inc.

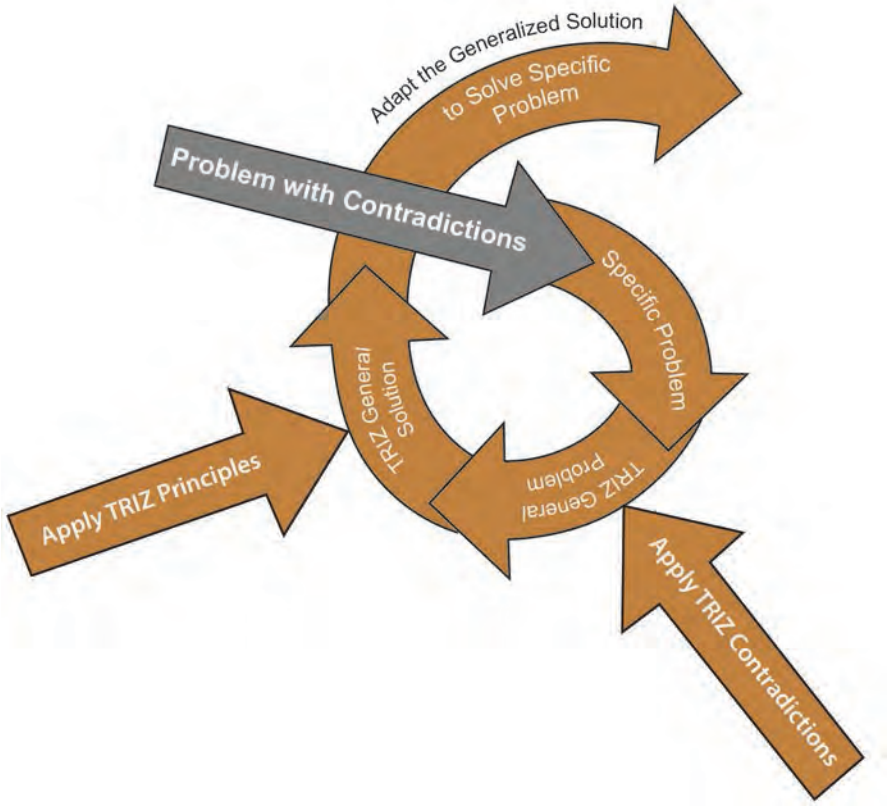


Figure 3.2: TRIZ problem solving process (adapted from reference 7).

The next step is to use the main functions and establish contradictions in your specific problem. In other words, to decide what is getting better (good) and what is getting worse (bad).

The following step is to convert the specific problem into a TRIZ general problem – develop contradictions – identify the negative effect with a "worsening feature" in the Contradiction Matrix (Tables 3.1 through Table 1.6). Then identify positive effects with an "improving feature" in the Contradiction Matrix.

For example, increasing the strength of an aircraft's structural parts (improving feature) can result in increasing the weight (worsening feature) of the aircraft. There is a contradiction between these two pairs of the 39 TRIZ contradiction parameters: one gets better while the other gets worse. In TRIZ, 39 contradictions have been identified to help us to consider the problem. TRIZ contradictions are listed in Table 3.1 through Table 3.6. An explanation of the 39 parameters of the contradiction matrix is given in Table 3.7.

Finally, using TRIZ inventive principles (see Table 3.8) corresponding to TRIZ contradictions, a TRIZ general solution can be found.

3.2.1 Contradictions

A contradiction is a situation of two parameters in opposition to one another. There are three kinds of contradictions in TRIZ: administrative, technical, and physical contradictions.

Administrative contradiction: tells a desire to improve a characteristic of a system without having a promising focus of solution – it is temporary, has no heuristic value, and stays at the surface of the problem.

Technical Contradiction: *Technical contradictions* are the typical engineering "trade-offs." When something gets better, something else is affected and gets worse – an attempt to improve one engineering parameter results in the worsening of another parameter. The following are some examples of trade-offs:

- The part products get stronger (good) but the weight increases (bad).
- Vehicles can be built to run faster (good) but the fuel efficiency decreases (bad).
- To have a nice dinner at a fancy restaurant (good) but the cost will be very high (bad).
- Deep-fried food is delicious to us because of the high energy and calorie level (good) but it increases cholesterol level (bad).
- Having a fast aircraft cruising speed (good) can decrease the maximum lift/load capacity (bad).

Physical Contradiction: Technical contradictions occur between two parameters whereas a *physical contradiction* occurs when there is a conflict within a parameter itself. For example, if we use a long regular magnetic tool to pick up objects as shown in Figure 3.3(a), it may not be handy to carry. If we use a shorter magnetic tool for the same reason it may not be long enough to reach. In this case, the length of the tool is a parameter that creates a contradiction within a parameter (length) itself. The length of the magnetic tool should be long enough to reach but it should be short enough to easily carry – in this problem length is the physical contradiction. There are several ways of solving this contradiction. For example, if we use a telescopic magnetic tool to pick up various objects as shown in Figure 3.3(b), it is short enough to carry easily, and if we extend it will be long enough to reach.[9]

[9] Adapted from reference 8.



Figure 3.3: Magnetic pickup tool: (a) regular, (b) telescopic.

EXAMPLE 3.1

A new material for aircraft structural parts needed.The design of an aircraft takes into consideration a variety of factors. One of the most important ones is the strength-to-weight ratio of the aircraft's structural parts. The strength/weight conflict plays an important role in the design of aircraft structural parts. Use TRIZ analysis to resolve the conflict that will improve the strength/weight ratio.

ANALYSIS OF STATEMENT

Aircraft structural parts should be strong, but not heavy.

STEP 1:
Identify the contradiction(s)

- Strength (improves) versus
- Weight (worsens)

STEP 2:
Check Tables 3.1 through Table 3.6 and identify the improving and worsening features.

- Strength – #14
- Weight – #1

EXAMPLE 3.1 (continued)

STEP 3:
Identify which are improving features and which are worsening features and identify which principles can be used for this problem (see Figure 3.4).

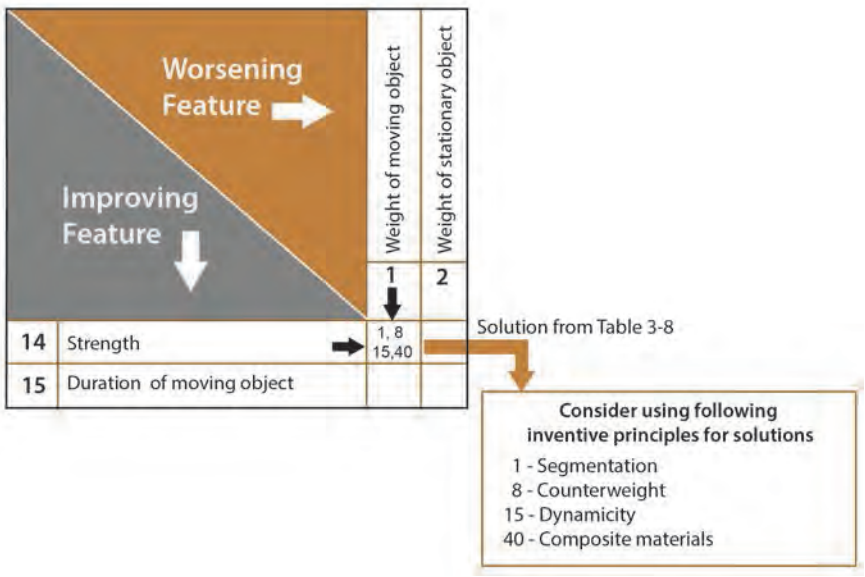


Figure 3.4: Identifying improving and worsening features.

STEP 4:
The intersection of Column 2 and Row 14 provides the following principles (see Table 3.8):

1 - Segmentation
8 - Counterweight
15 - Dynamicity
40 - Composite materials

STEP 5: The Next step is to think which principle is useful to solve our problem. Principle 40 (composite material) is the most useful one for our problem (see TRIZ tool: http://www.rb-tdinstitute.org/index.php/blog-2/infinite-12):

3.2.2 TRIZ Separation of Principles

TRIZ Separation Principles is used to solve physical contradictions or when other ideation techniques are unsuccessful in resolving them. Separation removes the physical contradiction within a parameter and allows each requirement to be satisfied. For example, we require water in our house to be "cold" and "hot" for different functions. These two conflicting requirements within the parameter of "water" can be resolved by using the separation of principles. Separation of Principles is the more powerful and effective solution principle and tool among the broad category of TRIZ Principles.[10] There are four separations of principles to resolve physical contradiction:

1. Separation in time
2. Separation in space
3. Separation between the parts (components) and the whole (system)
4. Separation upon condition

1. Separation of Conflicting Properties in Time: Changing a property, response, and behavior vs. time. For example, by changing the cargo ship propeller blades to the optimal pitch in time, higher efficiency can be obtained, thus saving fuel (see Figure 3.5).

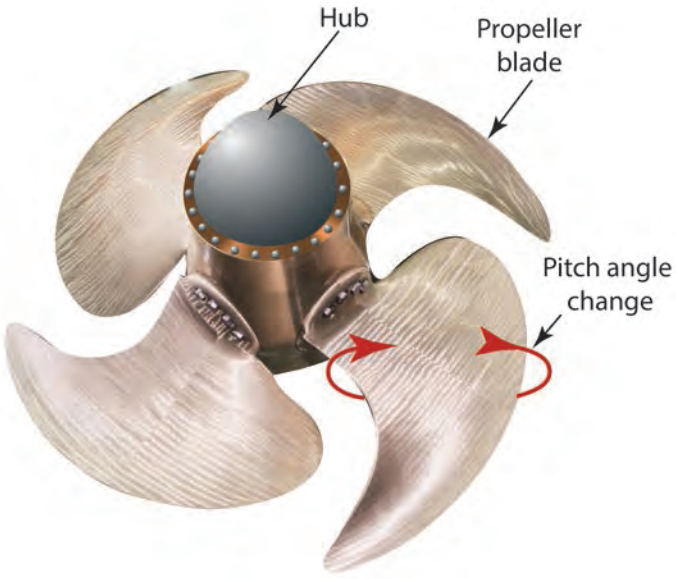


Figure 3.5: Controllable pitch propeller.

[10]Hipple, J. (1999). The Use of TRIZ Separation Principles to Resolve the Contradictions of Innovation Practices in Organizations. *The Triz Journal,* https://triz-journal.com/use-triz-separation-principles-resolve-contradictions-innovation-practices-organizations/, accessed July 19, 2020.

The rotational speed of the main engine is the only operational variable for fixed-pitch propellers. If you would like to run the ship in a forwarding and astern direction you have to stop the engine and change the engine's rotational direction. This will cause a waste of energy. Also, if you want to change the speed of the ship, you have to change the RPM of the engine – the speed of the ship will be handled from the navigation bridge and the marine engineer will be overwhelmed to change the ship's speed. So, how we can overcome the problems related to the fixed-pitch propellers mentioned?

Applying separation in time results in an inventive solution of controllable pitch propellers. Changing the pitch of the propeller in time will run the ship in forward and astern directions both, without the change of engine rotational direction. Changing the pitch of the propeller in time determines the amount of thrust generated by the propeller – thus changing the speed of the ship. With this design approach, the weight of the engine and propulsion machinery is reduced considerably.

From Table 3.8, TRIZ principles most applicable to "separation in time" are 9, 10, 11, 12, 15, 16, 18, 19, 20, 21, 35, 36, 37, 38, and 39.

2. Separation of Conflicting Properties in Space: Changing a property, response, or behavior based on a special location. For example, As shown in Figure 3.6, the knee brace is used after a knee injury to provide support while the knee injury is healing. They are designed to limit movement of the knee while it is healing after an injury or surgery. However, certain conditions will cause the kneecap to track improperly, causing pain in other locations. The pain is present in one place (around the knee joint) and absent in another place. The solution is having a small hole as shown in Figure 3.6 to support the kneecap. The hole in the brace will separate the space and cover the kneecap and help to keep it on track.

From Table 3.8, TRIZ principles most applicable to "separation in space" are 1, 3, 4, 5, 7, 8, 13, 14, 15, 16, 17, 26, 27, 30, 31, and 32.



Figure 3.6: Knee brace.

3. The separation between the Parts and the Whole: Changing a property, response,

and behavior to make it different at the component or system level. In other words, exists at the system level but does not exist at the component level (or vice versa). For example, plastic body fillers and hardeners shown in Figure 3.7 are liquids, but when you mix them combination becomes solid.

From Table 3.8, TRIZ principles most applicable to "between parts and the whole" are 2, 3, 6, 7, 24, 26, 27, 33, 34, and 40.

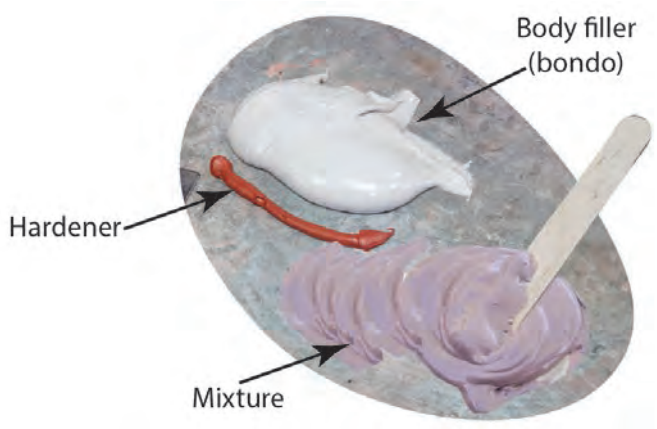


Figure 3.7: Mixing body filler and hardener.

4. Separation upon Condition: Changing the property, response, or behavior on condition. Properties can be high under one condition and low under another condition. A good example of this case is transition lenses with a light-sensitive photochromic coating as shown in Figure 3.8. The lenses are light or dark changing the conditions of UV radiation present.

From Table 3.8, TRIZ principles most applicable to "separation of conditions" are 6, 15, 16, 18, 19, 22, 28, 29, and 32.

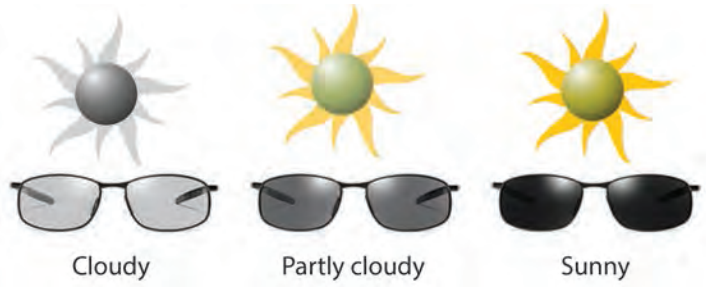


Figure 3.8: Light-sensitive photochromic coating lenses.

3.2.3 Ideality

The ideality approach is one of the most powerful fundamental TRIZ concepts, which is defined as the sum of the useful functions/effects in a system divided by the harmful functions/effects in a system. In other words, ideality is the ratio between all the good things you want (benefits) and any negative aspects (costs and harms). In the equation, ideality can be written as:

$$\begin{aligned} \text{Ideality} &= \frac{\sum \text{Useful Functions or Effects}}{\sum \text{Harmful Functions or Effects}} \\ &= \frac{\sum \text{Benefits}}{\sum \text{Costs} + \sum \text{Harms}} \end{aligned} \tag{3.1}$$

In Eq 3.1, benefits are all the useful functions/effects, harms are all the harmful functions/effects, and costs are all the inputs necessary to achieve the system functionality such as money, resources, time, manpower, energy, etc.

All systems include useful and harmful functions. According to ideality, the ideal state of the system is where all its functions are achieved without creating harmful effects. The term "useful" refers to features or properties of a system that maximize satisfaction and minimize unpleasant occurrences – this makes customers happy. But all of this comes with a cost. The term "harmful" refers to functions that include expense, noise, inefficient energy use, resources required, etc. Let's consider the following ideality example.

EXAMPLE 3.2

Ideality Example: Oil industry and refineries. The domestic petroleum industry in the U.S. began in 1859 and changed America's economy, standard of living, and culture. Now, petroleum's current status has become a key component of politics, society, and technology. After oil discovery, the 19th century was the beginning of rapid industrialization. The iron and steel industry produced new materials for construction, the railroads linked the country and the discovery of oil provided an opportunity for a new source of fuel.[a]

ANALYSIS Benefits of the Oil Industry and refineries (useful function):

EXAMPLE 3.2 (continued)

ANALYSIS Benefits of the Oil Industry and refineries (useful function):

- Impact on rapid industrialization.
- High-value products such as gasoline, diesel fuel, and jet fuel.
- Refineries produce a wide variety of different products such as gasoline, diesel fuel, jet fuel, etc. By-products from oil refining include the production of plastics and chemicals, different kinds of lubricants, waxes, tars, and asphalts.
- It is the world's most important source of energy.
- Oil products support modern society, by providing energy to the power industry and supplying fuel for vehicles and airplanes to transport goods and people all over the world. And many others.

But, these benefits come at a cost. The costs involved with the harmful functions. They are:

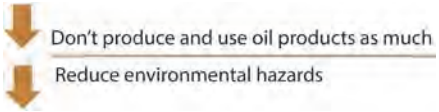
- Costs (workers)
  - Explosions
  - Exposure to gas
  - Exposure to chemicals
  - Burns
- Costs (society)
  - Environmental hazards (potential environmental hazards related to refineries have begun to increase concern for societies near them.)
  - Air pollution hazards
  - Water pollution hazards
  - Soil pollution hazards

Now, we can define invention as:
Invention is anything that improves ideality and resolves contradictions. In other words, as seen from the below figure, improving the useful functions or effects and reducing the harmful effects improves the ideality. The goal is to optimize ideality without creating harmful effects.

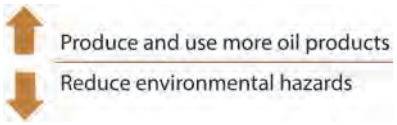


EXAMPLE 3.2 (continued)

Now consider inventing a better and environmentally friendly refinery. For this example, assume the useful function of providing energy against the harmful function of environmental hazards. As shown in the below figure, we can think that environmental hazards can be reduced by not producing and using oil products as much. But, this process doesn't invent anything because it doesn't improve ideality – that is nothing but give and take (compromise solutions).



However, as seen from the below figure, if we say, we can reduce environmental hazards even though we produce and use more oil products. This process improves ideality – that is inventive.



[a] Adapted from "Introduction to TRIZ (Ideality, Resources, and Enabling Technologies)." https://www.youtube.com/watch?v=WzfhH4Lm2AM, accessed July 23, 2020.

Table 3.1: TRIZ Contradiction Matrix (Engineering Characteristics).

Improving Feature ↓ / Worsening Feature →		1 Weight of moving object	2 Weight of stationary object	3 Length of moving object	4 Length of stationary object	5 Area of moving object	6 Area of stationary object	7 Volume of moving object	8 Volume of stationary object	9 Speed	10 Force	11 Tension or Pressure	12 Shape	13 Stability of object
1	Weight of moving object			15,8 29,34		29,17 38,34		29,2 40,28		2,8 15,38	8,10 18,37	10,36 37, 40	10, 14 35, 40	1,35 19, 39
2	Weight of stationary object				10,1 29,35		35,30 13,2		5,35 14,2		8,10 19,35	13, 29 10,18	13, 10 29,14	26,39 1,40
3	Length of moving object	8,15 29,34				15,17 4		7,17 4,35		13,4 8	17,10 4	1,8 35	1,8 10,29	1,8 15,34
4	Length of stationary object		35,28 40,29				17,7 10,40		35,8 2,14		28,10	1,14 35	13,14 15,7	39,37 35
5	Area of moving object	2,17 29,4		14,15 18,4				7,14 17,4		29,30 4,34	19,30 35,2	10,15 36, 28	5,34 29,4	11,2 13,39
6	Area of stationary object		30,2 14,18		26,7 9,39						1,18 35,36	10,15 36,37		2,38
7	Volume of moving object	2,26 29,40		1,7 4,35		1,7 4,17				29,4 38,34	15,35 36,37	6,35 36,37	1,15 28, 4	28,10 1,39
8	Volume of stationary object		35,10 19,14	19,14	35,8 2,14						2,18 37	24, 35	7,2 35	34,28 35,40
9	Speed	2,28 13,38		13,14 8		29,30 34		7,29 34			13,28 15,19	6,18 38,40	35,15 18,34	28,33 1,18
10	Force	8,1 37,18	18,13 1,28	17,19 9,36	28,10	19,10 15	1,18 36,37	15,9 12,37	2,36 18,37	13,28 15,12		18,21 11	10,35 40,34	35,10 21
11	Tension or Pressure	10,36 37,40	13,29 10,18	35,10 36	35,1 14,16	10,15 36,28	10,15 36,37	6,35 10	35,24	6,35 36	36,35 21		35,4 15,10	35,33 2,40
12	Shape	8,10 29,40	15,10 26,3	29,34 5,4	13,14 10,7	5,34 4,10		14,4 15,22	7,2 35	35,15 34,18	35,10 37,40	34,15 10,14		35,40 24,31
13	Stability of object	21,35 2,39	26,39 1,40	13,15 1,28	37	2,11 13	39	28,10 19,39	34,28 35,40	33,15 28,18	10,35 21,16	2,35 40	22,1 18,4	
14	Strength	1,8 40,15	40,31 2,1	1,15 8,35	15,14 28,26	3,34 40,29	9,40 28	10,15 14,7	9,14 17,15	8,13 26,14	10,18 3,14	10,3 18,40	10,30 35,40	13,17 35
15	Duration of moving object	19,5 34,31		2,19 9		3,17 19		10,2 19,30		3,35 5	19,2 16	19,3 27	14,26 28,25	13,3 35
16	Duration of stationary object		6,27 19,16		1,40 35				35,34 38					39,3 35,23
17	Temperature	36,22 6,38	22,35 32	15,19 9	15,19 9	3,35 39,18	35,38	34,39 40,18	35,6 4	2,28 36,30	35,10 3,21	35,39 19,2	14,22 19,32	1,35 32
18	Brightness	19,1 32	2,35 32	19,32 16		19,32 26		2,13 10		10,13 19	26,19 6		32,30	32,3 27
19	Energy spent by moving object	12,18 28,31		12,28		15,19 25		35,13 18		8,15 35	16,26 21,2	23,14 25	12,2 29	19,13 17,24
20	Energy spent by stationary object		19,9 6,27								36,37			27,4 29,18

The following sources are used to create Tables 3.1 through 3.6.
Creating Minds, http://creatingminds.org/tools/triz/triz_contradiction_1.htm;
TRIZ 40, Solid Creativity http://www.triz40.com/aff_Matrix_TRIZ.php;
Darrell Mann and Simon Dewulf, Updating the Contradiction Matrix, https://www.researchgate.net/publication/237303841_Updating_the_Contradiction_Matrix

Table 3.2: TRIZ Contradiction Matrix (Engineering Characteristics).

Improving Feature ↓ / Worsening Feature →		Strength	Duration of moving objectt	Duration of non-moving object	Temperature	Brightness	Energy spent by moving object	Energy spent by stationary object	Power	loss of energy	loss of substance	loss of information	loss of time	Amount of substance
		14	15	16	17	18	19	20	21	22	23	24	25	26
1	Weight of moving object	28,27 18,40	5,34 31,35		6,29 4,38	19,1 32	35,12 34,31		12,36 18,31	6,2 34,19	5,35 3,31	10,24 35	10,35 20,28	3,26 18,31
2	Weight of stationary object	28,2 10,27		2,27 19, 6	28,19 32,22	19,32 35		18,19 28,1	15,19 18,22	18,19 28,15	5,8 13,30	10,15 35	10,20 35,26	19,6 18,26
3	Length of moving object	8,35 29,34	19		10,15 19	32	8,35 24		1,35	7,2 35,39	4,29 23,10	1,24	15,2 29	29,35
4	Length of stationary object	15,14 28,26		1,10 35	3,35 38,18	3, 25			12,8	6,28	10,28 24,35	24,26	30,29 14	
5	Area of moving object	3,15 40,14	6,3		2,15 16	15,32 19,13	19,32		19,10 32,18	15,17 30,26	10,35 2,39	30,26	26,4	29,30 6,13
6	Area of stationary object	40		2,10 19,30	35,39 38				17,32	17,7 30	10,14 18,39	30,16	10,35 4,18	2,18 40,4
7	Volume of moving object	9,14 15,7	6,35 4		34,39 10,18	2,13 10	35		35,6 13,18	7,15 13,16	36,39 34,10	2,22	2,6 34,10	29,30 7
8	Volume of stationary object	9,14 17,15		35,34 38	35,6 4				30,6		10,39 35,34		35,16 32,18	35,3
9	Speed	8,3 26, 14	3,19 35,5		28,30 36,2	10,13 19	8,15 35,38		19,35 38,2	14,20 19,35	10,13 28,38	13,26		10,19 29,38
10	Force	35,10 14,27	19,2		35,10 21		19,17 10	1,16 36,37	19,35 18,37	14,15	8,35 40,5		10,37 36	14,29 18,36
11	Tension or Pressure	9,18 3,40	19,3 27		35,39 19,2		14,24 10,37		10,35 14	2,36 25	10,36 3,37		37,36 4	10,14 36
12	Shape	30,14 10,40	14,26 9,25		22,14 19,32	13,15 32	2,6 34,14		4,6 2	14	35,29 3,5		14,10 34,17	36,22
13	Stability of object	17,9 15	13,27 10,35	39,3 35,23	35,1 32	32,3 27,16	13,19	27,4 29,18	32,35 27,31	14,2 39,6	2,14 30,40		35,27	15,32 35
14	Strength		27,3 26		30,10 40	35,19	19,35 10	35	10,26 35,28	35	35,28 31,40		29,3 28,10	29,10 27
15	Duration of moving object	27,3 10			19,35 39	2,19 4,35	28,6 35,18		19,10 35,38		28,27 3,18	10	20,10 28,18	3,35 10,40
16	Duration of a stationary object				19,18 36,40				16		27,16 18,38	10	28,20 10,16	3,35 31
17	Temperature	10,30 22,40	19,13 39	19,18 36,40		32,30 21,16	19,15 3,17		2,14 17,25	21,17 35,38	21,36 29,31		35,28 21,18	3,17 30,39
18	Brightness	35,19	2,19 6		32,35 19		32,1 19	32,35 1,15	32	19,16 1,6	13,1	1,6	19,1 26,17	1,19
19	Energy spent by moving object	5,19 9,35	28,35 6,18		19,24 3,14	2,15 19			6,19 37,18	12,22 15,24	35,24 18,5		35,38 19,18	34,23 16,18
20	Energy spent by stationary object	35				19,2 35,32					28,27 18,31			3,35 31

***Table 3.3**:* TRIZ Contradiction Matrix (Engineering Characteristics).

Improving Feature ↓ / Worsening Feature →		Reliability	Accuracy of measurement	Accuracy of manufacturing	Harmful factor acting on object	Harmful side-effects	Manufacturibility	Convenience of use	Repairability	Adaptability	Complexity of device	Complexity of control	Level of automation	Productivity
		27	28	29	30	31	32	33	34	35	36	37	38	39
1	Weight of moving object	3,11 1,27	28,27 35,26	28,35 26,18	22,21 18,27	22,35 31,39	27,28 1,36	35,3 2,24	2,27 28,11	29,5 15,8	26,30 36,34	28,29 26,32	26,35 18,19	35,3 24,37
2	Weight of stationary object	10,28 8,3	18,26 28	10,1 35,17	2,19 22,37	35,22 1,39	28,1 9	6,13 1,32	2,27 28,11	19,15 29	1,10 26,39	25,28 17,15	2,26 35	1,28 15,35
3	Length of moving object	10,14 29,40	28,32 4	10,28 29,37	1,15 17,24	17,15	1,29 17	15,29 35,4	1,28 10	14,15 1,16	1,19 26,24	35,1 26,24	17,24 26,16	14,4 28,29
4	Length of stationary object	15,29 28	32,28 3	2,32 10	1,18		15,17 27	2,25	3	1,35	1,26	26		30,14 7,26
5	Area of moving object	29,9	26,28 32,3	2,32	22,33 28,1	17,2 18,39	13,1 26,24	15,17 13,16	15,13 10,1	15,30	14,1 13	2,36 26,18	14,30 28,23	10,26 34,2
6	Area of stationary object	32,35 40,4	26,28 32,3	2,29 18,36	27,2 39,35	22,1 40	40,16	16,4	16	15,16	1,18 36	2,35 30,18	23	10,15 17,7
7	Volume of moving object	14,1 40,11	25,26 28	25,28 2,16	22,21 27,35	17,2 40,1	29,1 40	15,13 30,12	10	15,29	26,1	29,26 4	35,34 16,24	10,6 2,34
8	Volume of stationary object	2,35 16		35,10 25	34,39 19,27	30,18 35,4	35		1		1,31	2,17 26		35,37 10,2
9	Speed	11,35 27,28	28,32 1,24	10,28 32,25	1,28 35,23	2,24 35,21	35,13 8,1	32,28 13,12	34,2 28,27	15,10 26	10,28 4,34	3,34 27,16	10,18	
10	Force	3,35 13,21	35,10 23,24	28,29 37,36	1,35 40,18	13,3 36,24	15,37 18,1	1,28 3,25	15,1 11	15,17 18,20	26,35 10,18	36,37 10,19	2,35	3,28 35,37
11	Tension or Pressure	10,13 19,35	6,28 25	3,35	22,2 37	2,33 27,18	1,35 16	11	2	35	19,1 35	2,36 37	35,24	10,14 35,37
12	Shape	10,40 16	28,32 1	32,30 40	22,1 2,35	35,1	1,32 17,28	32,15 26	2,13 1	1,15 29	16,29 1,28	15,13 39	15,1 32	17,26 34,10
13	Stability of object		13	18	35,24 30,18	35,40 27,39	35,19	32,35 30	2,35 10,16	35,30 34,2	2,35 22,26	35,22 39,23	1,8 35	23,35 40,3
14	Strength	11,3	3,27 16	3,27	18,35 37,1	15,35 22,2	11,3 10,32	32,40 25,2	27,11 3	15,3 32	2,13 28,25	27,3 15,40	15	29,35 10.14
15	Duration of moving object	11,2 13	3	3,27 16,40	22,15 33,28	21,39 16,22	27,1 4	12,27	29,10 27	1,35 13	10,4 29,15	19,29 39,35	6,10	35,17 14,19
16	Duration of stationary object	34,27 6,40	10,26 24		17,1 40,33	22	35,10	1	1	2		25,34 6,35	1	10,20 16,38
17	Temperature	19,35 3,10	32,19 24	24	22,33 35,2	22,35 2,24	26,27	26,27	4,10 16	2,18 27	2,17 16	3,27 35,31	26,2 19,16	15,28 35
18	Brightness		11,15 32	3,32	15,19	35,19 32,39	19,35 28,26	28,26 19	15,17 13,16	15,1 19	6,32 13	32,15	2,26 10	2,25 16
19	Energy spent by moving object	19,21 11,27	3,1 32		1,35 6,27	2,35 6	28,26 30	19,35	1,15 17,28	15,17 13,16	2,29 27,28	35,38	32,2	12,28 35
20	Energy spent by stationary object	10,36 23			10,2 22,37	19,22 18	1,4					19,35 16,25		1,6

***Table 3.4**:* TRIZ Contradiction Matrix (Engineering Characteristics).

Improving Feature ↓ / Worsening Feature →		1 Weight of moving object	2 Weight of stationary object	3 Length of moving object	4 Length of stationary object	5 Area of moving object	6 Area of stationary object	7 Volume of moving object	8 Volume of stationary object	9 Speed	10 Force	11 Tension or Pressure	12 Shape	13 Stability of the object
21	Power	8,36 38,31	19,26 17,27	1,10 35,37		19,38	17,32 13,38	35,6 38	30,6 25	15,35 2	26,2 36,35	22,10 35	29,14 2,40	35,32 15,31
22	Waste of energy	15,6 19,28	19,6 18,9	7,2 6,13	6,38 7	15,26 17,30	17,7 30,18	7,18 23	7	16,35 38	36,38			14,2 39,6
23	Waste of substance	35,6 23,40	35,6 22,32	14,29 10,39	10,28 24	35,2 10,31	10,18 39,31	1,29 30,36	3,39 18,31	10,13 28,38	14,15 18,40	3,36 37,10	29,35 3,5	2,14 30,40
24	Loss of information	10,24 35	10,35 5	1,26	26	30,26	30,16		2,22	26,32				
25	Waste of time	10,20 37,35	10,20 26,5	15,2 29	30,24 14,5	26,4 5,16	10,35 17,4	2,5 34,10	35,16 32,18		10,37 36,5	37,36 4	4,10 34,7	35,3 22,5
26	Amount of substance	35,6 18,31	27,26 18,35	29,14 35,18		15,14 29	2,18 40,4	15,20 29		35,29 34,28	35,14 3	10,36 14,3	35,14	15,2 17,40
27	Reliability	3,8 10,40	3,10 8,28	15,29 28,11	15,9 14,4	17,10 14,16	32,35 40,4	3,10 14,24	2,35 24	21,35 11,28	8,28 10,3	10,24 35,19	35,1 16,11	
28	Accuracy of measurement	32,35 26,28	28,35 25,26	28,26 5,16	32,28 3,16	26,28 32,3	26,28 32,3	32,13 6		28,13 32,24	32,2	6,28 32	6,28 32	32,35 13
29	Accuracy of manufacturing	28,32 13,18	28,35 27,9	10,28 29,37	2,32 10	28,33 29,32	2,29 18,36	32,23 2	25,10 35	10,28 32	28,19 34,36	3,35	32,30 40	30,18
30	Harmful factors acting on object	22,21 27,39	2,22 13,24	17,1 39,4	1,18	22,1 33,28	27,2 39,35	22,23 37,35	34,39 19,27	21,22 35,28	13,35 39.18	22,2 37	22,1 3,35	35,24 30,18
31	Harmful side-effects	19,22 15,39	35,22 1,39	17,15 16,22		17,2 18,39	22,1 40	17,2 40	30,18 35,4	35,28 3,23	35,28 1,40	2,33 27,18	35,1	35,40 27,39
32	Manufacturability	28,29 15,16	1,27 36,13	1,29 13,17	15,17 27	13,1 26,12	16,40	13,29 1,40	35	35,13 8,1	35,12	35,19 1,37	1,28 13,27	11,13 1
33	Convenience of use	25,2 13,15	6,13 1,25	1,17 13,12		1,17 13,16	18,16 15,39	1,16 35,15	4,18 39,31	18,13 34	28,13 35	2,32 12	15,34 29,28	32,35 30
34	Repairability	2,27 35,11	2,27 35,11	1,28 10,25	3,18 31	15,13 32	16,25	25,2 35,11	1	34,9	1,11 10	13	1,13 2,4	2,35
35	Adaptability	1,6 15,8	19,15 29,16	35,1 29,2	1,35 16	35,30 29,7	15,16	15,35 29		35,10 14	15,17 20	35,16	15,37 1,8	35,30 14
36	Complexity of a device	26,30 34,36	2,36 35,39	1,19 26,24	26	14,1 13,16	6,36	34,26 6	1,16	34,10 28	26,16	19,1 35	29,13 28,15	2,22 17,19
37	Complexity of a control	27,26 28,13	6,13 28,1	16,17 26,24	26	2,13 18,17	2,39 30,16	29,1 4,16	2,18 26,31	3,4 16,35	30,28 40,19	35,36 37,32	27,13 1,39	11,22 39,30
38	Level of automation	28,26 18,35	28,26 35,10	14,13 17,28	23	17,14 13		35,13 16		28,10	2,35	13,35	15,32 1,13	18,1
39	Productivity	35,26 24,37	28,27 15,3	18,4 28,38	30,7 14,26	10,26 34,31	10,35 17,7	2,6 34,10	35,37 10,2		28,15 10,36	10,37 14	14,10 34,40	35,3 22,39

Table 3.5: TRIZ Contradiction Matrix (Engineering Characteristics).

Improving Feature \ Worsening Feature		Strength	Duration of moving object	Duration of stationary object	Temperature	Brightness	Energy spent by moving object	Energy spent by stationary object	Power	Waste of energy	Waste of substance	loss of information	loss of time	Amount of substance
		14	15	16	17	18	19	20	21	22	23	24	25	26
21	Power	26,10 28	19,35 10,38	16	2,14 17,25	16,6 19	16,6 19,37			10,35 38	28,27 18,38	10,19	35,20 10,6	4,34 19
22	Waste of energy	26			19,38 7	1,13 32,15			3,38		35,27 2,37	19,10	10,18 32,7	7,18 25
23	Waste of substance	35,28 31,40	28,27 3,18	27,16 18,38	21,36 39,31	1,6 13	35,18 24,5	28,27 12,31	28,27 18,38	35,27 2,31			15,18 35,10	6,3 10,24
24	Loss of information		10	10		19			10,19	19,10			24,26 28,32	24,28 35
25	Waste of time	29,3 28,18	20,10 28,18	28,20 10,16	35,29 21,18	1,19 26,17	35,38 19,18	1	35,20 10,6	10,5 18,32	35,18 10,39	24,26 28,32		35,38 18,16
26	Amount of substance	14,35 34,10	3,35 10,40	3,35 31	3,17 39		34,29 16,18	3,35 31	35	7,18 25	6,3 10,24	24,28 35	35,38 18,16	
27	Reliability	11,28	2,35 3,25	34,27 6,40	3,35 10	11,32 13	21,11 27,19	36,23	21, 11 26,31	10,11 35	10,35 29,39	10,28	10,30 4	21,28 40,3
28	Accuracy of measurement	28,6 32	28,6 32	10,26 24	6,19 28,24	6,1 32	3,6 32		3,6 32	26,32 27	10,16 31,28		24,34 28,32	2,6 32
29	Accuracy of manufacturing	3,27	3,27 40		19,26	3,32	32,2		32,2	13,32 2	35,31 10,24		32,26 28.18	32,30
30	Harmful factor acting on object	18,35 37,1	22,15 33,28	17,1 40,33	22,33 35,2	1,19 32,13	1,24 6,27	10,2 22,37	19,22 31,2	21,22 35,2	33,22 19,40	22,10 2	35,18 34	35,33 29,31
31	Harmful side-effects	15,35 22,2	15,22 33,31	21,39 16,22	22,35 2,24	19,24 39,32	2,35 6	19,22 18	2,35 18	21,35 2,22	10,1 34	10,21 29	1,22	3,24 39,1
32	Manufacturability	1,3 10,32	27,1 4	35,16	27,26 18	28,24 27,1	28,26 27,1	1,4	27,1 12,24	19,35	15,34 33	32,24 18,16	35,28 34,4	35,23 1,24
33	Convenience of use	32,40 3,28	29,3 8,25	1,16 25	26,27 13	13,17 1,24	1,13 24		35,34 2,10	2,19 13	28,32 2,24	4,10 27,22	4,28 10,34	12,35
34	Repairability	11,1 2,9	11,29 28,27	1	4,10	15,1 13	15,1 28,16		15,10 32,2	15,1 32,19	2,35 34,27		32,1 10,25	2,28 10,25
35	Adaptability	35,3 32,6	13,1 35	2,16	27,2 3,35	6,22 26,1	19,35 29,13		19,1 29	18,15 1	15,10 2,13		35,28	3,35 15
36	Complexity of a device	2,13 26	10,4 28,15		2,17 13	24,17 13	27,2 29,28		20,19 30,34	10,35 13,2	35,10 28,29		6,29	13,3 27,10
37	Complexity of a control	27,3 15,28	19,29 39,25	25,24 6,35	3,27 35,16	2,24 26	35,38	19,35 16	18,1 16,10	35,3 15,19	1,18 10,24	35,33 27,22	18,28 32,9	3,27 29,18
38	Level of automation	25,13	6,9		26,2 19	8,32 18	2,32 13		28,2 27	23,28	35,10 18,5	35,33	24,28 35,30	35,13
39	Productivity	29,28 10,18	35,10 2,18	10,20 16,38	35,21 28,10	26,17 19,1	35,10 38,19	1	35,20 10	28,10 29,35	28,10 35,23	13,15 23		35,38

***Table 3.6**:* TRIZ Contradiction Matrix (Engineering Characteristics).

Improving Feature ↓ / Worsening Feature →		27 Reliability	28 Accuracy of measurement	29 Accuracy of manufacturing	30 Harmful factor acting on object	31 Harmful side-effects	32 Manufacturibility	33 Convenience of use	34 Repairability	35 Adaptability	36 Complexity of device	37 Complexity of control	38 Level of automation	39 Productivity
21	Power	19,24 26,31	32,15 2	32,2	19,22 31,2	2,35 18	26,10 34	26,35 18	35,2 10,34	19,17 34	20,19 30,34	19,35 16	28,2 17	28,35 34
22	Waste of energy	11,10 35	32		21,22 35,2	21,35 2,22		35,32 1	2,19		7,23	35,3 15,23	2	28,10 29,35
23	Waste of substance	10,29 39,35	16,34 31,28	35,10 24,31	33,22 30,40	10,1 34,29	15,34 33	32,28 2,24	2,35 34,27	15,10 2	35,10 28,24	35,18 10,13	35,10 18	28,35 10,23
24	Loss of information	10,28 23			22,10 1	10,21 22	32	27,22				35,33	35	13,23 15
25	Waste of time	10,30 4	24,34 28,32	24,26 28,18	35,18 34	35,22 18,39	35,28 34,4	4,28 10,34	32,1 10	35,28	6,29	18,28 32,10	24,28 35,30	
26	Amount of substance	18,3 28,40	13,2 28	33,30	35,33 29,31	3,35 40,39	29,1 35,27	35,29 25,10	2,32 10,25	15,3 29	3,13 27,10	3,27 29,18	8,35	13,29 3,27
27	Reliability		32,3 11,23	11,32 1	27,35 2,40	35,2 40,26		27,17 40	1,11	13,25 8,24	13,35 1	27,40 28	11,13 27	1,35 29,38
28	Accuracy of measurement	5,11 1,23			28,24 22,26	3,33 39,10	6,35 25,18	1,13 17,34	1,32 13,11	13,35 2	27,35 10,34	26,24 32,28	28,2 10,34	10,34 28,32
29	Accuracy of manufacturing	11,32 1			26,28 10,36	4,17 34,26		1,32 35,23	25,10		26,2 18		26,28 18,23	10,18 32,39
30	Harmful factors acting on object	27,24 2,40	28,33 23,26	26,28 10,18			24,35 2	2,25 28,39	35,10 2	35,11 22,31	22,19 29,40	22,19 29,40	33,3 34	22,35 13,24
31	Harmful side-effects	24,2 40,39	3,33 26	4,17 34,26							19,1 31	2,21 27,1	2	22,35 18,39
32	Manufacturability		1,35 12,18		24,2			2,5 13,16	35,1 11,9	2,13 15	27,26 1	6,28 11,1	8,28 1	35,1 10,28
33	Convenience of use	17,27 8,40	25,13 2,34	1,32 35,23	2,25 28,39		2,5 12		12,26 1,32	15,34 1,16	32,26 12,17		1,34 12,3	15,1 28
34	Repairability	11,10 1,16	10,2 13	25,10	35,10 2,16		1,35 11,10	1,12 26,15		7,1 4,16	35,1 13,11		34,35 7,13	1,32 10
35	Adaptability	35,13 8,24	35,5 1,10		35,11 32,31		1,13 31	15,34 1,16	1,16 7,4		15,29 37,28	1	27,34 35	35,28 6,37
36	Complexity of device	13,35 1	2,26 10,34	26,24 32	22,19 29,40	19,1	27,26 1,13	27,9 26,24	1,13	29,15 28,37		15,10 37,28	15,1 24	12,17 28
37	Complexity of control	27,40 28,8	26,24 32,38		22,19 29,28	2,21	5,28 11,29	2,5	12,26	1,15	15,10 37,28		34,21	35,18
38	Level of automation	11,27 32	28,26 10,34	28,26 18,23	2,33	2	1,26 13	1,12 34,3	1,35 13	27,4 1,35	15,24 10	34,27 25		5,12 35,26
39	Productivity	1,35 10,38	1,10 34,28	18,10 32,1	22,35 13,24	35,22 18,39	35,28 2,24	1,28 7,10	1,32 10,25	1,35 28,37	12,17 28,24	35,18 27,2	5,12 27,2	

Table 3.7: TRIZ Contradictions Matrix explanations.

No.	Parameters	Description
1	Weight of moving object	The mass of the moving object which gravitational force acts on it (weight). The force that the moving body exerts on its support or suspension.
2	Weight of stationary object	The mass of the stationary object in a gravitational force acts on it (weight). The force that the stationary body exerts on its support or suspension, or on the surface on which it rests.
3	Length (or angle) of moving object	Any linear or angular dimension, involving a moving object with respect to its surroundings. It can be any distance: linear or rotational, small or large distance (tolerance, depth, height, etc.).
4	Length (or angle)of stationary object	Any linear or angular dimension, involving a stationary object with respect to its surroundings.
5	Area of moving object	Any geometrical dimension involving surface or surface area occupied by the moving object, either internal or external, of a moving object.
6	Area of stationary object	Any geometrical dimension involving surface or surface area occupied by the stationary object, either internal or external, of a stationary object.
7	Volume of moving object	Any cubic measure of geometrical dimension occupied by the moving object with respect to its surroundings.
8	Volume of stationary object	Any cubic measure of geometrical dimension occupied by the stationary object with respect to its surroundings.
9	Speed	Rate of position change of an object in time or rate of any kind of process or action. Speed can be relative or absolute, linear or angular.
10	Force	Force measures the interaction between systems. In Newtonian physics, force = mass x acceleration. In TRIZ, force is any interaction that is intended to change an object's condition (its magnitude and directions).
11	Stress or pressure	Stress is the amount of force applied per unit area, experienced by an object (it can be tensile, compressive, bending, torsional, static or dynamic). Pressure is the amount of force that is applied per unit area.

Table 3.7: TRIZ Contradictions Matrix explanations (continued).

No.	Parameters	Description
12	Shape	The external contour or appearance characteristic of an object or a system.
13	Stability of the object's composition	The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition and disassembly are all decreases the stability of an object. Increasing entropy is decreasing stability.
14	Strength	The extent to which the object is able to resist changing in response to force. Resistance to breaking/ failure. The capacity of an object to withstand a critical force or pressure before it fails.
15	Duration of action by a moving object	The time that a moving object or system takes to perform an action without fails. Service life, mean time between failures is a measure of the duration of an action.
16	Duration of action by a stationary object	The time that a stationary object or system takes to perform an action without fails. Service life, mean time between failures is a measure of the duration of an action.
17	Temperature	The thermal condition of the object or system. Temperature is a measurement of the average kinetic energy of the molecules in an object or a system. Includes other thermal parameters, such as heat capacity, that affect the rate of change of temperature.
18	Illumination intensity	Light flux per unit area, also any other illumination characteristics of the system such as brightness, light quality etc.
19	Use of energy by moving object	The measure of a moving object's capacity or ability for doing work. In classical mechanics, energy is the product of force x distance. This includes the use of energy provided by the super-system (such as electrical energy or heat). Energy required doing a particular job.
20	Use of energy by stationary object	The measure of a stationary object's capacity or ability for doing work. In classical mechanics, energy is the product of force x distance. This includes the use of energy provided by the super-system (such as electrical energy or heat.) Energy required doing a particular job.
21	Power	The time rate at which work is performed. The rate of use of energy.

Table 3.7: TRIZ Contradictions Matrix explanations (continued).

No.	Parameters	Description
22	Loss of energy	A part of energy that does not contribute to the job being done. See 19. Reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category.
23	Loss of substance	Loss of substance may be partial or complete, permanent or temporary: loss of some of a system's materials, substances, parts or subsystems.
24	Loss of information	Loss of information may be partial or complete, permanent or temporary: loss of data or access to data in or by a system. Frequently includes sensory data such as aroma, texture, sound.
25	Loss of time	Time represents the duration of an activity. Improving the loss of time means reducing the time taken for the activity. â€˜Cycle time reductionâ€™ is a common requirement.
26	Quantity of substance/the matter	The number or amount of a system's materials, substances, parts or subsystems which might be changed fully or partially, permanently or temporarily.
27	Reliability	A system's ability to perform its intended functions in predictable ways and the same repeated result under the same conditions.
28	Measurement accuracy	The closeness of the measurements to a specific value of a property of a system. Reducing the error in a measurement increases the accuracy of the measurement.
29	Manufacturing precision	The extent to which the actual characteristics of a system or an object match the specified or required characteristics.
30	External harm affects the object	Susceptibility of a system to externally generated (harmful) effects.
31	Object-generated harmful factors	A harmful effect is one that reduces the efficiency or quality of the functioning of an object or a system. These harmful effects are generated by an object or a system, as part of its operation.
32	Ease of manufacture	The degree of facility, comfort or effortlessness in manufacturing or fabricating an object or a system.
33	Ease of operation	Operation can be done easily, without difficulty or effort. Simplicity: A process is not easy if it requires a large number of people, large number of steps in the operation, needs special tools and so on. & quote; Hardâ€™ processes have low yield and â€˜easyâ€™ processes have high yield; they are easy to do right.

Table 3.7: TRIZ Contradictions Matrix explanations (continued).

No.	Parameters	Description
34	Ease of repair	Quality characteristics such as convenience, comfort, simplicity and time to repair faults, failures or defects in a system.
35	Adaptability or versatility	The extent to which a system/object positively responds to external changes. Also, a system that can be used in multiple ways in a variety of circumstances.
36	Device complexity	The number, interaction, and diversity of elements and element interrelationships within a system. The user may be an element of the system that increases the complexity. The difficulty of mastering the system is a measure of its complexity.
37	Difficulty of detecting and measuring	Measuring or monitoring systems that are complex, costly, require much time and labor to set up and use, or that have complex relationships between components or components that interfere with each other all demonstrate â€˜difficulty of detecting and measuringâ€™. Increasing cost of measuring to a satisfactory error is also a sign of increased difficulty of measuring.
38	Extent of automation	The extent to which a system or object performs its functions without human interface. The lowest level of automation is the use of a manually operated tool. For intermediate levels, humans program the tool, observe its operation, and interrupt or reprogram as needed. For the highest level, the machine senses the operation needed, programs itself, and monitors its own operations.
39	Productivity	The number of functions or operations performed by a system per unit time. The time for a unit operation. The output per unit time, or the cost per unit output.
	Explanation of Moving objects	Objects which can easily change position in space, either on their own, or as a result of external forces. Vehicles and objects designed to be portable are the basic members of this class.
	Explanation of Stationary objects	Objects which do not change position in space, either on their own, or as a result of external forces. Consider the conditions under which the object is being used.

Information in Table 3.7 is adapted from "Domb, E., 1998. The 39 features of Altshuller's contradiction matrix. TRIZ J." Also see https://www.sciencedirect.com/topics/engineering/altshuller

Table 3.8: Altshuller's TRIZ – 40 Principles.

Principles	**Principles**
1. Segmentation	21. Rushing through
2. Extraction (taking out)	22. Convert harm into benefit
3. Local Quality	23. Feedback
4. Asymmetry	24. Mediator (intermediary)
5. Combination (merging)	25. Self-service
6. Universality	26. Copying
7. Nesting	27. Inexpensive short life
8. Counterweight (anti-weight)	28. Replacement of a mechanical system
9. Prior Counteraction	29. Use pneumatic or hydraulic systems
10. Prior Action	30. Flexible film or thin membranes
11. Cushion in Advance	31. Use of porous materials
12. Equipotentiality	32. Changing the color
13. Inversion (the other way round)	33. Homogeneity
14. Spheroidality- Curvature	34. Rejecting and regenerating parts
15. Dynamicity	35. Parameter Change
16. Partial, overdone or excessive action	36. Phase transition
17. Moving to a new dimension	37. Thermal expansion
18. Mechanical vibration	38. Use strong oxidizers
19. Periodic action	39. Inert environment
20. Continuity of useful action	40. Composite materials

Source of Table 3.8: Altshuller G. 40 Principles: TRIZ Keys to Technical Innovation. Technical Innovation Center; 2001.

CHAPTER 4

Interpretive Structural Modeling (ISM)

We live in a highly complex, technological world – and it's not entirely obvious what's right and what is wrong in any given situation unless you can parse the situation, and deconstruct it. People just don't have the insight to be able to do that very effectively.

Christopher Langan

4.1 Introduction

A *structural model* is a collection of components (elements) showing their relationship in a diagram that consists of nodes and the links that connect them. Using structural modeling we can gain a broad understanding of the system as a whole by studying a structural model of the components within the system. Warfield defines the structural modeling as:[1]

> "Structural modeling is a methodology which employs graphics and words in carefully defined pattern to portray the structure of a complex issue, a system, or a field of study."

Interpretive Structural Modeling (**ISM**) is an effective methodology used to cope with novel, ill-defined problems in complex, real-world settings. It is a transdisciplinary tool used to understand complex situations that occur in diverse knowledge domains such as: when developing plans, managing organizations, and designing large-scale systems, and used in many other kinds of human endeavors.

ISM is a well-established systematic and comprehensive method for dealing with complex issues. It was proposed by Warfield in 1973. ISM identifies relationships among specific factors, which are relevant to the problem or issue. This helps researchers to structure a set of different and directly related factors (parameters) affecting the system into a comprehensive hierarchical model so that unclear and poorly expressed conceptual system models will be well-defined.

The fundamental approach of the ISM process is to use experts from diverse knowledge domains (academic and non-academic) with practical experience and knowledge to decompose a complex issue into smaller sub-issues and build an easily understandable multilevel structural model.

[1] J. Warfield, "Structuring Complex Systems," Battelle Memorial Institute, Columbus, OH, Battelle Monograph, No. 3, 1974.

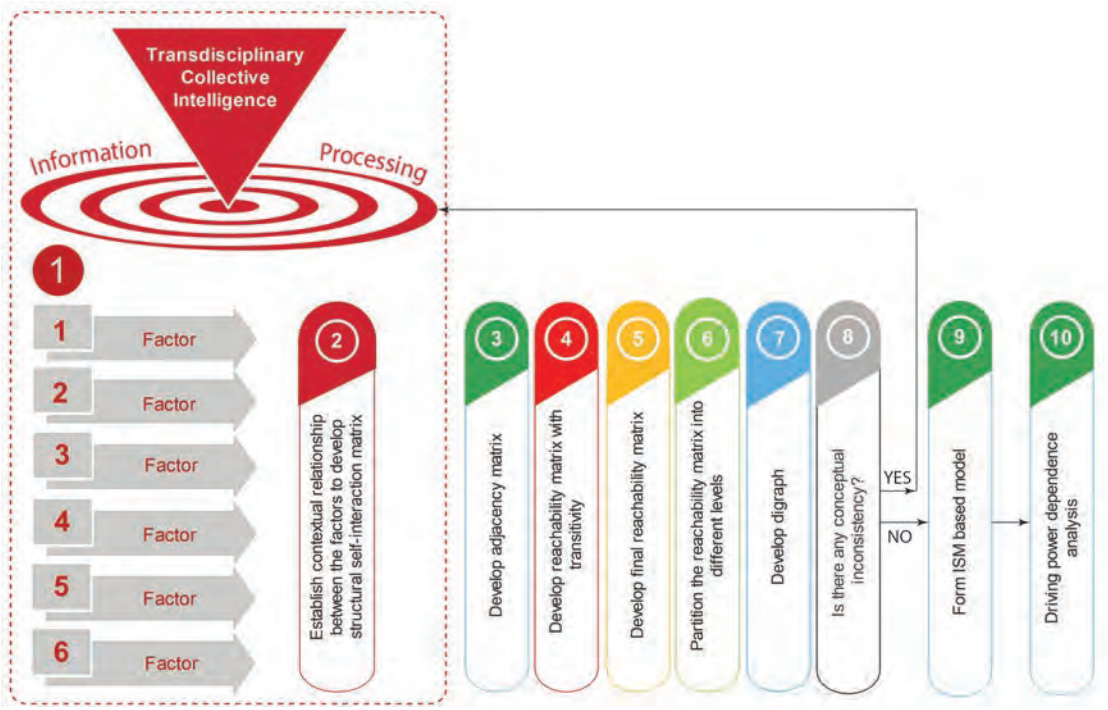


Figure 4.1: ISM process.

4.2 ISM Process

As shown in Figure 4.1, the following steps are followed to developed the ISM process.

Step 1 Development of TD collective intelligence: ISM approach starts with the development of transdisciplinary (TD) collective intelligence which includes identifying the main factors affecting complexity and establishing contextual relationships between the factors (Step-1) to develop the Structural Self-Interaction Matrix (SSIM) (Step-2). This will be accomplished by exercising the Interactive Collective Intelligence Management workshop which was covered in Module 1.

Step 2 Structural Self-Interaction Matrix: The next step is to establish a contextual relationship between the factors to develop a Structural Self-Interaction Matrix (SSIM) shown in Figure 4.2. During this phase, the transdisciplinary collective intelligence workshop participants must decide upon the pairwise relationship between the factors (element). The contextual relationship for each factor, the relationship between any two factors (i and j), and the associated direction of the relation will be decided through the workshop participants' debate. The four symbols used to indicate the direction of the relationship between the factors i and j are given below:

- V = for the relation from i to j but not in both directions;
- A = for the relation from j to i but not in both directions;
- X = for both-direction relations: from i to j and j to i; and
- O= if the relation between the elements does not appear to be valid

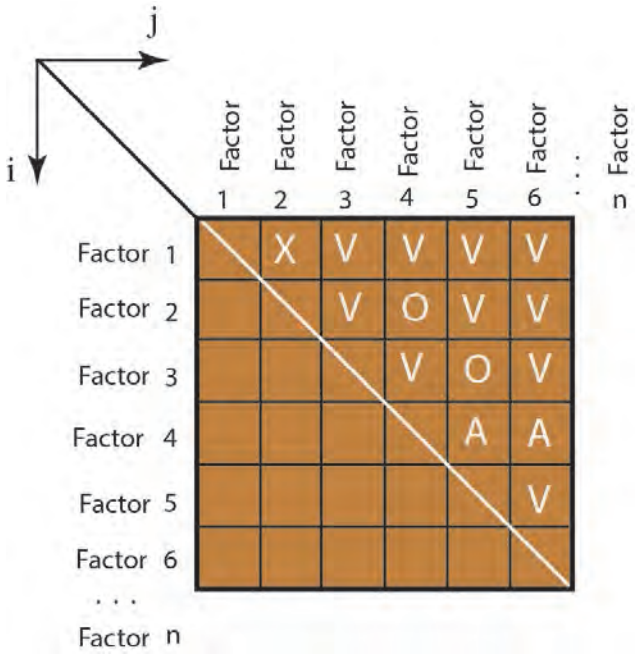


Figure 4.2: Structural self-interaction matrix (SSIM).

STEP 3 Develop Adjacency Matrix: As shown in Figure 4.3, replace the entries V, A, X, and O of the SSIM into 1 and 0, following the below rules:

- When the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry becomes 0.
- When the (i, j) entry in the SSIM is A, then the (i, j) entry in the reachability matrix becomes 0 and the (j, i) entry becomes 1.
- when the (i, j) entry in the SSIM is X, then both the (i, j) and (j, i) entries of the reachability matrix become 1.
- when the (i, j) entry of the SSIM is O, then both the (i, j) and (j, i) entries of the reachability matrix become 0.

$R_a =$

	1	2	3	4	5	6
Factor 1	1	1	1	1	1	1
Factor 2	1	1	1	0	1	1
Factor 3	0	0	1	1	0	1
Factor 4	0	0	0	1	0	0
Factor 5	0	0	0	1	1	1
Factor 6	0	0	0	1	0	1

Figure 4.3: Adjacency matrix.

STEP 4 Reachability Matrix with Transitivity: Figure 4.4 shows the reachability matrix with transitivity. The reachability matrix is tested for the transitivity rule and is updated until transitivity is confirmed. The transitivity rule is "if **A** has a relationship to **B** and **B** has a relationship to **C**, then **A** has a relationship to **C**". Following the transitivity rule a reachability matrix shown in Figure 4.4 is developed.

$R_t =$

	1	2	3	4	5	6
Factor 1	1	1	1	1	1	1
Factor 2	1	1	1	1	1	1
Factor 3	0	0	1	1	0	1
Factor 4	0	0	0	1	0	0
Factor 5	0	0	0	1	1	1
Factor 6	0	0	0	1	0	1

Figure 4.4: Reachability matrix with transivity.

STEP 5 Final Reachability Matrix: *Final reachability matrix* in Figure 4.5 shows *Driving power* and *dependence* of factors. The summation of ones in the corresponding rows gives the driving power and the summation of ones in the corresponding columns gives the dependence. Figure 4.5 is the final form of the relationships of all the factors involved with the problem under consideration. Calculated driving power and dependence in Figure 4.5 will be used for MICMAC analysis.

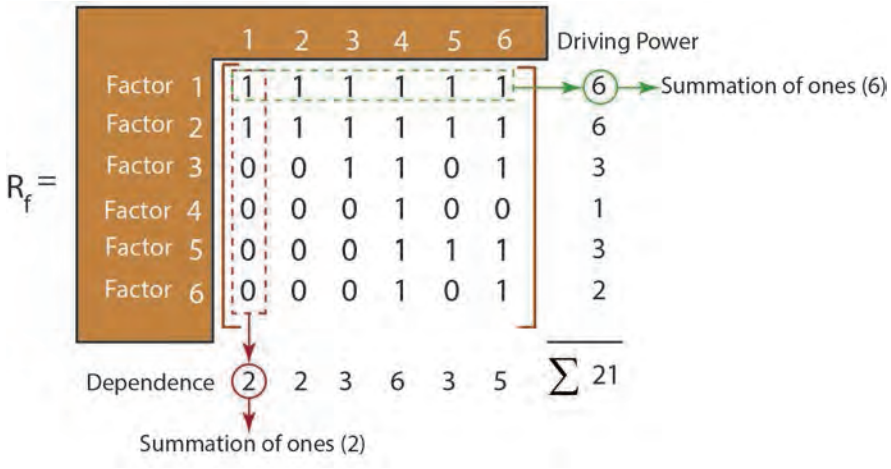


Figure 4.5: Final reachability matrix.

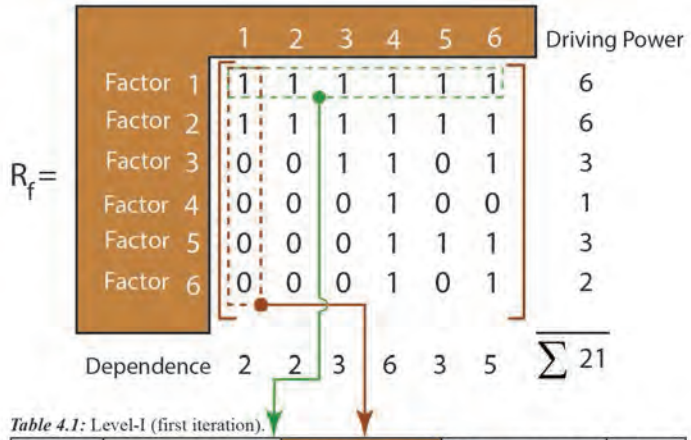


Table 4.1: Level-I (first iteration).

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1, 2, 3, 4, 5, 6	1, 2	1, 2	
2	1, 2, 3, 4, 5, 6	1, 2	1, 2	
3	3, 4, 6	1, 2, 3	3	
4	4	1, 2, 3, 4, 5, 6	4	I
5	4, 5, 6	1, 2, 5	5	
6	4, 6	1, 2, 3, 5, 6	6	

Since factor 4 has the same reachability and intersection set, it is the level-I.

Figure 4.6: Identifying level 1.

STEP 6 Level Partition: The driving force and dependence obtained from the final reachability matrix will help us to classify the factors. As shown in Figure 4.6, the intersection of antecedent and reachability sets will

provide an intersection set. In other words, the factors common in the reachability set and the antecedent set are included in the intersection set. These three sets will help us to identify the levels of the factors. When the factors of the intersection and reachability sets are the same, then that factor will be identified as the top-level group (level I group) in the ISM hierarchy. Once the top-level factors are identified, they are deleted from the set to identify the next level. As seen in Tables 1 through 4, this iteration process is repeated until all the levels are identified. These levels will be used to build the digraph and ISM model.

Table 1: Level-I (first iteration).

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1, 2, 3, 4, 5, 6	1, 2	1, 2	
2	1, 2, 3, 4 ,5, 6	1, 2	1, 2	
3	3, 4, 6	1, 2, 3	3	
4	4	1, 2, 3, 4, 5, 6	4	I
5	4, 5, 6	1, 2, 5	5	
6	4, 6	1, 2, 3, 5, 6	6	

Delete factor 4 and level-I from the table for the next iteration.

↓

Table 2: Level-II (second iteration).

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1, 2, 3, 5, 6	1, 2	1, 2	
2	1, 2, 3, 5, 6	1, 2	1, 2	
3	3, 6	1, 2, 3	3	
5	5, 6	1, 2, 5	5	
6	6	1, 2, 3, 5, 6	6	II

Delete factor 6 and level-II from the table for the next iteration.

↓

Table 3: Level-III (third iteration).

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1, 2, 3,5	1, 2	1, 2	
2	1, 2, 3, 5	1, 2	1, 2	
3	3	1, 2, 3	3	III
5	5	1, 2, 5	5	III

Delete factors 3 and 5 and levels-II and III from the table for the next iteration.

↓

Table 4: Level-IV (fourth iteration).

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
1	1, 2	1,2	1, 2	IV
2	1, 2	1, 2	1, 2	IV

STEP 7 Formation of Digraph: The digraph is a diagram that shows the connections of the direct and indirect relationships between the factors. As shown in Figure 4.7, the relationship of factors and binary associations through matrices can now be translated into graphical form by using the theory of digraphs

(directed graphs).[2] For example, consider factor 1. Factor 1 is reaching factor 3 (see red circle on the final reachability matrix). But factor 3 is not reaching factor 1 (see the line without arrow from 3 to 1). Another example is the relationships between factors 4 and 6. While factor 6 is reaching factor 4, factor 4 is not reaching factor 6. In this analysis "0" means there is no relationship among the factors whereas "1" means there is a relationship.

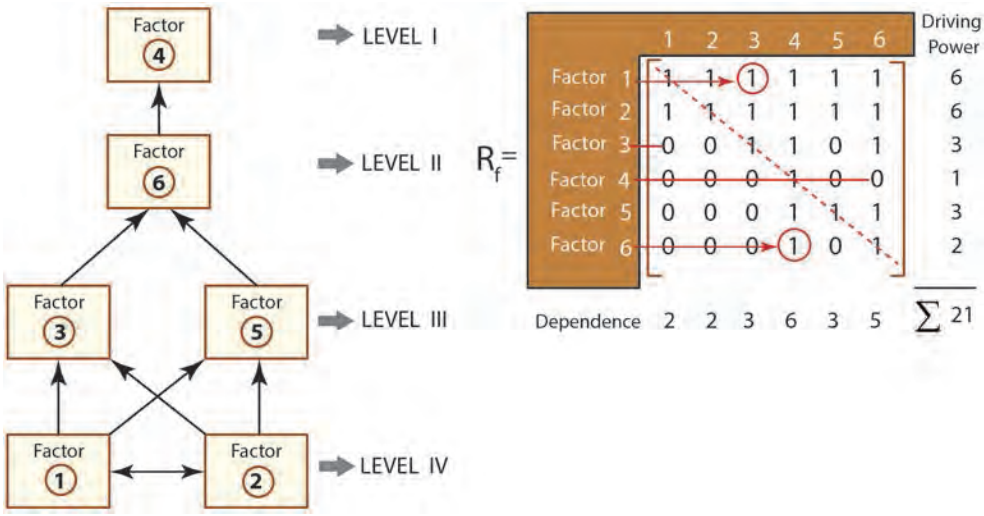


Figure 4.7: Digraph.

STEP 8 Conceptual Inconsistency: If there is any conceptual inconsistency, go back to Steps 1 and 2 to re-iterate the problem – carefully check the relationships among the factors.

STEP 9-10 MICMAC Analysis: The MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée á un Classement) (cross-impact matrix multiplication applied to classification) analysis was developed by Duperrin and Godet in 1973 to analyze the driving power and the dependence of the factors affecting the issue in hand.[3] As shown in Figure 4.8, factors are placed concerning their driving power and dependence in four clusters:[4] (1) autonomous, (2) dependent, (3) linkage, and (4) independent factors. The driving power and dependence of each of the factors are imported from Figure 4.5. For example, the coordinates of factor 4 are Dependence = 6 and Driving power = 1, thus factor 4 is placed at the very bottom right corner of the MICMAC diagram.

[2]F. Harary, R. V. Norman, and D. Cartwright, Structural Models: An Introduction to the Theory of Directed Graphs, Willey, New York, 1965.

[3]J. C. Duperrin and M. Godet, Methode De Hierar Chization des Elements D'um System, Rapport Economique de CEA, 1973, pp.45–51.

[4]A. Mandal and S. G. Deshmukh, Vendor Selection Using Interpretive Structural Modelling (ISM), International Journal of Operations & Production Management, 14(6), 1994, pp.

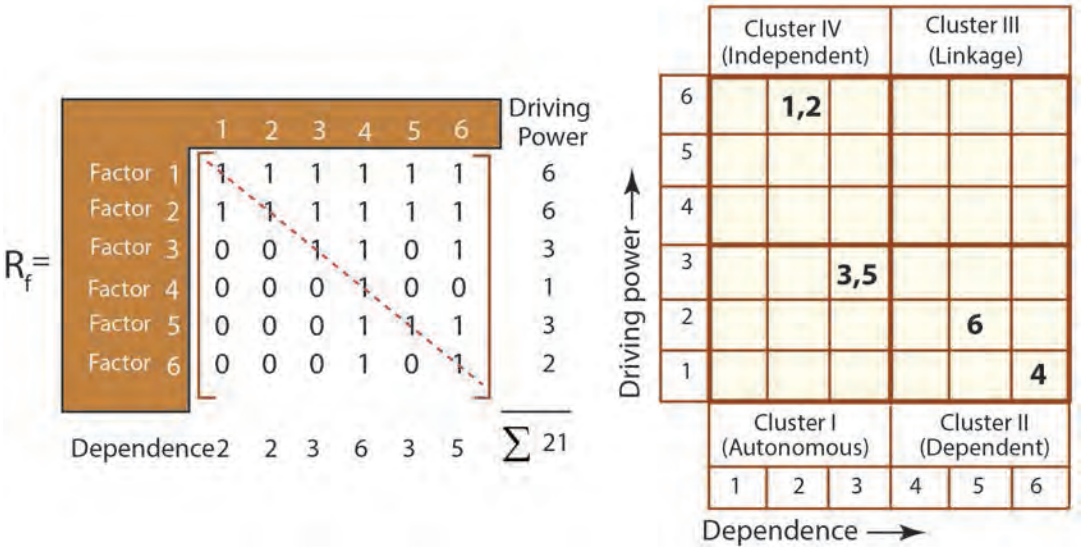


Figure 4.8: MICMAC analysis.

EXAMPLE 4.1

Figure 4.9 shows the relationships of five elements of a system. Develop:

(a) the adjecency matrix;

(c) the final reachability matrix;

(d) the level partition;

(e) the digraph.

SOLUTION

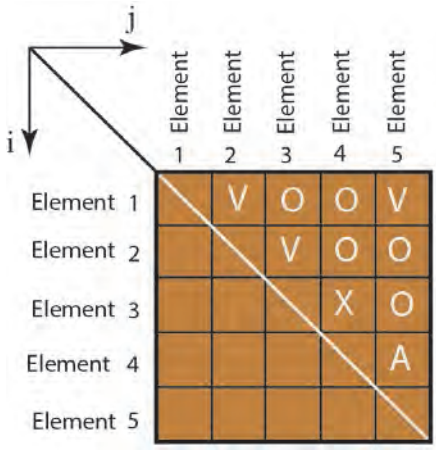


Figure 4.9: Structural self-interaction matrix.

EXAMPLE 4.1 (continued)

(a) The adjacency matrix shown in Figure 4.10 is obtained by transforming SSIM into a binary matrix by substituting V, A, X, and O by 1 and 0.;

$R_a =$

	1	2	3	4	5
Factor 1	1	1	0	0	1
Factor 2	0	1	1	0	0
Factor 3	0	0	1	1	0
Factor 4	0	0	1	1	0
Factor 5	0	0	0	1	1

Figure 4.10: Adjacency matrix.

(b) Final Reachability matrix with transitivity is shown in Figure 4.11. As shown in this figure, the summation of ones in the corresponding rows gives the driving power of 15 and the summation of ones in the corresponding columns gives the dependence of 15.;

$R_f =$

	1	2	3	4	5	Driving power
Factor 1	1	1	1	1	1	5
Factor 2	0	1	1	1	0	3
Factor 3	0	0	1	1	0	2
Factor 4	0	0	1	1	0	2
Factor 5	0	0	1	1	1	3
Dependence	1	2	5	5	2	$\sum$ 15

Figure 4.11: Reachability matrix with transitivity.

EXAMPLE 4.1 (continued)

(c) The final reachability matrix, R_f is used to develop the level partition. If the intersection and reachability sets of any individual factor are the same, then that factor is identified as the top-level group (level I group) in the ISM hierarchy. As shown in Table 4.5, once the top-level factors are known, they are removed from the set to identify the next level. This iteration process is repeated until all the levels are recognized.

Table 4.5: Reachability set, antecedent set, iteration levels.

Factor Numbers	Reachability Set	Antecedent Set	IntersectionSet	Factor Levels
1	1, 2, 3, 4, 5	1	1	
2	2, 3, 4	1, 2	2	
3	3, 4	1, 2, 3, 4, 5	3, 4	I
4	3, 4	1, 2, 3, 4, 5	3, 4	I
5	3, 4, 5	1, 5	5	
1	1, 2, 5	1	1	
2	2	1, 2	2	II
5	5	1, 5	5	II
1	1	1	6	III

(d) As shown in Figure 4.12, the initial digraph can be developed by using an adjacency matrix. As seen from the adjacency matrix, element 1 is reaching elements 2 and 5 (first row of the matrix). Element 2 is reaching element 3 (second row of the matrix). Element 3 is reaching element 4 (third row of the matrix). Element 4 is reaching element 3 (fourth row of the matrix). Finally, element 5 reaches element 4 (the fifth row of the matrix).

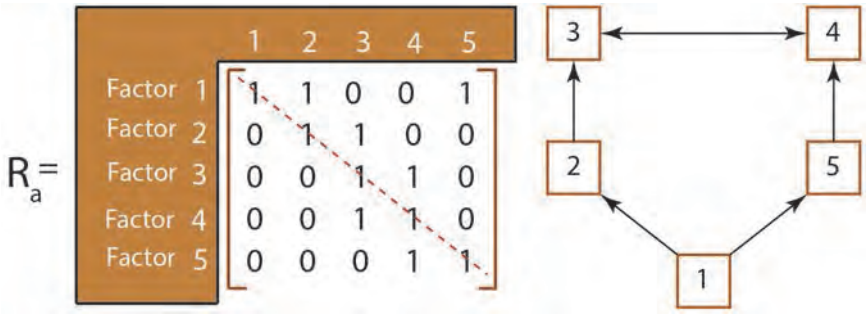


Figure 4.12: Digraph through adjacency matrix.

EXAMPLE 4.1 (continued)

The final digraph which takes transitivity into account can be developed by using the final reachability matrix as follows (see figure 4.13):

- Element 1 reaches Element 2 (arrow should go from 1 to 2) and reaches component 5 (arrow should go from 1 to 5). Note that, element 1 also reaches to elements 3 and 4 through elements 2 and 5.
- Element 2 reaches Element 3 (arrow should go from 2 to 3)
- Element 3 reaches Element 4 (arrow should go from 3 to 4)
- Element 4 reaches Element 3 (arrow should go from 4 to 3)
- Element 5 reaches Element 4 (arrow should go from 5 to 4)

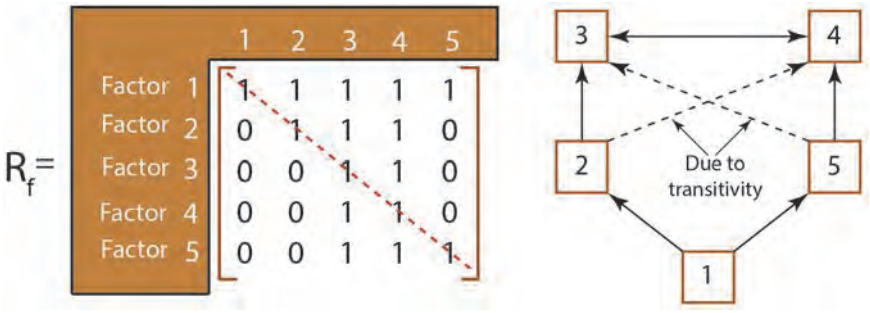


Figure 4.13: Digraph through adjacency matrix.

EXAMPLE 4.2

Figure 4.14 shows the relationships of eight elements of a system. Develop:

(a) the adjecency matrix;

(c) the final reachability matrix;

(e) the digraph.

SOLUTION

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8
Factor 1		V	O	O	O	O	O	O
Factor 2			V	O	O	O	O	O
Factor 3				O	O	V	V	O
Factor 4					X	O	O	O
Factor 5						O	O	O
Factor 6							O	O
Factor 7								O
Factor 8								

Figure 4.14: Structural self-interaction matrix.

(a) The adjacency matrix shown in Figure 4.15 is obtained by transforming SSIM into a binary matrix by substituting V, A, X, and O by 1 and 0.;

$R_a =$

	1	2	3	4	5	6	7	8
Factor 1	1	1	0	0	0	0	0	0
Factor 2	0	1	1	0	0	0	0	0
Factor 3	0	0	1	0	0	1	1	0
Factor 4	0	0	0	1	1	0	0	0
Factor 5	0	0	0	1	1	0	0	0
Factor 6	0	0	0	0	0	1	0	0
Factor 7	0	0	0	0	0	0	1	0
Factor 8	0	0	0	0	0	0	0	1

Figure 4.15: Adjacency matrix.

EXAMPLE 4.2 (Continued)

(b) Final Reachability matrix with transitivity is shown in Figure 4.16.

$R_f =$

	1	2	3	4	5	6	7	8	Driving power
Factor 1	1	1	1	0	0	0	0	0	3
Factor 2	0	1	1	0	0	1	1	0	4
Factor 3	0	0	1	0	0	1	1	0	3
Factor 4	0	0	0	1	1	0	0	0	2
Factor 5	0	0	0	1	1	0	0	0	2
Factor 6	0	0	0	0	0	1	0	0	1
Factor 7	0	0	0	0	0	0	1	0	1
Factor 8	0	0	0	0	0	0	0	1	1
Dependence	1	2	3	2	2	3	3	1	Σ 17

Figure 4.16: Final reachability matrix with transitivity.

(c) Digraph is shown in Figure 4.17.

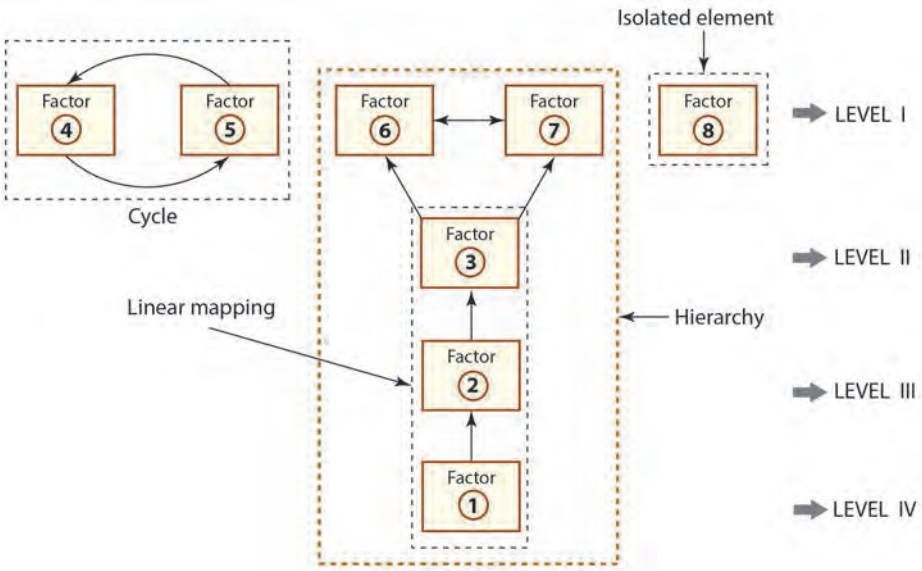


Figure 4.17: Digraph.

EXAMPLE 4.2 (continued)

As shown in Figure 4.17, factor 8 is isolated since it is not adjacent to any factor – this factor does not influence system performance. Factors 1, 2, and 3 represent the linear mapping of the system. The system contains one cycle between factors 4 and 5. Factor 1 is the source element since it has only outgoing paths. As shown in this figure system also contains a hierarchy.

4.2.1 Structural Types

Figure 4.18 shows different kinds of structural types that can occur in the analysis of a complex issue. Any combination of those types will make the system of hybrid structure. The previous example showed some of the structural types in one system description.

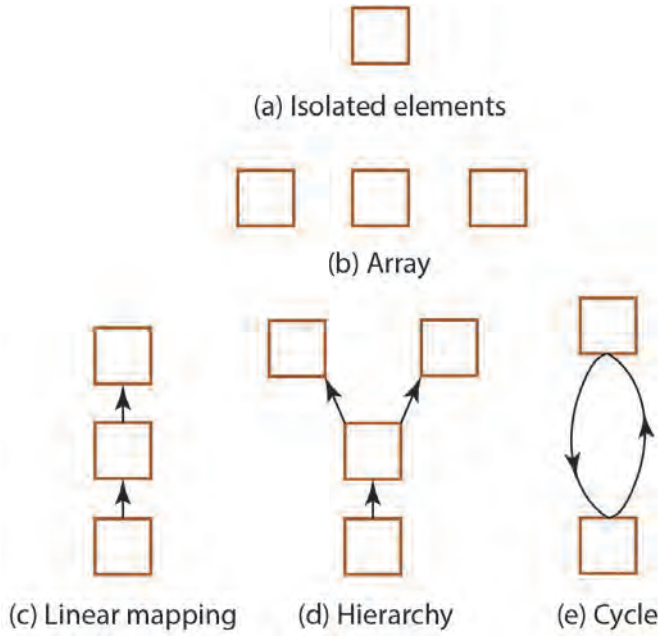


Figure 4.18: Structural types.

CASE STUDY 4.1

Complexity of Global Refugee Crisis: Needs for Global Transdisciplinary Collaboration

People are on the move for many reasons such as war and civil war, human rights, violation, economic, social, climate, environmental, political, and individual reasons that create these changing aspects. In such complex situations, the need to flee (***forcibly displaced***) versus the choice to leave (***migration***) can be difficult to determine. The issue of refugee resettlement is complex and includes many factors to consider. Factors being considered for their impact on resettlement include budget and cost issues, federal law and policies, administration challenges, security screening process, education and training, health and housing, crime rate, socioeconomic issues, and many others. The objective of this case study is to discuss how the aforementioned factors relate and interact with one another using Interpretive Structural Modeling (ISM).[a]

ANALYSIS

The worldwide population of *forcibly displaced* rose by 2.3 million people in 2018 reaching 70.8 million – 20 people are displaced every minute a day. The worldwide population of forcibly dislocated people grew considerably from 43.3 million in 2009 to 70.8 million in 2018, reaching a record high. This increase took place between 2014 and 2015, caused mainly by the Syrian conflict along with other conflicts in the region such as in Iraq, Yemen, and Sudan as well as other poor countries. The complexity of the issue makes it difficult to understand global refugee problems.

The issue of refugee resettlement is complex and includes many other factors to consider. Factors being considered for their impact on resettlement include budget and cost issues, federal law and policies, administration challenges, security screening process, education and training, health and housing, crime rate, socioeconomic issues, and many others.

The objective of this case study is to discuss how the aforementioned factors relate and interact with one another using Interpretive Structural Modeling (ISM).

[a] From (Moran, D., Gulbulak, U., Ertas, A., and students from senior design class of ME-TTU, (2020). The complexity of Global Refugee Crisis: Needs for Global Transdisciplinary Collaboration. *Transdisciplinary Journal of Engineering & Science*, Vol. 11, pp. 115-131).

CASE STUDY 4.1 (continued)

Context

Transdisciplinary Collective Intelligence: ISM methodology implementation against this problem consisted of a group of 25 undergraduate students in senior design class, all pursuing Mechanical Engineering degrees at Texas Tech University, two Ph.D. students, one faculty member in design, four research engineers from different companies. This group recognized significant difficulties and challenges in carrying out successful refugee resettlement and sought to identify the main factors affecting the problem and how they were interrelated, to improve the rate of success for these displaced individuals.

Process

Effectiveness in accepting and integrating immigrants into a new home country requires transdisciplinary collaboration among, and within, institutional sectors in the receiving countries. Partnering and joining must occur between organizations such as social services; education; government; community-based organizations, and others.

The working group developed transdisciplinary collective intelligence using the Interactive Collective Intelligent Management (ICIM) workshop to investigate the issue. (1) The Nominal Group Technique (NGT) was used to develop and clarify a list of factors affecting the complex issue, (2) Interpretive Structural Modeling (ISM) process was used to develop:

(a) Structural self-interaction matrix

(b) Final reachability matrix

(c) Digraph

(d) MICMAC Analysis

The working group identified nine factors for how to handle complex issues of refugee settlement. The factors were grouped into six levels. Through MICMAC analysis, it was shown how these factors are interrelated to support the successful refugee settlement.

Content

The working group developed a set of factors affecting the complex issues of refugee settlement showing how selected factors of the problem they identified were related to each other. One of the Ph.D. students who are familiar with the ICIM facilitated the workshop.

Identifying Factors

During the first stage of the workshop, potential factors which affect the successful refugee settlement were identified. One of the methodologies that have been found useful is the NGT structured method for group brainstorming which encourages contributions from group members and enables quick agreement on the relative importance of issues, problems, or solutions.

CASE STUDY 4.1 (continued)

NGT was used to obtain and specify potential factors. The working group developed twenty factors affecting the issue at hand.

Structuring Factors

Following the development of factors, a part of the NGT process was used to determine which of the factors were most important. From the set of twenty factors, the following subset of nine was structured using the methodology of ISM. Those were the ones receiving the highest scores in the voting on the most important main factors.

Budget (Cost)

There are various costs that the Office of Refugee Resettlement (ORR) takes into account in the budget for funding refugee resettlement. The first and most obvious are the monetary costs: funding for transitional and medical services, social services, preventive health, shelter, utilities, supplies, training, education, etc. To determine the most feasible investment, depending on factors such as federal law and policies, the budget request is formulated based on the number of people in need.

Policies and Rules

Federal (Nation-State) laws and policies are significant when dealing with a wave of refugees trying to enter a new country. They dictate how effectively a refugee crisis can be handled by a host country. Furthermore, the laws and policies set up how the country is going to respond to the situation. Whether it could be a temporary or permanent solution, the host country is responsible for accommodating the refugees and creating the laws that will govern them. The host country creates these laws and policies to offer protection, shelter, and life to the refugees – facilitating the process of resettlement. Nation-state policies and rules can also, on the contrary, limit the number of refugees entering the country and hinder the resettlement processes

Screening Process

Refugees seeking resettlement must pass through a series of steps planned to ensure they will not pose a security risk to the hosting country – security is among the top priorities of a nation. In the last couple of years, nations have come a long way in finding ways to intercept threats and stop them before they can happen. This is in part because of new technologies that can pick up encrypted communication and a certain pattern of messages being transmitted around the globe paired with the work of the various intelligence communities for host countries.

CASE STUDY 4.1 (continued)

Administration Challenges

Administration challenges regarding the logistics and bureaucracy in the execution of decisions for resettling refugees will delay resettlement. Obtaining information about the refugees and how they are faring is the only way to know if current administration policies are achieving their desired goals. One key metric for successful resettlement is measuring the time between the influx of refugees and successful resettlement.

Health and Shelter

During the resettlement phase, health care needs to be provided to the refugees. In doing so, this factor will affect the cost and the crime rate of the shelter. Although health care is a large expense, it will ensure a high survival rate. The more services physicians provide, the higher the cost will be to maintain that standard of care. As a result of having healthier patients both physically and mentally, the crime rate decreases. The opposite will occur if no health care is provided.

The health care set by the host government is completely structured by the federal policies of said government. The benefits that refugees receive are based on federal administrative regulations. Adversely, health care is dependent on federal policy, and not the other way around. In terms of economics, a government-subsidized healthcare program can create an entirely new market of jobs, specifically ones set up to support the refugees as they are taken in. Economics slowly transforms from micro to macro level depending on the length of government-funded care, and the number of refugees supported.

Education and Training Programs

Education and training programs are crucial for refugees to adapt and make a life for themselves in society. Without these programs, refugees are left to fend for themselves and survive in a culture they are most likely very unfamiliar with.

Self Sufficiency

To help refugees become self-sufficient, there must be help from the country where they are settling in. In the United States, the Refugee Career Pathways program helps refugees to achieve self-sufficiency by providing different types of training. The training consists of, assistance in creating personalized career development plans, classroom, and work-based learning opportunities, career coaching and mentoring, connections with educational opportunities, apprenticeships, on-the-job training, re-credentialing and credential recognition, and vocational English language training.[a]

[a]Refugee Career Pathways. ACF, www.acf.hhs.gov/orr/programs/refugee-career-pathways, accessed February 26, 2020)

CASE STUDY 4.1 (continued)

Safety and Security

"Protecting the physical security of refugees entails securing their areas of residence, or taking steps to prevent their safety from being jeopardized. It also requires that the living environment of refugees should be peaceful, humanitarian and civilian, free of violence and criminal activity, and conducive to the realization of human dignity...".[b]

Social Issues and Economic Impact

Economic issues that affect the countries where refugees reside are mainly the cost of their well-being. The governments of those countries are responsible for food, housing, and education to name a few. Large-scale refugee populations can have a serious impact on the social, economic, and political life of host countries (in particular developing countries) and create strain on the local administration. Refugees will compete with the host country's citizens for resources of host countries. Gradually, their presence will cause considerable demands on natural resources, education and health facilities, energy, transportation, social services, and finally employment.[c]

Interpretive Structural Modelling (ISM)

Structural Self-Interaction Matrix (SSIM)

Structural Self-Interaction Matrix (SSIM)

The above factors are assumed to be interrelated, rather than independent, where it is noted that some factors may increase the effects of other factors. The next step was to determine the contextual relationships to develop a structural self-interaction matrix shown in Figure 4.19. Using expert opinions along with working members the SSIM was developed.

Adjacency matrix

Then the adjacency matrix, R_a, shown in Figure 4.20 is developed via transforming SSIM into a binary matrix, by substituting V, A, X, and O by 1 and 0 per the schema described previously in STEP 3:

[b]Protection Guidelines Relating to Refugee Security. https://www.refworld.org/pdfid/4124bee54.pdf. Accessed March 13, 2020.

[c]Social and economic impact of large refugee populations on host developing countries, EC/47/SC/CRP.7, UNHCR Standing Committee (1997). https://www.unhcr.org/en-us/excom/standcom/3ae68d0e10/social-economic-impact-large-refugee-populations-host-developing-countries.html. Accessed March 12, 2020.

CASE STUDY 4.1 (continued)

		Policies & Rules 1	Administrative Challenges 2	Education & Training 3	Social Issues & economic Impact 4	Health & Shelter 5	Safety & Security 6	Screening Process 7	Self Sufficiency 8	Budget 9
		1	2	3	4	5	6	7	8	9
Policies & Rules	1		X	V	V	V	V	V	V	V
Administrative Challenges	2			V	O	V	V	A	X	A
Education & Training	3				V	O	V	O	V	A
Social Issues & economic Impact	4					A	A	O	A	A
Health & Shelter	5						V	O	O	A
Safety & Security	6							A	O	A
Screening Process	7								O	A
Self Sufficiency	8									A
Budget	9									

Figure 4.19: Structural Self-Interaction Matrix (SSIM).

$R_a =$

	1	2	3	4	5	6	7	8	9
Policies & Rules 1	1	1	1	1	1	1	1	1	1
Administrative Challenges 2	1	1	1	0	1	1	0	1	0
Education & Training 3	0	0	1	1	0	1	0	1	0
Social Issues & economic Impact 4	0	0	0	1	0	0	0	0	0
Health & Shelter 5	0	0	0	1	1	1	0	0	0
Safety & Security 6	0	0	0	1	0	1	0	0	0
Screening Process 7	0	1	0	0	0	1	1	0	0
Self Sufficiency 8	0	1	0	1	0	0	0	1	0
Budget 9	0	1	1	1	1	1	1	1	1

Figure 4.20: Adjacency matrix.

CASE STUDY 4.1 (continued)

Reachability Matrix with Transitivity

Using the transitivity rule, a reachability matrix, R_t, shown in Figure 4.21 was obtained. The transitivity rule states that, if a factor 'A' is related to factor 'B' and if factor 'B' is related to factor 'C', then factor 'A' is related to factor 'C'. This matrix was updated until transitivity was established.

$R_t =$

		1	2	3	4	5	6	7	8	9
Policies & Rules	1	1	1	1	1	1	1	1	1	1
Administrative Challenges	2	1	1	1	1	1	1	1	1	1
Education & Training	3	0	1	1	1	0	1	0	1	0
Social Issues & economic Impact	4	0	0	0	1	0	0	0	0	0
Health & Shelter	5	0	0	0	1	1	1	0	0	0
Safety & Security	6	0	0	0	1	0	1	0	0	0
Screening Process	7	1	1	1	1	1	1	1	1	0
Self Sufficiency	8	1	1	1	1	1	1	0	1	0
Budget	9	1	1	1	1	1	1	1	1	1

Figure 4.21: Reachability matrix with transitivity.

Final Reachability Matrix

The final reachability matrix as shown in Figure 4.22 was established by including driving power and dependence of factors. The summation of ones in the corresponding rows gives the driving power and the summation of ones in the corresponding columns gives the dependence.

$R_f =$

		1	2	3	4	5	6	7	8	9	Driving power
Policies & Rules	1	1	1	1	1	1	1	1	1	1	9
Administrative Challenges	2	1	1	1	1	1	1	1	1	1	9
Education & Training	3	0	1	1	1	0	1	0	1	0	5
Social Issues & economic Impact	4	0	0	0	1	0	0	0	0	0	1
Health & Shelter	5	0	0	0	1	1	1	0	0	0	3
Safety & Security	6	0	0	0	1	0	1	0	0	0	2
Screening Process	7	1	1	1	1	1	1	1	1	0	8
Self Sufficiency	8	1	1	1	1	1	1	0	1	0	7
Budget	9	1	1	1	1	1	1	1	1	1	9
Dependence		5	6	6	9	6	8	4	6	3	$\Sigma = 53$

Summation of ones (9)

Summation of ones (5)

Figure 4.22: Final reachability matrix.

CASE STUDY 4.1 (continued)

Level Partition

As shown in Table 4.6, The reachability and antecedent set for each variable are obtained from the final reachability matrix.

Table 4.6: Reachability set, antecedent set, iteration levels.

Factor Numbers	Reachability Set	Antecedent Set	IntersectionSet	Factor Levels
1	1, 2, 3, 4, 5, 6, 7, 8, 9	1, 2, 7, 8, 9	1, 2, 7, 8	
2	1, 2, 3, 4, 5, 6, 7, 8, 9	1, 2, 3, 7, 8, 9	1, 2, 3, 7, 8, 9	
3	2, 3, 4, 6, 8	1, 2, 3, 4, 5, 6, 7, 8, 9	2, 3, 8	
4	4	1, 2, 3, 4, 5, 6, 7, 8, 9	4	I
5	4, 5, 6	1, 2, 5, 7, 8, 9	5	
6	4, 6	1, 2, 3, 5, 6, 7, 8, 9	6	
7	1, 2, 3, 4, 5, 6, 7, 8	1, 2, 7, 9	1, 2, 7	
8	1, 2, 3, 4, 5, 6, 8	1, 2, 3, 7, 8, 9	1, 2, 3, 8	
9	1, 2, 3, 4, 5, 6, 7, 8, 9	1, 2, 9	1, 2, 9	
1	1, 2, 3, 5, 6, 7, 8, 9	1, 2, 7, 8, 9	1, 2, 7, 8, 9	
2	1, 2, 3, 5, 6, 7, 8, 9	1, 2, 3, 7, 8, 9	1, 2, 3, 7, 8, 9	
3	2, 3, 6, 8	1, 2, 3, 7, 8, 9	2, 3, 8	
5	5, 6	1, 2, 5, 7, 8, 9	5	
6	6	1, 2, 3, 5, 6, 7, 8, 9	6	II
7	1, 2, 3, 5, 6, 7, 8	1, 2, 7, 9	1, 2, 7	
8	1, 2, 3, 5, 6, 8	1, 2, 3, 7, 8, 9	1, 2, 3, 8	
9	1, 2, 3, 5, 6, 7, 8, 9	1, 2, 9	1, 2, 9	
1	1, 2, 3, 5, 7, 8, 9	1, 2, 7, 8, 9	1, 2, 7, 8, 9	
2	1, 2, 3, 5, 7, 8, 9	1, 2, 3, 7, 8, 9	1, 2, 3, 7, 8, 9	
3	2, 3, 8	1, 2, 3, 5, 7, 8, 9	2, 3, 8	III
5	5	1, 2, 5, 7, 8, 9	5	III
7	1, 2, 3, 5, 7, 8	1, 2, 7, 9	1, 2, 7	
8	1, 2, 3, 5, 8	1, 2, 3, 7, 8, 9	1, 2, 3, 8	
9	1, 2, 3, 5, 7, 8, 9	1, 2, 9	1, 2, 9	
1	1, 2, 7, 8, 9	1, 2, 7, 8, 9	1, 2, 7, 8, 9	IV
2	1, 2, 7, 8, 9	1, 2, 7, 8, 9	1, 2, 7, 8, 9	IV
7	1, 2, 7, 8	1, 2, 7, 9	1, 2, 7	
8	1, 2, 8	1, 2, 7, 8, 9	1, 2, 8	IV
9	1, 2, 7, 8, 9	1, 2, 9	1, 2, 9	
7	7	7, 9	7	V
9	7, 9	9	9	
9	9	9	9	VI

CASE STUDY 4.1 (continued)

Formation of Digraph

The digraph is an illustration that shows the existence of the direct and indirect relationships between the factors. After removing transitivity, as shown in Figure 4.23, the relationship of sets and binary associations through matrices can now be translated into graphical form by using the theory of digraphs.

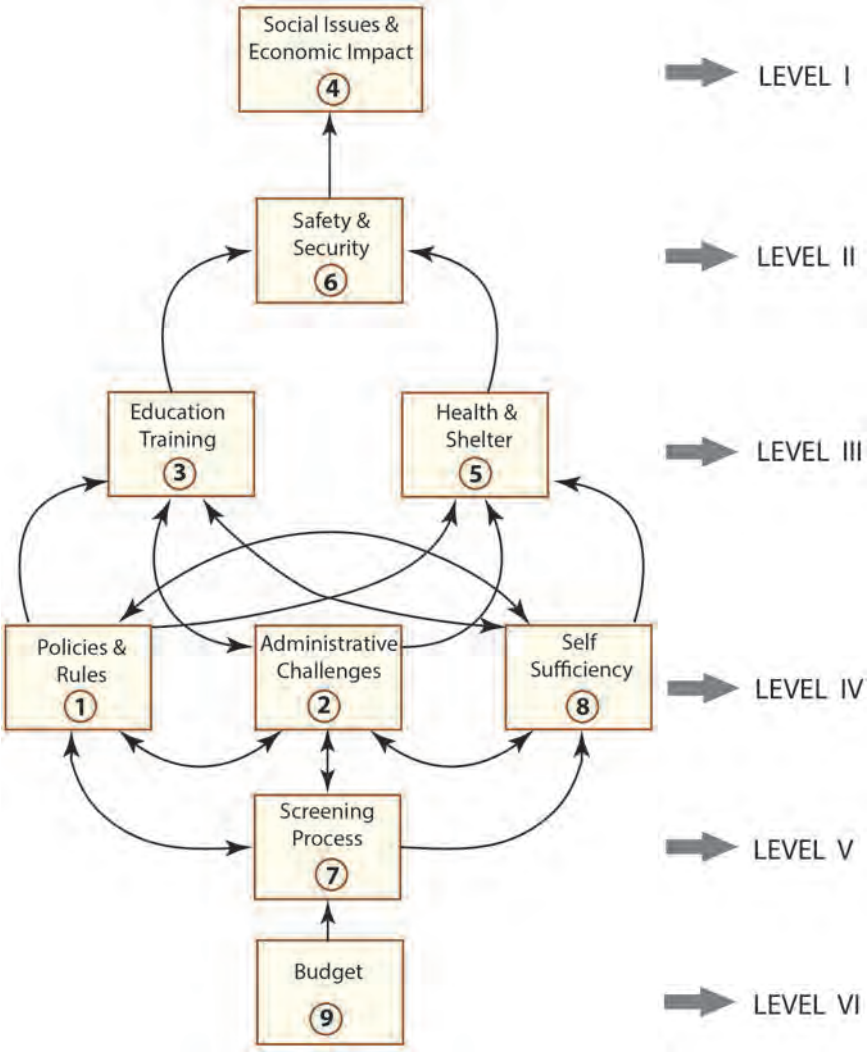


Figure 4.23: Digraph.

CASE STUDY 4.1 (continued)

MICMAC Analysis – Classification of Performance Measures

Through MICMAC analysis, factors are arranged concerning their driving power and dependence in four clusters: (1) autonomous, (2) dependent, (3) linkage, and (4) independent factors. The driving power and dependence of each of the factors are imported from Figure 4.22. Figure 4.24 shows the driving power-dependence map for refugee resettlement success factors.

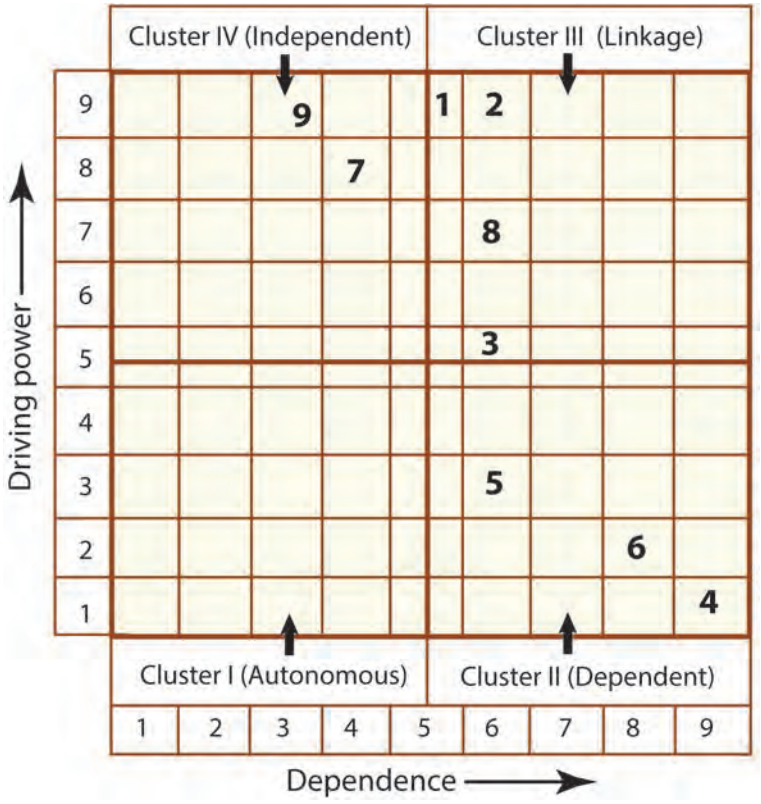


Figure 4.24: MICMAC Analysis.

Discussions

The factors affecting successful refugee settlement in a multi-project environment are presented in Figure 4.23 show complex interactions among them. This complexity can be described using Cyclomatic complexity through digraphs as:

$$M = E - N + 2P \tag{4.1}$$

CASE STUDY 4.1 (continued)

where
E = the number of edges of the graph
N = the number of nodes of the graph
P = the number of connected components

The number of edges (depicted as arrows) shown in Figure 4.23 is 16, the number of nodes (depicted as rectangles) is 9, and the number of connected components, P is equal to 1. Then, the Cyclomatic complexity M of the digraph given in Figure 4.23 is

$$M = 16 - 9 + 2 \times 1 = 9$$

A higher number of Cyclomatic complexity means that the complexity of an issue will be complicated to understand. The acceptable upper bound that has been used for Cyclomatic complexity is 10. Since the digraph gives close to the complexity of 10, the issue of refugee settlement is too complex to understand. As seen from Figure 4.23, the issue of refugee settlement consists of multiple levels of combinations, and functional behaviors can arise at many of the levels. It is usually difficult to deal with complex issues such as this one. The existence of directly or indirectly related factors complicates the solution of the issue which may or may not be articulated clearly.

The issue of refugees is complex and includes many factors. As shown in Figure 4.23, Level IV is the most complex one because of many interactions with the other levels. Administration plays an important role in the success of the refugee settlement by implementing policies and rules to help refugees become self-sufficient. Level IV effort should support education and training programs as well as health care needs which are crucial for refugees to adapt and make a life for themselves in society. A source factor of establishing a realistic budget should be allocated to separated families, detained children, threatened immigrants, and also all the required activities for secure and successful resettlement of refugees. However, this effort should not be at the cost of crucial education, housing, and nutritional assistance programs that promote public safety and improve poverty in hosting countries.

Figure 4.24 shows that there are no autonomous factors. The absence of these factors shows that all the considered factors influence successful refugee resettlement. Health & shelter, safety and security, and social issues, and economic impact are in the category of the dependent quadrant. This means that these issues have little driving power but strong dependence (called driven factors).

The linkage cluster consists of four factors, including the policies and rules (factor 1), administrative challenges (factor 2), Self-sufficiency (factor 8), and education and training (factor 3). These factors have strong driving power, as well as strong dependence power, therefore they are considered key factors for the success of the refugee settlement. These factors are critical, meaning that any action on these factors may influence the other factors and have an effect on themselves by the other factors.

CASE STUDY 4.1 (continued)

The fourth quadrant includes independent barriers that have a low dependence but strong driving power. In this research, budget & cost (factor 9) and screening process (factor 7) are in this quadrant. It can be assumed that these factors may be considered as the important key parameters, as well as the root cause of problematic issues. Management should give the greatest attention to these factors to meet the terms of the success of the goal of the refugee settlement.

As shown in Figure 4.23, factors of safety and security (factor 6), social issues, and economic impact (factor 4) are positioned at the top of the hierarchy. They are also very significant measures for the successful development of a refugee settlement as they are being affected by other factors: the living environment of refugees should be peaceful, humanitarian, and civilian, free of violence and criminal activity, and conducive to the realization of human dignity.

Concluding Remarks

It has been shown that the issue of refugee settlement consists of multiple levels of combinations and functional behaviors can arise at many of the levels – the problem of refugee settlement is too complex to understand. In this research, budget & cost (factor 9) and screening process (factor 7) are considered the important key parameters, as well as the root cause of problematic issues. Management should give the greatest attention to these factors to meet the terms of the success of the goal of the refugee settlement.

It is important to note that ISM is a tool to identify the order and directions of the complexity of relationships among the factors affecting certain issues. It does not provide any relative weight associated with the factors. Complex systems such as this one, require communications and the exchange of information among responsible organizations. Information flow between organizations can be created using a Design Structure Matrix (DSM) to better map organizational responsibilities and their interactions to address the problems associated with refugee resettlement. Clustering (integration) of organizations can provide new understandings of organizational decomposition and integration.

CHAPTER 5

Design Structure Matrix (DSM)

Every company has two organizational structures: The formal one is written on the charts; the other is the everyday relationship of the men and women in the organization.

Harold Geneen

5.1 Introduction

Design Structure Matrix (DSM) also referred to as dependency structure matrix is a tool for managing complexity. The initial DSM matrix corresponds to an adjacency matrix of ISM discussed in the previous module. DSM is a tool used in:

- complex systems management
- product development,
- project planning, management, and organizations
- system decomposition and integration

DSM helps the project team to agree on the design of a complex product promptly and it helps to design a complex product to be modular so that portions of it can be more easily changed or modified.

Management of complexity using a DSM was initiated by Don Steward in 1981. The DSM is a method for picturing relations and dependencies within a certain activity.[1] It is a matrix-based tool that represents information flows that allow the representation of complex task (or team) relationships to determine a sensible sequence (or grouping) for the tasks (or teams) being modeled.[2]

5.2 Classification of DSM

As shown in Figure 5.1, there are four different types of DSM are used for different types of data:[3]

[1] Danilovic, M. & Börjesson, H., "Managing Multi-project Environment," The 3rd International Dependence Structure Matrix (DSM) Workshop, Proceedings, October 29-30, 2001, Massachusetts Institute of Technology (MIT), Massachusetts, Boston, Cambridge, USA.

[2] Ali A. Yassine, An Introduction to Modeling and Analyzing Complex Product Development Processes Using the Design Structure Matrix (DSM) Method. https://staff.aub.edu.lb/ ay11/DSM-Tutorial_English.pdf, accessed August 1, 2002.

[3] Tyson R. Browning," Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions," *IEEE Transactions on Engineering Management,* Vol. 48, No. 3, 2001.

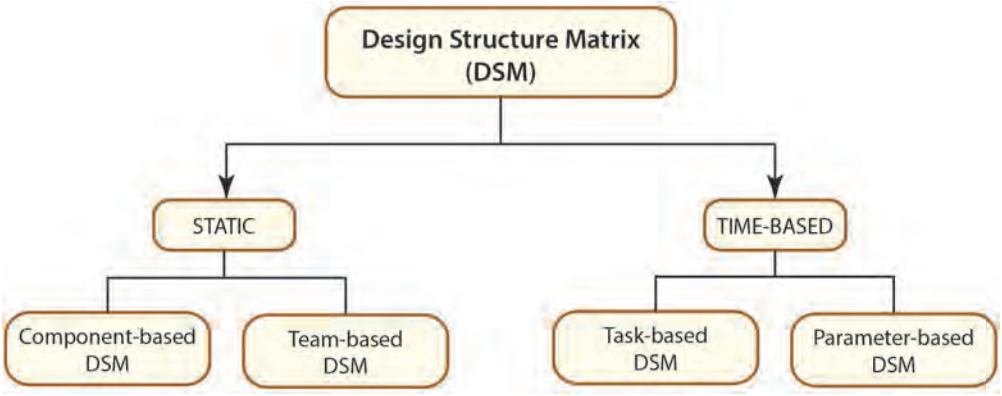


Figure 5.1: DSM types.

Component-based DSM: Analyzes relations and interactions among components in complex system architecture. An organized grouping of components will help to differentiate types of interactions. Four types of component grouping is shown in Table 5.1.[4,5]

Table 5.1: System component interaction types (4,5).

Special	Associations of physical space and alignment, needs for adjacency or orientation between two components
Energy	Needs for energy transfer/exchange between two components (e.g., power supply)
Information	Needs for data or signal exchange between two components
Material	Needs for material exchange between two components

As sown in Table 5.2, a quantification arrangement among the components enables weighting interactions relative to each other.[4,5]

Team-based DSM: is used for complex organizational analysis to show interactions and information flow among organizational entities, design teams, and team members. Different types of interaction among the team members are shown in Table 5.3.[6]

[4]T. U. Pimmler and S. D. Eppinger, (1994). Integration Analysis of Product Decompositions. in Proc. ASME 6th Int. Conf. on Design Theory and Methodology, Minneapolis, MN, 1994.

[5]Tyson R. Browning, (2001). Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions. *IEEE Transactions on Engineering Management,* Vol.48, No. 3 pp: 292-306.

[6]The Design Structure matrix, https://dsmweb.org/different-dsm-types/, accessed August 2, 2020.

Table 5.2: Spatial component interaction quantification arrangement (4,5).

(+2)→Required	Physical adjacency is necessary for functionality.
(+1)→Desired	Physical adjacency is beneficial, but not necessary for functionality.
(0)→Indefferent	Physical adjacency does not affect functionality.
(-1)→Undesired	Physical adjacency causes negative effects but does not prevent functionality.
(-2)→Undesired	Physical adjacency must be prevented to achieve functionality.

Table 5.4: DSM techniques for types of DSMs.

DSM Types	Representation	Application	Analysis method
Task-based	Task/Activity, input/otput, relationship	Project scheduling, activity sequencing	Partitioning, Tearing, Banding
Parameter-based (low level process)	Design parameter relationships	Low level activity sequencing & process construction	Partitioning, Tearing, Banding
Team-based (organization)	Teams organization and their relationships	Organizational design, interface management, team integration	Clustering
Component-based	Component relationship	System architecting, engineering design etc.	Clustering

Table 5.3: Different types of interaction among the team members.

Level of Detail	Sparse (documents, e-mail) to reach (models, face-to-face).
Frequency	Low (batch, on-time) to high (on-line, real).
Directions	One-way to two-way.
Timing	Early (preliminary, incomplete, partial) to late (final).

Task/activity-based DSM: analyzes relations among tasks or activities such as project scheduling and process modeling.

Parameter-based DSM: analyzes relationships among a set of design parameters in complex system architecture. Building and analyzing a parameter-based DSM is similar to an activity-based DSM.

Table 5.4 shows the applications of different types of DSMs.[7]

5.2.1 Design Dependencies

Figure 5.2 shows three possible dependencies among elements. Consider a sub-system that is composed of two elements: element "A", and element "B". The directionality of influence from one element to another is shown by an arrow.

In the parallel configuration shown in Figure 5.2(a), the elements do not interact with each other. Task B is said to be independent of task A and no information exchange is required between the two activities – both activities can start anytime independently without affecting each other.

In the sequential configuration shown in Figure 5.2(b), one element influences the decision of another element. For example, system parameters of element B are selected based on the system parameters of element A – task A should be performed before task B.

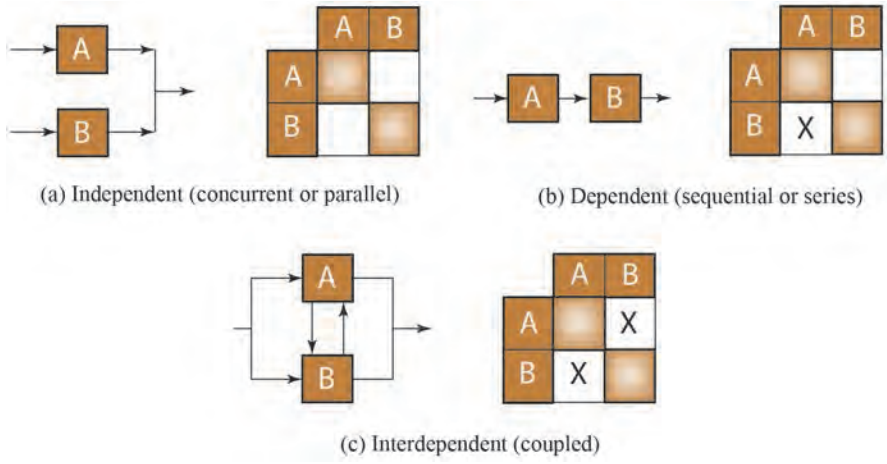


Figure 5.2: Dependencies among elements.

In the coupled system shown in Figure 5.2(c), the flow of information is intertwined: the activities of element A influence the activities of element B and element B influences A. This would occur when activities of element A could not be determined without first knowing element B and B could not be determined without knowing element A. This type of dependency is called "Circuit" or "Cycle" as explained in the first Module.

[7]Adapted from Bartolomei, J., Cokus, M., Dahlgren, J., de Neufville, R., Maldonado, D., Wilds, J. Analysis and applications of design structure matrix, domain mapping matrix, and engineering system matrix frameworks. Massachusetts Institute of Technology Engineering Systems Division. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.163.9694&rep=rep1&type=pdf

5.2.2 Matrix-Based Systems Modeling

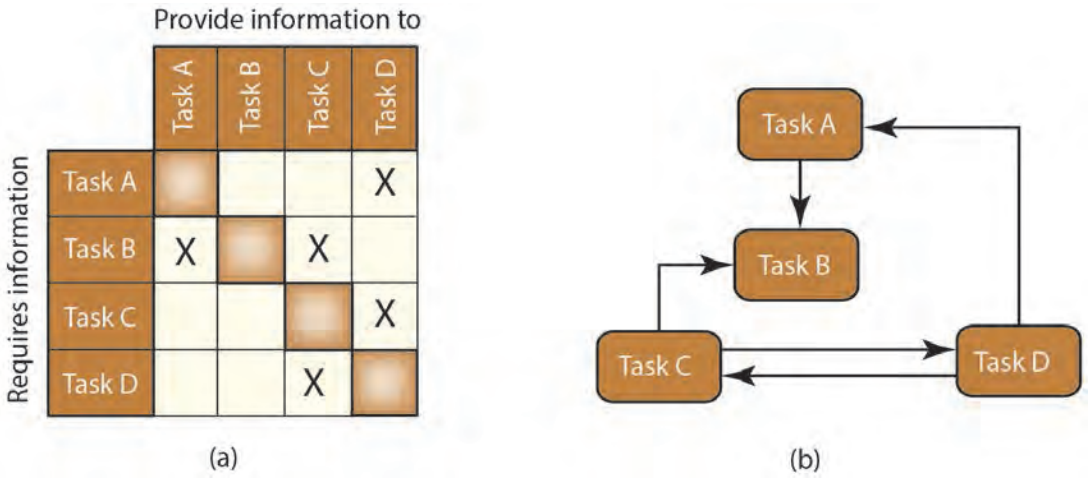


Figure 5.3: Dependencies among DSM elements.

DSM is the graphical representation of a matrix. An example of DSM is shown in Figure 5.3. It is a basic matrix used to show relationships of entities of one kind to another, for example, task to task.[8] A DSM is arranged by listing all tasks as rows and columns in a square $n \times n$ matrix, where n is the number of tasks. The tasks are placed in the matrix close to the order they should be completed. DSM can be symbolized as binary (shows the existence of a relation), or numerical (represents the strength of a relation). Note that diagonal elements have no significance in DSM.

Figure 5.3(b) shows a simple process consisting of four task activities which shows the corresponding information exchange patterns – which tasks provide input to others and which tasks are coupled and thus require iteration. For example, in Figure 5.3(a), A provides information to B and D provides information to A, and tasks C and D are coupled (cycle). In short,“ Xs” indicate column tasks and provide direct input to corresponding row tasks.

[8]Steward, D.V. The design structure system: A method for managing the design of complex systems. IEEE Transactions on Engineering Management, 1981, 28, 71–74.

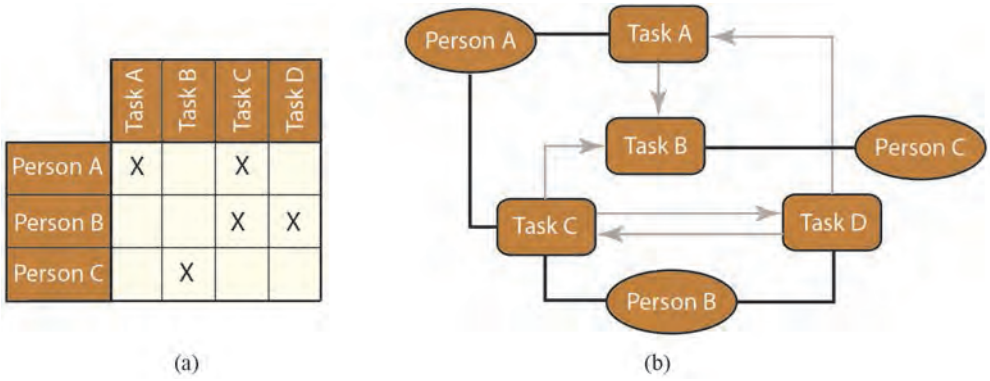


Figure 5.4: Domain mapping matrix.

Domain Mapping Matrices (DMM) shown in Figure 5.4(a) is an extension of DSM which includes domain mapping between two domains. For example, tasks to people or activities to people. Figure 5.4(b) shows how these people (team members) can be mapped to certain task activities. DMM is a rectangular matrix.

	Scheduling/ Planning	Risk Analysis	Production	Testing	Budget	. . .	. . .	. . .
John	A	R	A	A				
Mark	R				A			
Jesse			R					A
Person					R			
Person							R	
. . .						A		

Figure 5.5: Distributing responsibilities through domain mapping matrix.

Figure 5.5 shows the distributions of responsibilities to perform a design project. In this figure **R** indicates the responsible person who does the work to complete the task. **A** indicates that the person is finally accountable for the correct and thorough completion of the task (signs and approves the work that the responsible provides). Accountable could be a project leader.

Multiple Domain Matrix (MDM) which combines DSM and DMM was proposed by Eppinger and Salminen to show the interactions among different types of dependencies and domains as shown in Figure 5.6.[9]

[9]Eppinger, S.D., and Salminen, V., "Patterns of product development interactions," International Conference on engineering design, ICED 01, Glasgow, 21-23 August 2001.

The modeling of complex systems often requires the modeling of multiple domains with different aspects (people, activities, etc.). In complex system analysis, DSM can be limited to meet the demands of extensive information exchanges across the entire engineering system. MDM is used to model entire systems consisting of multiple domains, each having multiple elements, connected by different relationship types.[10] The MDM includes DSMs along its diagonal and DMMs outside the diagonal Figure 5.6.

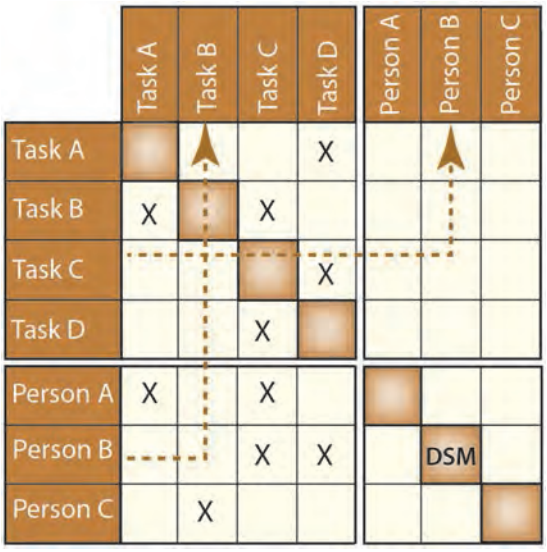


Figure 5.6: Multiple domain matrix.

5.3 Design Structure Matrix Partitioning

Figure 5.7 shows an example of partitioning for a matrix of twelve activities (tasks.)[11] Figure 5.7(a) shows the unpartitioned DSM in its initial form. As seen from Figure 5.7(a), task E requires information from tasks F, H, and K. Task B transfers information to tasks C, F, G, J, and K. Figure 5.7(b) shows the partitioned matrix after manipulated to move the "Xs" to lower triangle or move as close as possible to the diagonal of the matrix.

The process of the partitioning of a DSM is performed by reordering DSM rows and columns so that the new DSM turns out to be a block-diagonal matrix (i.e., lower triangular matrix). However, for complex engineering systems, it is difficult to have a lower triangular matrix by simple manipulation of rows and columns.[12] Above the diagonal of DSM (upper triangular matrix), marks of feedback or cycles are not desirable – require time-consuming iterations.

Once the DSM is partitioned as shown in Figure 5.7(b), tasks in series are identified and executed sequentially, and parallel tasks are executed concurrently. Execution of coupled tasks requires iteration by assuming a proper initial guess.

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[10]Maurer, M., Structural awareness in complex product design. Dissertation, Technischen Universität, München, Germany, 2007.

[11]Adapted from Yassine, A., and Braha, D., "Complex Concurrent Engineering and the Design Structure Matrix Method, Concurrent Engineering," *Research and Applications,'* Volume 11 Number 3, pp. 165-176, 2003.

[12]Moraes, N. A. Compreensão e Visualização de Projetos Orientados an Objetos com Matriz de Dependâncias, Universidade Federal da Bahia, 2007.

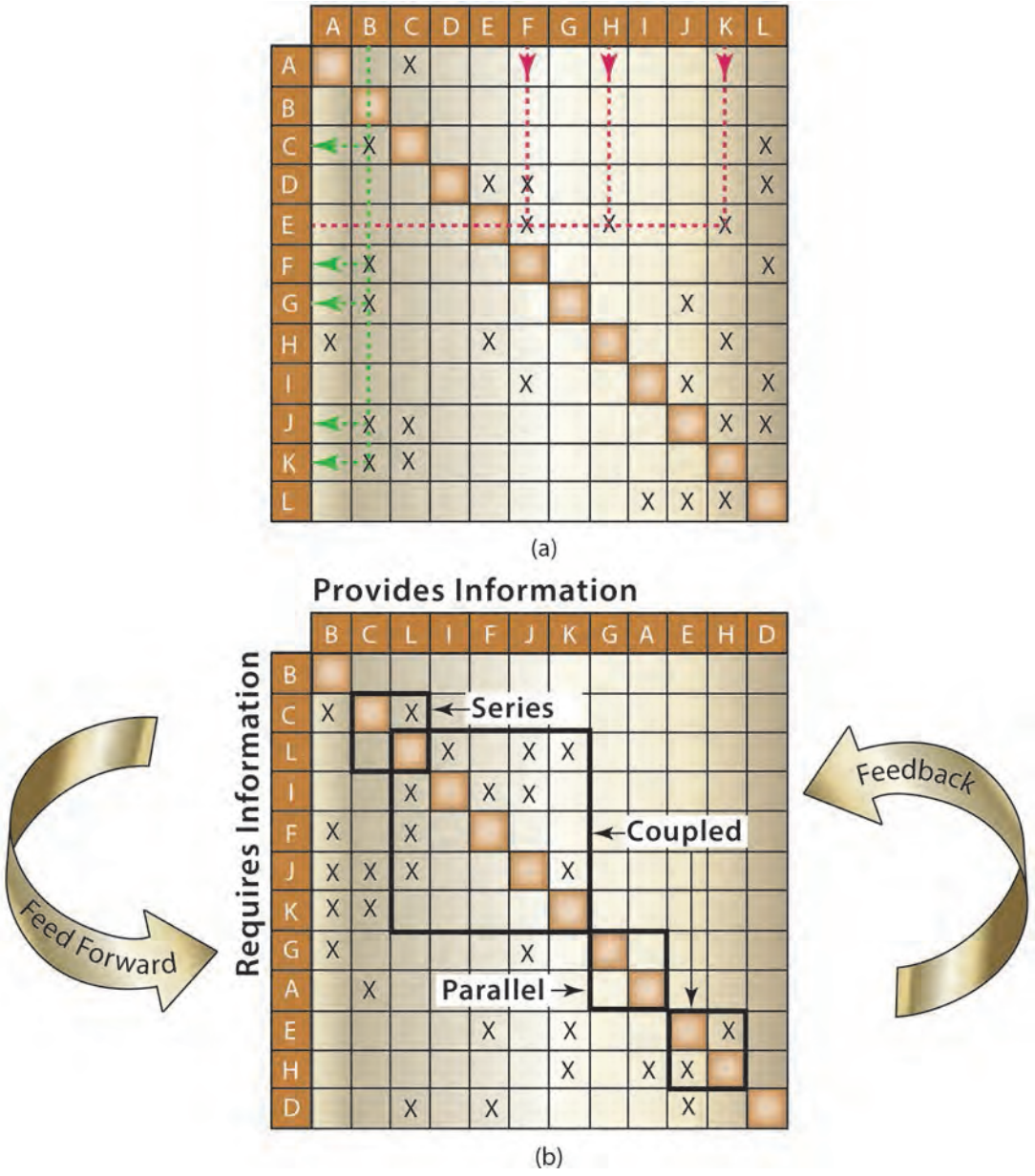


Figure 5.7: (a) Base DSM; (b) Partitioned DSM. (Adapted from Yassine, A., and Braha, D., "Complex Concurrent Engineering and the Design Structure Matrix Method, Concurrent Engineering," *Research and Applications,'* Volume 11 Number 3, pp. 165-176, 2003.)

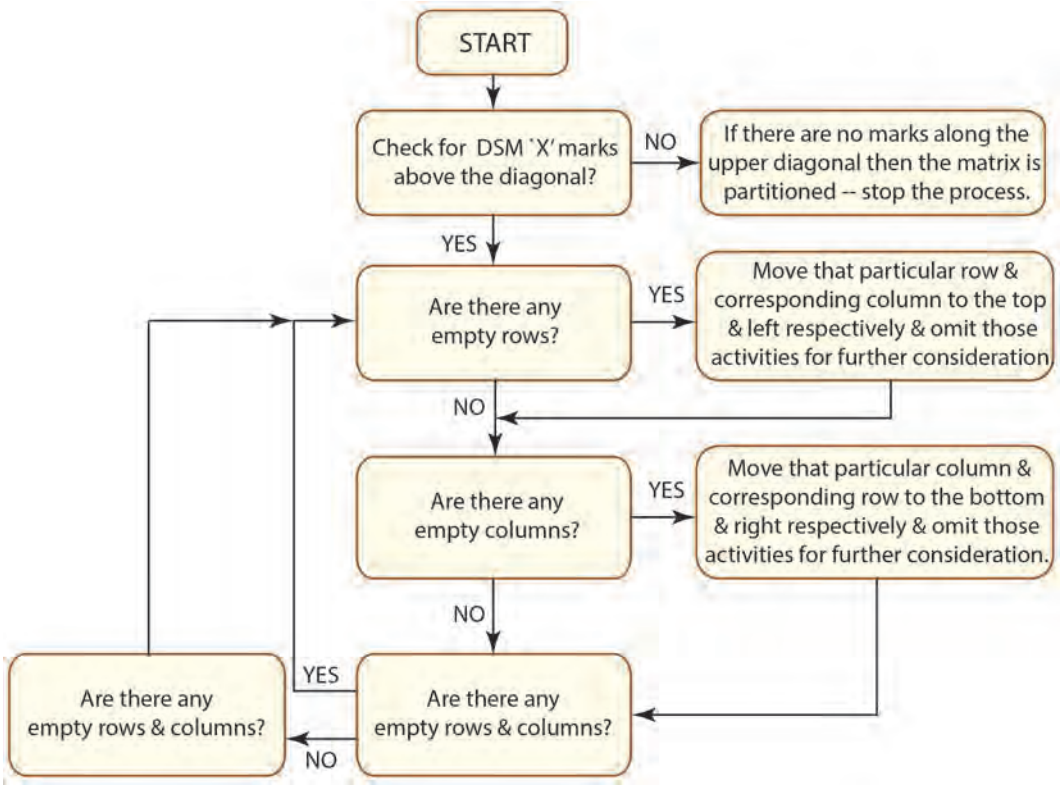


Figure 5.8: Process of partitioning of DSM.

As seen from the flowchart given in Figure 5.8, the steps for the partitioning process are given as follows:[13]

1. Check for the existence of any 'X' mark along the upper diagonal of the DSM matrix. If there are no marks along the upper diagonal then the matrix is partitioned. Hence, stop the procedure.
2. Check for empty rows in the DSM matrix and move all those empty rows to the top of the matrix and the corresponding columns to the left of the matrix and remove them from the DSM for further consideration.
3. For the remaining matrix, check for any empty columns and move all those empty columns to the right and the corresponding rows to the bottom of the DSM matrix and remove them from the DSM for further consideration.
4. Repeat steps 2 & 3 until there are no empty rows & columns in the DSM matrix.
5. Using the path searching method identify cycles/loops and collapse the elements involved in a single composite element then go to step 2.

[13]A. Ertas, (2018). *Transdisciplinary Engineering Design Process.* John Wiley &Sons, Inc.

5.3.1 Design Structure Matrix Tearing

Tearing is the process of reordering coupled tasks within a group (block) to find an initial ordering to start the iteration process.[14] Once coupled tasks are identified in a DSM, they are subjected to the next level of analysis – that is DSM *tearing*: identifying some of the feedback marks that have the least impact on the system design that can be removed from the matrix. Although tearing may help to reduce the complexity and size of the cluster and speed up the design process, the expense is a loss of information. That is why the number of tears should be kept to a minimum to avoid relying too much on initial guesses.

There is no optimal method exists for tearing, but when making tearing decisions the following criteria are recommend:[5,15]

- ***Minimal number of tears:*** Since tears represent an approximation or an initial guess to be used; it is advisable to reduce the number of guesses used in the tearing process.
- ***Limit tears to the smallest blocks along the diagonal:*** It is desirable to limit the inner iterations to a small number of tasks.

The process of tearing is based on guessing and assumptions. Thus, tearing should not be done unless necessary.[16]

5.3.2 Design Structure Matrix Banding

DSM banding is an alternative to DSM partitioning to identify the sets of independent (i.e. parallel or concurrent) elements.[17] As shown in Figure 5.9, alternating dark and light, there are five bands in the partitioned matrix. It is similar to partitioning the DSM using the Reachability Matrix Method without considering the feedback marks (a band corresponds to a level). As shown in Figure 5.9 (Yassine, 2004), each band consists of grouping activities that are independent and they do not depend on each other for information. For example, element 10 doesn't provide any information to element 5 and also element 5 doesn't require any information from element 10. Another example is, in row 5 there are three independent parameters and they do not depend on each other for information; therefore, they belong to the same band. The group of bands or levels within a DSM represents the critical path of the system. The fewer bands provide less concurrency and complexity in the project. A large number of bands indicates that the project is highly interdependent and complex.

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[14] G. Kron, 'Diakoptics', piecewise solution of large scale systems of equations. Ph.D. Thesis, University of Texas, Austin, 1963.

[15] Ali A. Yassine, "An Introduction to Modeling and Analyzing Complex Product Development Processes Using the Design Structure Matrix (DSM) Method," *Urbana,* Vol. 51, Issue: 9, pp. 1-17, 2004.

[16] Bartolomei, J., Cokus, M., Dahlgren, J., de Neufville, R., Maldonado, D., Wilds, J., Analysis, and applications of design structure matrix, domain mapping matrix, and engineering system matrix frameworks, Massachusetts Institute of Technology Engineering Systems Division, pp. 1-37

[17] Grose, David L., "Reengineering the Aircraft Design Process", Proceedings of the Fifth AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City Beach, FL, Sept. 7-9, 1994.

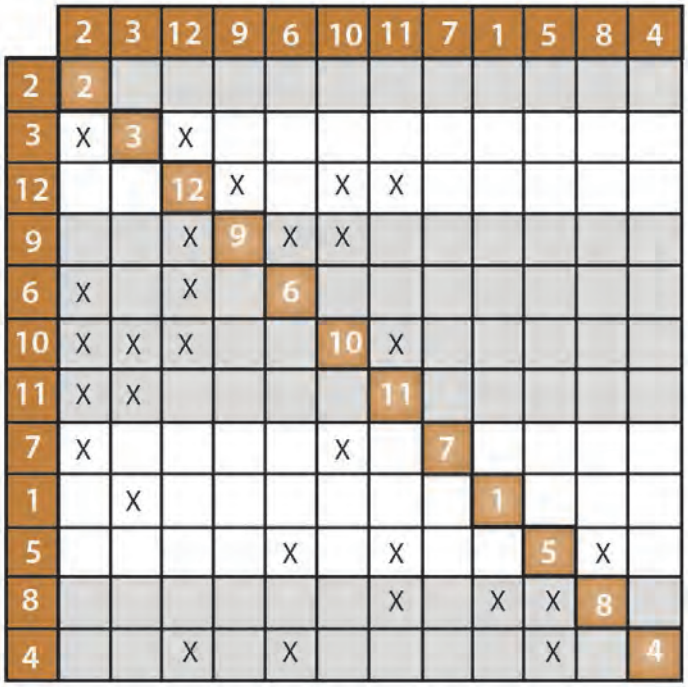


Figure 5.9: DSM Banding.

EXAMPLE 5.1

Figure 5.10 shows the relationships of four tasks. Using topological sorting and path searching method partition DSM matrix shown in Figure 5.10.

SOLUTION

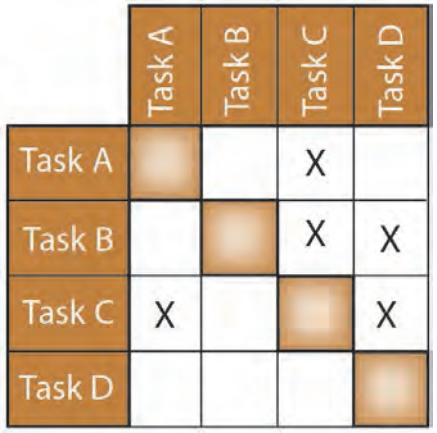


Figure 5.10: Unpartitioned DSM matrix.

As shown in Figure 5.10, there are four tasks in the upper triangular matrix. The following steps are used for partitioning the DSM matrix (see flowchart given by Figure 5.8):

(1) As shown DSM matrix in Figure 5.11 (a), Task D in row D is empty – this task does not require any information from any other task shown in the DSM matrix. Thus, schedule Task D to the top of the matrix and the corresponding column Task D to the left of the matrix and then remove it from the DSM. (see Figure 5.11(b) – row D and column D are blocked with dark black lines).

(2) As seen from Figure 5.11(b), Task B in column B is empty – for the same reason we mentioned in item(1), move Task B to the right, and the corresponding row B to the bottom of the DSM and remove them from the DSM for further consideration (see Figure 5.11(c) – column B and row B are blocked).

(3) Figure 5.11(c) shows that there are no more empty rows and empty columns left. There is a circle (cycle) between Task A and Task C. In other words, Task C provides information to Task A and Task A requires information from Task C. Since such a circle is identified and clustered on the diagonal of the DSM, the partitioning process ends. The final partitioned DSM matrix is shown in Figure 5.11(d). Note that, when rows and columns are reordered check for original relationships as in Figure 5.10 among the tasks remain the same.

EXAMPLE 5.1 (Continued)

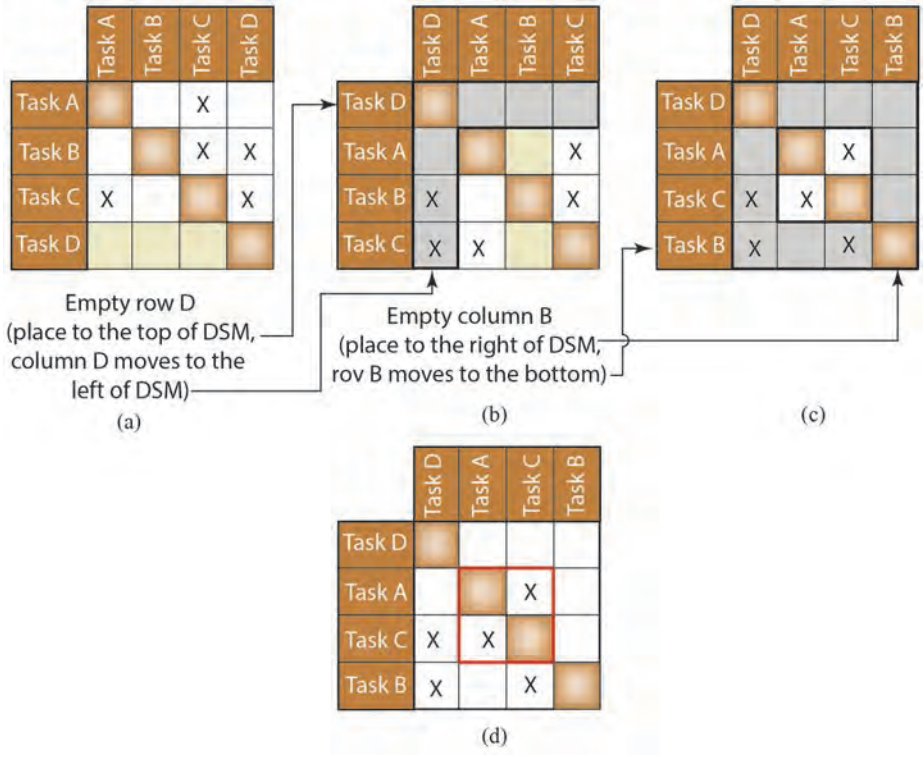


Figure 5.11: DSM partitioning.

EXAMPLE 5.2

Figure 5.12 shows the tasks rearrangement of Example 5.1. Using topological sorting and path searching method partition DSM matrix shown in Figure 5.12.

SOLUTION

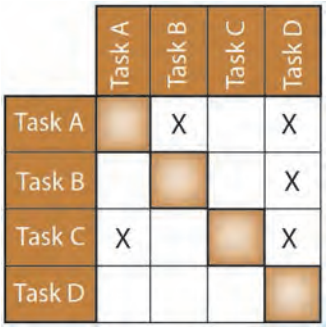


Figure 5.12: Unpartitioned DSM.

Following the same procedure as in Example 5.1, the partitioned DSM is given in Figure 5.13(d). As seen from the figure, the partitioned matrix is a lower triangle matrix. Therefore, all the tasks could run in the defined order without iterations.

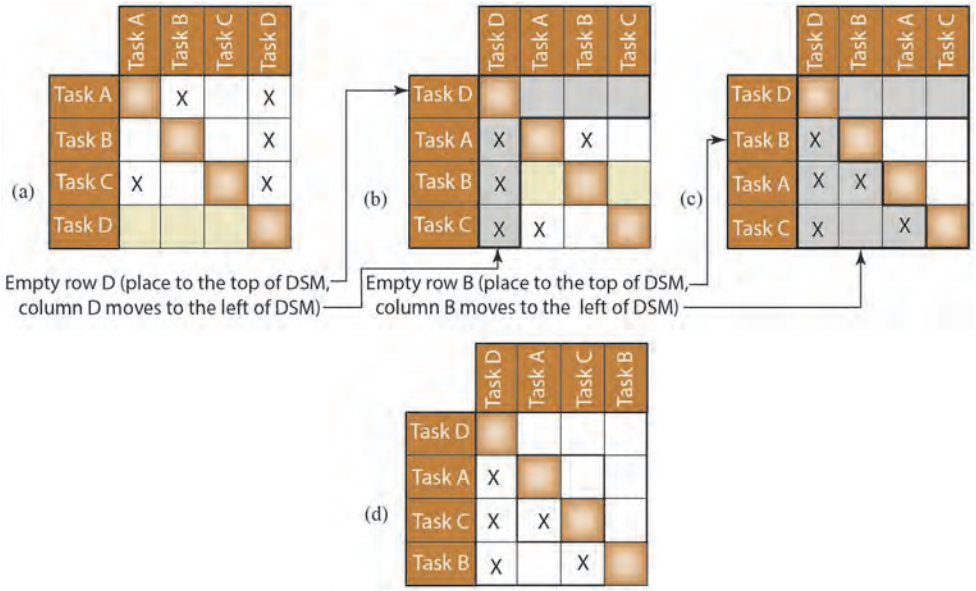


Figure 5.13: Partitioned DSM.

EXAMPLE 5.3

Assume that a team of seven students working on a design project. Use team-based DSM to show the information flow between the members within the sub-teams and the information flow (or interactions) among the sub-teams.

ANALYSIS

Team has following three sub-teams.

Team A = Members 1, 5, and 6

Team B = Members 4 and 5

Team C= Members 2, 3, 4, and 7

As shown in Figure 5.14, from the sub-team members list, the team-based DSM can be constructed. For example, from Team A team member 1 has a relationship with members 5 and 6 (see row #1 of DSM). Relationship of the team member 4 is through members 5 from Team B and also through members 2, 3, and 7 from Team C (see row # 4 of DSM).

	1	2	3	4	5	6	7
1					X	X	
2			X	X			X
3		X		X			X
4		X	X		X		X
5	X			X		X	
6	X				X		
7		X	X	X			

Figure 5.14: Rocket competition sub-team.

(a) **Partitioning**

DSM shown in Figure 5.14 can be partitioned to see the information flow among the team members within the sub-teams and the interactions between the sub-teams. For this case, we will manipulate rows and columns of the DSM shown in Figure 5.14 for the partitioning process to eliminate any feedback loops in the upper triangle of the matrix.

First, replace rows 2 and 3 with rows 5 and 6 as shown in Figure 5.15(b). This manipulation is logical because we would like to bring members of Team A together. Note that, the relationships of the members in the reorganized matrix remain the same as the original matrix.

EXAMPLE 5.3 (continued)

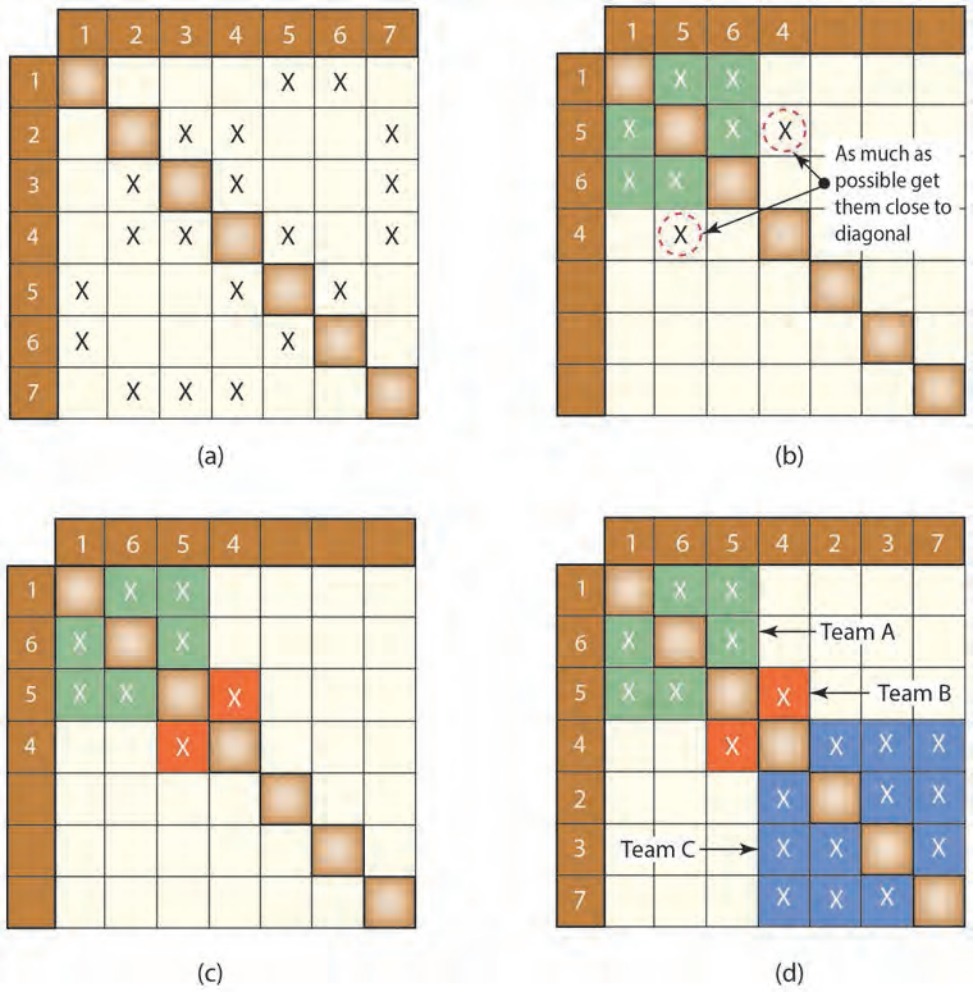


Figure 5.15: Sub-team partitioning.

Second step is to bring coupled entities 4 and 5 close to diagonal (see Figure 5.15(b)). To accomplish this, swap the places of row 5 and row 6 (see Figure 5.15(c)).

EXAMPLE 5.3 (continued)

The last step is to include remaining team members 2, 3, and 7 belonging to Team C. As seen from Figure 5.15(d), three teams are clustered along the diagonal of the DSM to highlight the inter-team interfaces. These clusters represent sub-team members that are closely interconnected. The exchange of information among the teams is also shown in Figure 5.15(d). Team B is the communication bridge between Team A and Team C, in other words interacting with Team A and also interacting with Team C.

(b) **Frequency of Team Interactions**

Figure 5.16 shows the frequency of interactions (daily, weekly, and monthly) within the teams and among the teams.

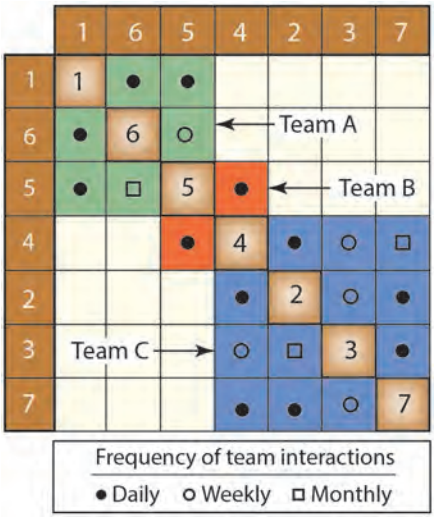


Figure 5.16: Frequency of team interactions.

In designing complex systems or products mistakes or failures can be avoided by making sure that team members or different teams responsible for development have the opportunity to communicate effectively.

Team members or teams working on a different part of a system or product must integrate their designs by frequent information exchange and communication with the other team members to make sure that the entire system or product will function properly as a whole.

EXAMPLE 5.3 (Continued)

(c) **Mapping the Teams to Project Activities**

it is important to map the team members to system or product development tasks as shown in Figure 5.17 – as an example, in this case, design and development, component testing, and manufacturing & documentation.

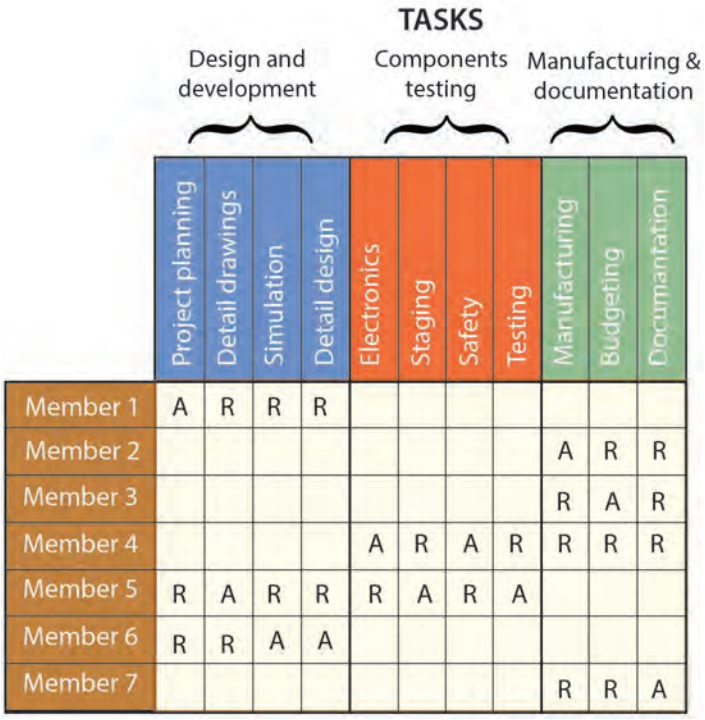


Figure 5.17: Responsibility assignment matrix.

In Figure 5.17, **"R"** designates a "Responsible" person who does the work to complete the task – they are responsible for the implementation of a project. Responsibility can be shared as shown in Figure 5.17. The degree of responsibility is assigned by the person who is "Accountable."

"A" designates the person finally accountable for the correct and thorough completion of the task (signs and approves the work that the responsible provides) – that is the person who is ultimately answerable for the decision to be made – the person who will take decisions and who will be blamed if something goes wrong?

EXAMPLE 5.3 (Continued)

In general, the manager of the project or office will be designated as the accountable person. However, as shown in Figure 5.17, there could be several accountable people for complex systems and product development. Usually, we should have a minimum number of people accountable for every task.

> "This is a story of four people named Everybody, Somebody, Anybody, and Nobody. There was an important job to be done and Everybody was asked to do it. Everybody was sure Somebody would do it. Anybody could have done it, but Nobody did it. Somebody got angry about that because it was Everybody's job. Everybody thought Anybody could do it, but Nobody realized that Everybody wouldn't do it. It ended that Everybody blamed Somebody when Nobody did what Anybody could have done."
>
> **Charles R. Swindoll**

5.4 Complex System Design

Although the definition of complex systems is very broad, for this module we will define complex systems as a system composed of many components which may interact with each other and contain feedback loops.

For example, consider a two-stroke marine engine power system shown in Figure 5.18. The 2-stroke marine engine is the main driving power source and also the largest machinery on a ship. A huge amount of effort, resources, and time is devoted to ensuring that this huge engine runs smoothly and efficiently, taking the ship from one port to another without failures. Considering the complexity and number of parts the 2-stroke marine engine power system has (see Figure 5.18), the operation of this system is not an easy task.

As seen from Figure 5.18, the 2-stroke marine engine power system has three sub-systems – fuel supply sub-system, steam supply sub-system, and fuel oil injection sub-system. Figure 5.19 shows a simplified version of two sub-systems, namely, the fuel supply sub-system and the steam supply sub-system. As seen from this figure, interactions within the sub-systems and among the sub-systems are evident. The next case study which will be presented in this section is good for describing and understanding the nature of those interactions.

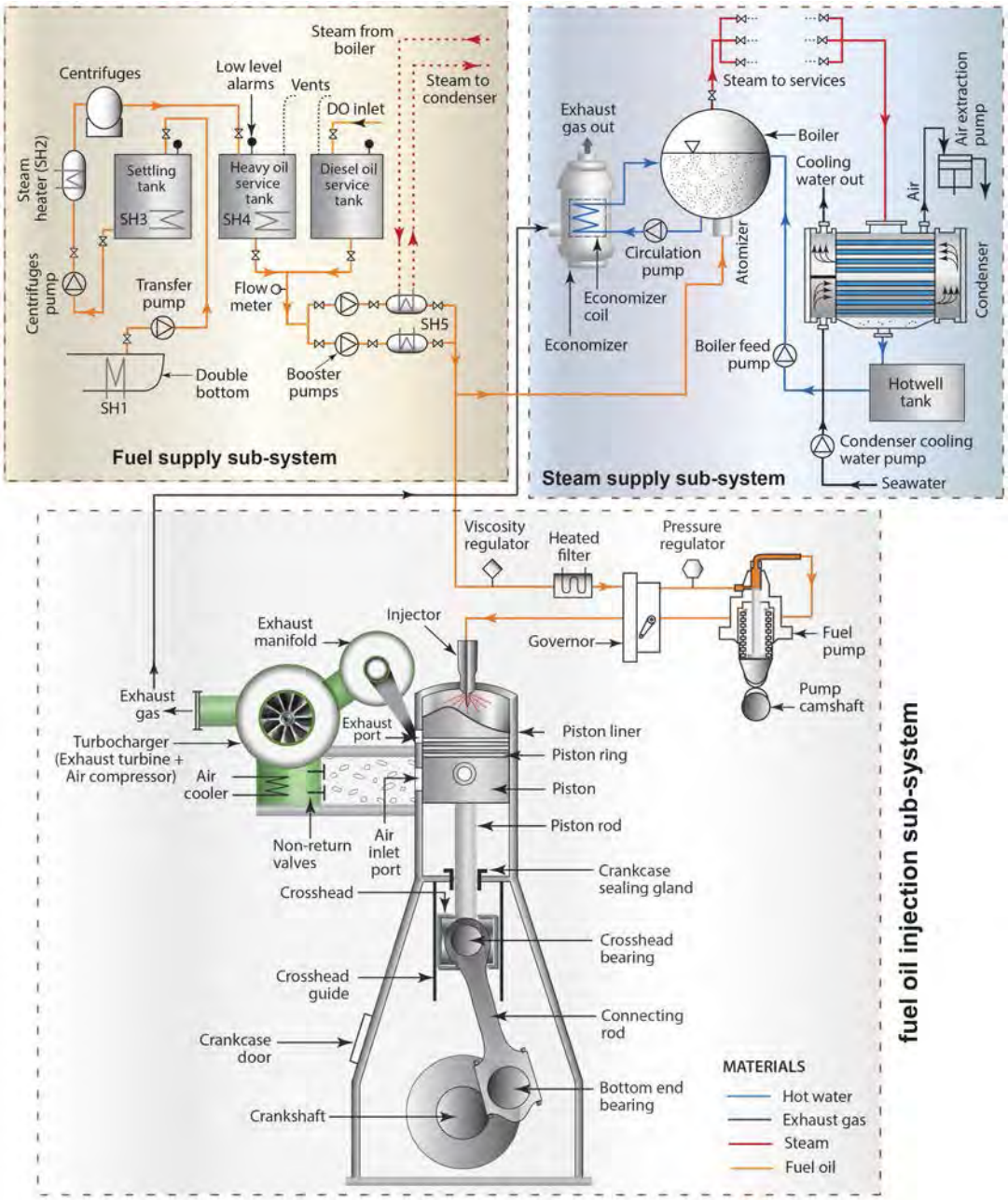


Figure 5.18: Two cycle marine diesel engine power system.

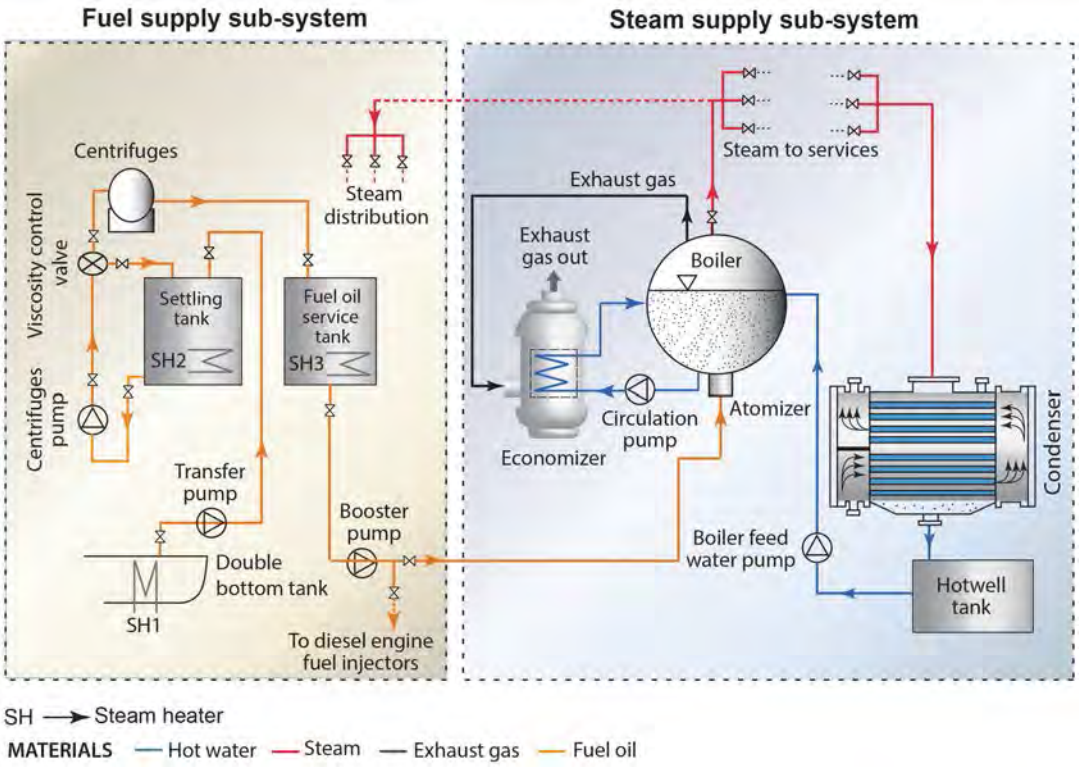


Figure 5.19: Fuel/Oil and boiler sub-systems.

CASE STUDY 5.1

Select the proper system components to design and build the sub-systems given in Figure 5.19 and investigate the interactions within and among the sub-systems. Complete the system analysis following Figure 5.20.[a]

ANALYSIS

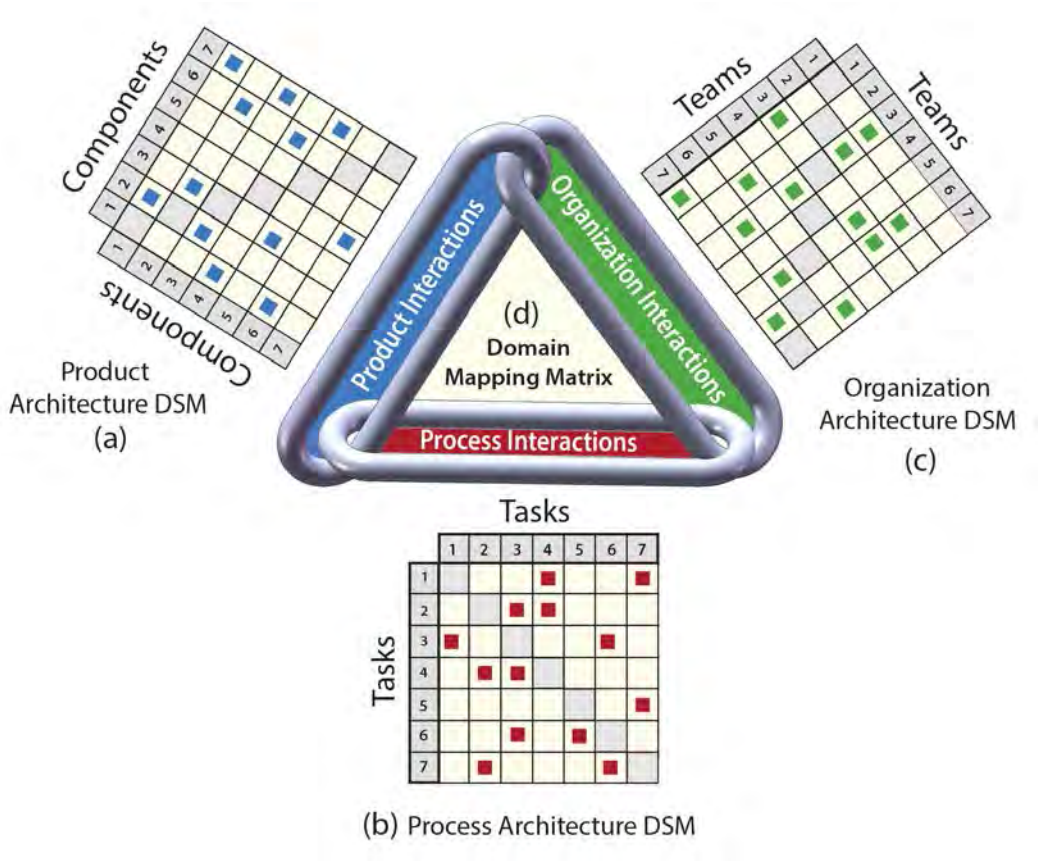


Figure 5.20: Creating DMMs from three basic DSMs.[b]

[a] Adapted from senior design project submitted to Dr. A. Ertas by Spencer Yancey, (2020). Two-Cycle Diesel Engine Power System. Mechanical Engineering Department. Texas Tech University.
[b] Adapted from Steven D. Eppinger and Tyson R. Browning, (2012). *Design Structure Matrix Methods and Applications.* The MIT Press Cambridge, Massachusetts London, England.

CASE STUDY 5.1 (continued)

(a) **Product (or system) Architecture DSM**

Using Figure 5.19, sixteen components that affect the functionality of the subsystems are identified for the analysis. Interactions between the components are designated by "numbers" instead of "X" marks in the DSM matrix as shown in Figure 5.21.

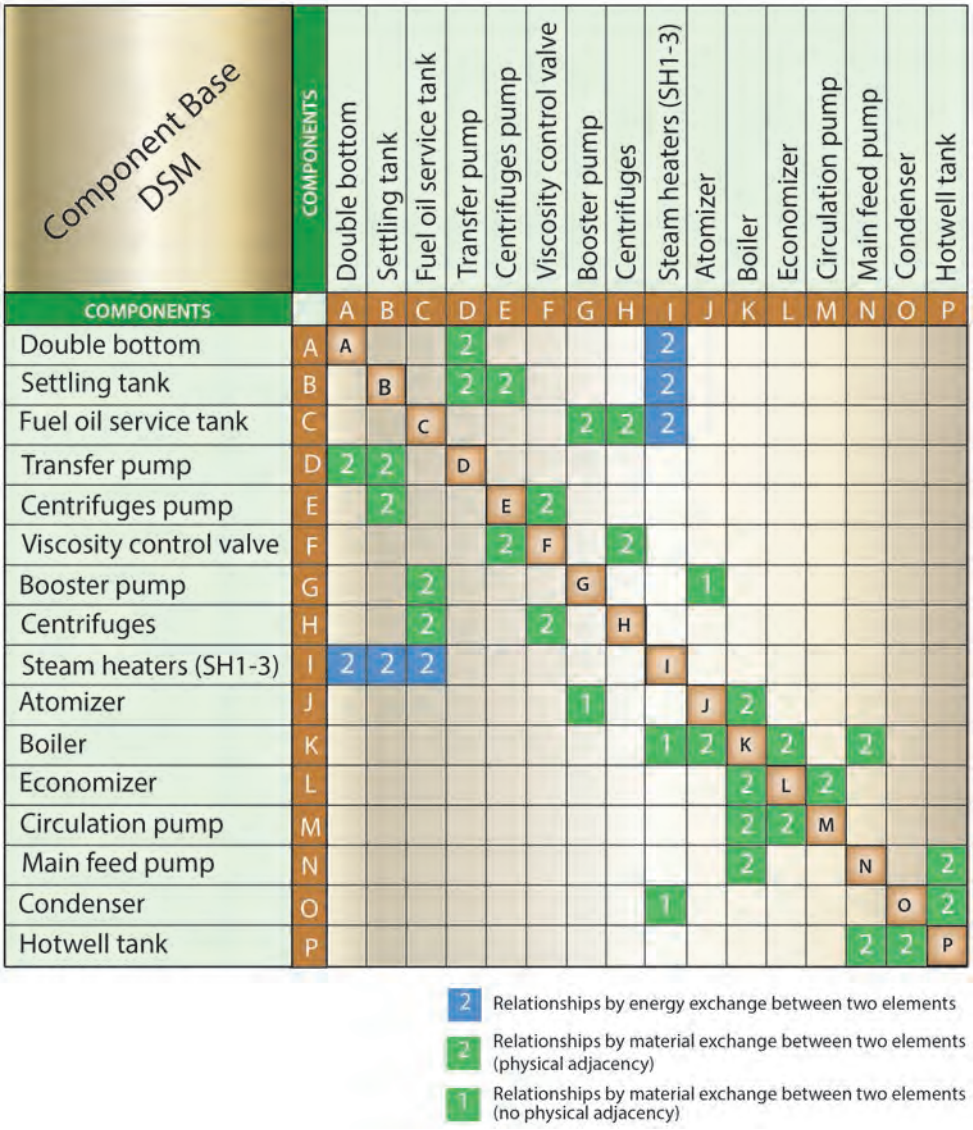


Figure 5.21: Product architecture DSM (identifies component interactions).

CASE STUDY 5.1 (continued)

Using Figure 5.21, partitioned matrix for the system components developed (see Figure 5.22. Different types of relationships between the components are defined in the legends of Figure 5.21 and Figure 5.22.

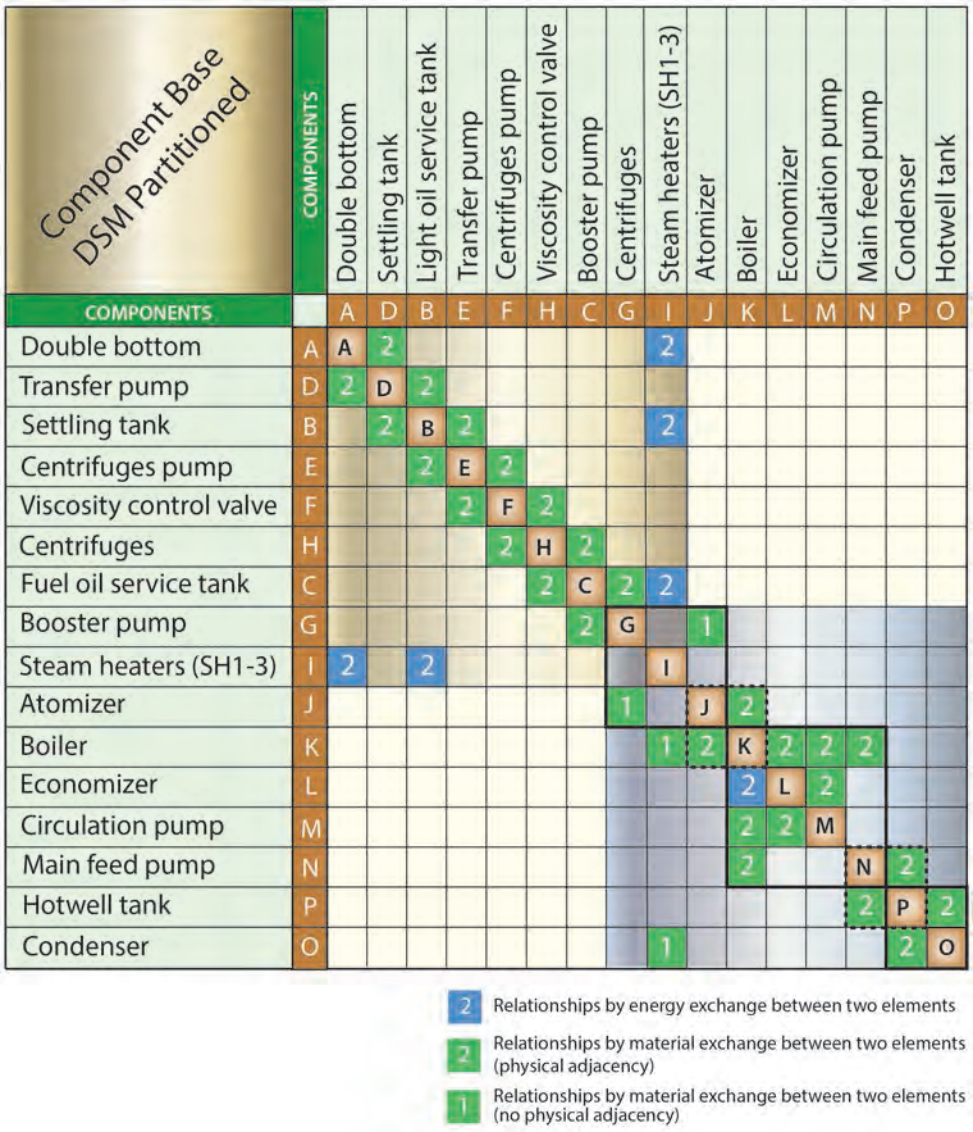


Figure 5.22: Sub-system components partitioned matrix.

CASE STUDY 5.1 (continued)

(b) **Process Architecture DSM**

Using Figure 5.19, tasks descriptions and requirements are defined as follows.

TASK DESCRIPTIONS

Component selections: Selection of a preexisting manufactured component or the selection of a bespoke design based on the fuel oil and water properties at that point in the system.

Steam Distribution: Determining the percentage of the boiler output that is going to be routed to specific tasks that rely on steam delivery (steam to services and steam distribution from the boiler).

Diesel Engine Requirement: Determining the fuel oil mixture properties that the diesel engine requires for optimum operation.

Viscosity Requirement: The monitoring of the fuel oil viscosity that each component needs for optimum performance and how the fuel oil viscosity changes as it travels through the system.

Overall System Efficiency: The determination of the ratio of system output (steam and exhaust) to system input (fuel oil and water) so that running cost can be estimated.

Overall System Flow Rate: The determination of the amount of fuel oil being consumed every hour so that the total time of operation per tank can be estimated. The determination of how much time passes from the commencement of boiler heating to max steam production occurring.

TASK INTERACTION DESCRIPTIONS (INFORMATION REQUIREMENTS)

Steam Distribution: None: The volume of steam needed by each service in the engine compartment and the steam heaters of the system is assumed to be known.

Diesel Engine Requirement: Note: The fuel oil properties required for the engine to combust optimally are assumed to be known.

Boiler Selection

Steam Distribution: The volume of steam required by each steam-dependent service dictates the output capability of the boiler.

Atomizer Selection: The heat generation capability of the atomizer will dictate the water volume of the boiler required so that an acceptable time interval passes from heat production to steam production.

CASE STUDY 5.1 (continued)

Steam Heater Selection

Steam Distribution:The higher the volume of steam output from the boiler not being sent to the steam heaters will increase the time interval from steam leaving the boiler to the steam heaters reaching their operating temperatures.

Boiler Selection: The performance of the boiler will dictate what kind of steam heaters must be selected; a good boiler will require cheaper steam heaters while a poor boiler will require more expensive steam heaters to make up for the boiler's shortcomings.

Atomizer Selection

Diesel Engine Requirement: The atomizer is fed fuel/oil in parallel with the diesel engine therefore the properties of the fuel/oil required by the diesel engine are going to dictate the combustion of the atomizer.

Boiler Selection: The size and shape of the boiler is going to dictate what kind of atomizer design will most efficiently heat the boiler through combustion.

Fuel Oil Pump Selections

Diesel Engine Requirement: The diesel engine will require fuel oil at a certain pressure for optimum combustion and efficiency.

Centrifuge Selection: The centrifuges will need to be supplied with fuel oil at a certain pressure for optimum separation to occur promptly.

Fuel Oil Tank Selection: The fuel oil must be pressurized enough to flow through the viscosity control valve, and centrifuges, and still fill the light oil service tank at the same rate fuel/oil leaves the tank to supply the diesel engine and atomizer.

Settling Tank Selection: The transfer pump selection is dictated by the settling rate of the highly viscous fuel/oil pumped out of the double bottom and must keep the tank full.

Centrifuge Selection

Fuel Oil Pump Selection: The centrifuges selected must be designed to operate at the incoming pressure and velocity of the fuel oil being pumped by the centrifuge pump for the optimum removal of impurities to occur.

Viscosity Requirement: The centrifuges must be selected to work with the viscosity of the fuel/oil at that point in the system because the viscosity of the fuel/oil will determine how fast they operate and how much wear they will experience.

CASE STUDY 5.1 (continued)

Fuel Oil Tank Selection

Diesel Engine Requirements: The fuel oil requirements of the diesel engine concerning viscosity and flow rate will dictate the size of the light oil tank to ensure that the fuel oil supply is constant. If the tank is too large the steam heater will not be able to maintain the fuel oil temperature needed for the required viscosity.

Atomizer Selection: The fuel oil tank will need to supply fuel oil to the atomizer at a constant flow rate and must be taken into consideration when selecting the size of the tank.

Viscosity Requirement: The viscosity of fuel oil entering the light oil tank must be within the allowable range for the steam heater to lower the viscosity further during the time interval until it is pumped out to the diesel engine and atomizer.

Viscosity Requirement

Diesel Engine Requirements, Atomizer Selection, Fuel/Oil Pump Selection, Centrifuge Selection, Light Oil Tank Selection, Settling Tank Selection.

The viscosity of the fuel oil entering the two tanks must be within an allowable range to allow the steam heaters acting on those tanks to lower the viscosity to an allowable exit value for the other components. The components supplied by the tanks are designed to operate optimally with a certain fuel oil viscosity and if that is not achieved the wear will be higher and the efficiency will be lower. The objective of the components is to deliver the correct fuel oil viscosity and pressure to the diesel engine and the atomizer and they must meet those requirements.

Settling Tank Selection

Diesel Engine Requirement: The settling tank must yield a high enough percentage of lowered viscosity fuel oil, from the double bottom, allowed through the viscosity control valve to continue to the diesel engine to meet the max requirement of the diesel engine. The volume of the tank and the flow rate must be large enough that the diesel engine receives its fuel oil requirement.

Fuel Oil Tank Selection: The fuel oil tank must maintain a level of fuel oil to allow for constant running for a specified number of hours and as such, the settling tank must keep up with the discharge rate of the light oil tank.

Viscosity Requirement: The viscosity of the fuel oil being pumped to the viscosity control valve must be low enough that an allowable minimum must be forwarded to the centrifuges to keep up with the flow rate demands of the diesel engine and atomizer.

CASE STUDY 5.1 (continued)

Economizer Selection

Boiler Selection: The economizer is used to increase the efficiency of the boiler and decrease the time needed for max steam production to occur by utilizing the atomizer exhaust gas to preheat the water in the boiler. The size of the economizer shall be determined by the size of the boiler since the economizer is supplementary to the boiler.

Atomizer Selection: The choice of atomizer dictates the flow rate and quality of heat to transfer via the exhaust gases following the combustion process that the economizer will utilize.

Condenser Selection

Steam Distribution: The amount of steam that the condenser will receive from the boiler will dictate its flow rate, size, and type needed to preserve as much heat in the water after the phase change process to maintain high efficiency.

Boiler Selection: The steam output properties from the boiler will dictate what type of condenser will be required to phase change the water back into liquid without overcooking it.

Hotwell Tank Selection

Boiler Selection: The volume of the boiler will dictate the size of the hotwell tank that is required. A smaller hotwell tank is desirable so less cooling will occur following condensation and more heat will be retained in the water as it is pumped back to the boiler.

Condenser Selection: The condenser limits the flow rate into the hotwell tank.

Feed Water Pump Selections

Boiler Selection: The circulation pump and main feed water pump control the volume of water present in the boiler. To regulate the temperature of the water in the boiler these two pumps need to work together to maintain a constant volume while steam leaves the boiler. The flow rate of steam leaving the boiler must be matched by the pumps feeding water to the boiler.

Economizer Selection: The economizer will require a certain flow rate of water from the circulation pump to raise the temperature of the water with the available heat from the exhaust gases.

Hotwell Tank Selection: The heat of the water pumped by the main feed-water pump from the hotwell tank may cause damage to pumps not designed to handle it and that must be considered.

CASE STUDY 5.1 (continued)

Overall System Efficiency

Steam Distribution, Diesel Engine Requirement, Steam Heater Selections, Atomizer Selection, Economizer Selection, and Condenser Selection: To estimate the efficiency of the complete system, the amount of fuel oil harvested from the double bottom minus the amount used by the diesel engine through the atomizer must be known. The exhaust gas volume and temperature from the combustion process used by the economizer and boiler must be known. The boiler and economizer water volume must be known as well as the heat transfer from the atomizer exhaust into those two volumes. The amount of steam produced by the boiler and sent to the steam heaters and the condenser must be known.

Overall System Flow Rate

Steam Distribution, Diesel Engine Requirement, Boiler Selection, Steam Heater Selections, Atomizer Selection, Fuel Oil Pump Selections, Centrifuge Selection, Viscosity Requirement, Economizer Selection, Condenser Selection, and Feed Water Pump Selections: To estimate the flow rate of fuel oil the selections of all fuel oil components must be known because the velocity, pressure, and viscosity of the fuel/oil will vary as it moves away from the double bottom. The flow rate at each component will enable the flow rate of the fuel oil from the double bottom to the atomizer to be calculated. The water flow rate will be determined in a similar manner using the water components so that the flow rate of water from the boiler to the steam heaters will be calculated.

CASE STUDY 5.1 (continued)

Using the aforementioned information, the task interaction matrix is developed as shown in Figure 5.23.

Task Interaction DSM	TASKS	Overall System Efficiency	Overall System Flow Rate:	Boiler Selection	Condenser Selection	Economizer Selection	Steam Distribution	Hotwell Tank Selection	Steam Heater Selection	Diesel Engine Requirement	Atomizer Selection	Centrifuge Selection	Settling Tank Selection	Fuel Oil Tank Selection	Fuel/Oil Pump Selections	Water Pump Selections	Viscosity Requirement
TASKS		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Overall System Efficiency	1	1			X	X	X		X	X	X						
Overall System Flow Rate	2		2	X	X	X	X		X	X	X	X			X	X	X
Boiler Selection	3			3			X				X						
Condenser Selection	4			X	4		X										
Economizer Selection	5			X		5					X						
Steam Distribution	6						6										
Hotwell Tank Selection	7			X	X			7									
Steam Heater Selection	8			X			X		8								
Diesel Engine Requirement	9									9							
Atomizer Selection	10			X						X	10						
Centrifuge Selection	11											11			X		X
Settling Tank Selection	12									X			12	X			X
Fuel Oil Tank Selection	13									X	X			13			X
Fuel/Oil Pump Selections	14									X		X	X	X	14		
Water Pump Selections	15			X		X		X								15	
Viscosity Requirement	16									X	X	X	X	X	X		16

Figure 5.23: Process architecture DSM (identifies tasks interactions).

CASE STUDY 5.1 (continued)

Partitioned form of Figure 5.23 is shown in Figure 5.24.

Task Base DSM Partitioned	TASKS	Steam Distribution	Diesel Engine Requirement	Boiler Selection	Atomizer Selection	Steam Heater Selection	Fuel Oil Pump Selections	Centrifuge Selection	Fuel Oil Tank Selection	Viscosity Requirement	Settling Tank Selection	Economizer Selection	Condenser Selection	Hotwell Tank Selection	Water Pump Selections	Overall System Efficiency	Overall System Flow Rate
TASKS		6	9	3	10	8	14	11	13	16	12	5	4	7	15	1	2
Steam Distribution	6	6															
Diesel Engine Requirement	9		9														
Boiler Selection	3	X		3	X												
Atomizer Selection	10		X	X	10												
Steam Heater Selection	8	X		X		8											
Fuel Oil Pump Selections	14		X				14	X	X		X						
Centrifuge Selection	11						X	11		X							
Fuel Oil Tank Selection	13		X		X				13	X							
Viscosity Requirement	16		X		X		X	X	X	16	X						
Settling Tank Selection	12		X						X	X	12						
Economizer Selection	5			X	X							5					
Condenser Selection	4	X		X									4				
Hotwell Tank Selection	7			X									X	7			
Water Pump Selections	15			X								X		X	15		
Overall System Efficiency	1	X	X		X	X						X	X			1	
Overall System Flow Rate	2	X	X	X	X	X	X	X		X		X	X		X		2

Figure 5.24: Partitioned tasks interaction matrix with loops clustered.

CASE STUDY 5.1 (continued)

Partitioning Process

Empty rows of Steam Distribution and Diesel Engine Requirements are moved to the top rows of the matrix and their corresponding columns are moved to the two left-most columns. Empty columns of Overall System Efficiency and Overall System Flow Rate are shifted to the last two columns and their corresponding rows are moved to the bottom two rows. The empty rows signify those tasks do not require information to be completed. The empty columns signify those tasks do not generate any information used by other tasks.

After five partitioning attempts the number of feedback marks above the main diagonal was reduced to seven. Feedback marks indicate tasks dependent on information from other tasks that must be completed beforehand or an iterative process based on estimations must be used until the error criteria is satisfied. The following tasks have feedback marks: Boiler Selection, Atomizer Selection, Fuel Oil Pump Selection, Centrifuge Selection, fuel Oil Tank Selection, and Viscosity Requirement. For instance, the task Boiler Selection must occur after the Steam Heater Selections and Atomizer Selection tasks have been completed. Alternatively, initial estimates for the steam heater and atomizer values may be used to select a boiler until the error criteria of the process reach an acceptable value.

Tasks without feedback marks possess forward marks below the main diagonal and can proceed without the completion of other tasks being required. While forward tasks do require information from other tasks to proceed, they can do so in sequence with each task as it is completed. For example, the Overall System Flow Rate can start as soon as information coming from any of its forward tasks becomes available and will be completed after the final proceeding task gives its information.

Minimizing feedback tasks is paramount to project efficiency since the greater number of iterations done will increase time usage and costs while waiting until other tasks are completed to start a task will do the same. The objective of partitioning is to minimize the number of feedback marks and thus reduce the number of feedback tasks. The development process interaction matrix is partitioned to achieve the least amount of feedback markers. A higher number of forwarding independent tasks will result in a more direct project progression and will reduce the time and costs required.

Partitioned Tasks Interaction Matrix Analysis: Tearing and Banding

Tasks 3 and 10 are interdependent or coupled therefore constant communication must occur between these two tasks. Multiple iterations may be required to complete both tasks after an initial assumption about one of them is made. The cluster loop of coupled tasks 14, 11, 13, 16, and 12 is the most complex and tedious part of the project. The highest number of iterations is going to occur with this cluster because of its size.

CASE STUDY 5.1 (continued)

Tearing-Case A: Tearing the feedback mark ("X" mark at the intersection of tasks 13 and 16 will be eliminated from the matrix) from task 13 will reduce the complexity and size of the cluster. But the number of tears should be kept to a minimum to avoid relying too much on initial guesses. Figure 5.25 shows the partitioned matrix after tearing. As seen from this figure, the complexity and size of the cluster reduced considerably compared with Figure 5.24.

Task Base DSM Partitioned After Tearing

TASKS		Steam Distribution	Diesel Engine Requirement	Atomizer Selection	Boiler Selection	Fuel Oil Tank Selection	Fuel Oil Pump Selections	Centrifuge Selection	Settling Tank Selection	Viscosity Requirement	Condenser Selection	Economizer Selection	Hotwell Tank Selection	Steam Heater Selection	Water Pump Selections	Overall System Efficiency	Overall System Flow Rate
TASKS		6	9	10	3	13	14	11	12	16	4	5	7	8	15	1	2
Steam Distribution	6	6															
Diesel Engine Requirement	9		9														
Atomizer Selection	10		X	10	X												
Boiler Selection	3	X		X	3												
Fuel Oil Tank Selection	13		X	X		13											
Fuel Oil Pump Selections	14		X			X	14	X	X								
Centrifuge Selection	11						X	11		X							
Settling Tank Selection	12		X			X			12	X							
Viscosity Requirement	16		X	X		X	X	X	X	16							
Condenser Selection	4	X			X						4						
Economizer Selection	5			X	X							5					
Hotwell Tank Selection	7				X						X		7				
Steam Heater Selection	8	X			X									8			
Water Pump Selections	15				X							X	X		15		
Overall System Efficiency	1	X	X	X							X	X		X		1	
Overall System Flow Rate	2	X	X	X	X		X	X		X	X	X		X	X		2

Figure 5.25: Partitioned tasks interaction matrix after tearing.

CASE STUDY 5.1 (continued)

Figure 5.26 shows the banding of partitioned matrix shown in Figure 5.25.

Task Base DSM Partitioned After Tearing

TASKS		Steam Distribution	Diesel Engine Requirement	Atomizer Selection	Boiler Selection	Fuel Oil Tank Selection	Fuel Oil Pump Selections	Centrifuge Selection	Settling Tank Selection	Viscosity Requirement	Condenser Selection	Economizer Selection	Hotwell Tank Selection	Steam Heater Selection	Water Pump Selections	Overall System Efficiency	Overall System Flow Rate
TASKS		6	9	10	3	13	14	11	12	16	4	5	7	8	15	1	2
Steam Distribution	6	6															
Diesel Engine Requirement	9		9														
Atomizer Selection	10		X	10	X												
Boiler Selection	3	X		X	3												
Fuel Oil Tank Selection	13		X	X		13											
Fuel Oil Pump Selections	14		X			X	14	X	X								
Centrifuge Selection	11						X	11		X							
Settling Tank Selection	12		X			X			12	X							
Viscosity Requirement	16		X	X		X	X	X	X	16							
Condenser Selection	4	X			X						4						
Economizer Selection	5			X	X							5					
Hotwell Tank Selection	7				X						X		7				
Steam Heater Selection	8	X			X									8			
Water Pump Selections	15				X							X	X		15		
Overall System Efficiency	1	X	X	X							X	X		X		1	
Overall System Flow Rate	2	X	X	X	X		X	X		X	X	X		X	X		2

Figure 5.26: Banding of partitioned matrix.

CASE STUDY 5.1 (continued)

Tearing-Case B: In this case, a different approach is used for tearing – removing the same feedback mark, "X", from the large cluster but keeping it in the matrix (not eliminating it from the matrix as we did in case A). This process may help to reduce the loss of information. Figure 5.27 shows the partitioned matrix after tearing. Following the tearing process, Task 13 can be completed before the tasks in the large cluster but the looping in the cluster is still problematic. Task 16 is causing the most problems because it has the most feedback marks. An assumption that Task 16 should be ignored until the selection of all fuel oil components have been selected seems like the best solution. Task 16 is an assurance task to double-check the component selections against the viscosity needed by connected components. Table 5.5 provides a potential algorithm to finish all tasks.

Task Base DSM Partitioned After Tearing	TASKS	Steam Distribution	Diesel Engine Requirement	Boiler Selection	Atomizer Selection	Steam Heater Selection	Fuel Oil Tank Selection	Viscosity Requirement	Fuel Oil Pump Selections	Centrifuge Selection	Settling Tank Selection	Economizer Selection	Condenser Selection	Hotwell Tank Selection	Water Pump Selections	Overall System Efficiency	Overall System Flow Rate
TASKS		6	9	3	10	8	13	16	14	11	12	5	4	7	15	1	2
Steam Distribution	6	6															
Diesel Engine Requirement	9		9														
Boiler Selection	3	X		3	X												
Atomizer Selection	10		X	X	10												
Steam Heater Selection	8	X		X		8											
Fuel Oil Tank Selection	13		X		X		13	X									
Viscosity Requirement	16		X		X		X	16	X	X	X						
Fuel Oil Pump Selections	14		X				X		14	X	X						
Centrifuge Selection	11							X	X	11							
Settling Tank Selection	12		X				X	X			12						
Economizer Selection	5			X	X							5					
Condenser Selection	4	X		X									4				
Hotwell Tank Selection	7			X									X	7			
Water Pump Selections	15			X								X		X	15		
Overall System Efficiency	1	X	X		X	X						X	X			1	
Overall System Flow Rate	2	X	X	X	X	X	X	X		X		X	X		X		2

Figure 5.27: Partitioned tasks interaction matrix after tearing.

CASE STUDY 5.1 (continued)

Table 5.5: Suggested task completion sequence.

Executed	Task(s) #	Reasoning
1st	6 and 9	Do not require any input but affect twelve other tasks.
2nd	3	6 is completed. Iterate assuming that 8 will be the most efficient option and reiterate if the boiler meets the steam requirements.
3rd	10	9 is completed and the iteration result for 3 will be checked.
4th	8, 5, and 4	6, 3, and 10 have been completed.
5th	7	3 and 4 have been completed.
6th	15 and 1	6, 9, 3, 10, 8, 5, 4, and 7 have been completed.
7th	13	9 and 10 have been completed. Iterate assuming the steam heater will be capable of providing the correct exit viscosity to the fuel oil inside the light oil tank.
8th	14a and 12	14a being the selection of the booster pump since all components interacting with it have been selected. The choice of the settling tank must reflect the size of the light oil tank which is known. Iterate assuming the steam heater will be capable of providing the correct exit viscosity to the fuel/oil inside the settling tank.
9th	14b and 11	14b being the selection of the centrifuges pump since that will influence the centrifuge type selected. Choose the cheapest type of centrifuge and assume that the inlet viscosity will be acceptable.
10th	14c and 16	14c being the selection of the transfer pump since it is the only pump left. Calculate the fuel oil viscosity at the inlet and outlet of all components to see if assumptions are acceptable or if another iteration is required.
Last	2	Requires the most inputs but is not required by other tasks.

CASE STUDY 5.1 (continued)

(c) **Organization Architecture DSM**

Once the task interactions and sequencing has been completed the research team(s) will be created to take responsibility for the tasks to be executed. The interactions between components and tasks are used to construct the team matrix. Clusters of team interactions can be used from meta-teams which are teams comprised of teams. The cluster relating Boiler Selection and Atomizer Selection shows a likely connection between the two meta-teams. Fuel oil and water component interactions can form two meta-teams quite easily. The nature of the interaction of the teams will be divided into daily, weekly, and once. The interaction between the teams will be an information exchange about the project tasks.

Team Interaction Matrix Analysis

As shown in Figure 5.28, two meta-teams of water (blue) and Fuel Oil (orange) have been created and partitioned together. The partitioning of the groups together necessitated moving an empty row (Diesel Engine Requirements) away from the top of the matrix. The teams that receive information from an empty row only need to meet once to receive the information needed to start their task. Therefore, the Steam Distribution and Diesel Engine Requirement teams will give their information to the teams that need it to begin their task at the beginning of the project. Overall System Efficiency and Overall System Flow Rate are dependent on final information from the other teams and will meet once with each upstream team after their upstream task. Teams within the same meta-team responsible for tasks that interact via component linkages will meet daily. For instance, Boiler Selection will meet Steam Heater Selection, Condenser Selection, Water Pump Selection, and Economizer Selection daily. Teams with tasks interacting with Viscosity Requirements will meet weekly to check if their iterations completed with assumptions about viscosity requirements are acceptable. Teams that interact across the two meta-teams (Atomizer Selection/Economizer Selection and Atomizer Selection/Boiler Selection) will meet weekly to share information. Quickly deciding on an atomizer and boiler will be the crucial step to project progression within each meta-team and project completion.

CASE STUDY 5.1 (Continued)

Team Base DSM

TASKS		Steam Distribution	Boiler Selection	Steam Heater Selection	Condenser Selection	Water Pump Selections	Economizer Selection	Hotwell Tank Selection	Diesel Engine Requirement	Atomizer Selection	Fuel Oil Tank Selection	Fuel Oil Pump Selections	Viscosity Requirement	Centrifuge Selection	Settling Tank Selection	Overall System Efficiency	Overall System Flow Rate
TASKS		6	3	8	4	15	5	7	9	10	13	14	16	11	12	1	2
Steam Distribution	6	6															
Boiler Selection	3	O	3							W							
Steam Heater Selection	8	O	D	8													
Condenser Selection	4	O	D		4												
Water Pump Selections	15		D			15	D	D									
Economizer Selection	5		D				5			W							
Hotwell Tank Selection	7		W		D			7									
Diesel Engine Requirement	9								9								
Atomizer Selection	10		W						O	10							
Fuel Oil Tank Selection	13								O	D	13		W				
Fuel Oil Pump Selections	14								O		D	14		D	D		
Viscosity Requirement	16								O	W	W	W	16	W	W		
Centrifuge Selection	11											D	W	11			
Settling Tank Selection	12								O		W		W		12		
Overall System Efficiency	1	O		O	O		O		O	O						1	
Overall System Flow Rate	2	O	O	O	O	O	O		O	O		O	O	O			2

O → Once D → Daily W → Weekly

Figure 5.28: Organization (team) interactions matrix.

CASE STUDY 5.1 (continued)

(d) **Domain Mapping Matrix**

To show the interactions between two domains (task and person responsible) DMM (Domain Mapping Matrix) will be used. Rows will represent individuals responsible for tasks and columns will represent tasks. This will be used to select group leaders and dictate the minimum personnel required at meetings between teams. Group leaders will do so by choosing individuals that have the most interactions. The Team DSM will be used as a starting point for the DMM construction however limiting the number of person/task interactions will modify it. As shown in Figure 5.29, each person will have two tasks, a primary task (indicated by a 1) and a secondary task (indicated by a 2). A primary task entails that person being the responsible party for that task's completion. A secondary task entails that person giving and receiving information from another person about their primary task. Secondary tasks pass information from person to person and then from team to team to complete each task and the project as a whole.

Domain Mapping Matrix Analysis

Boiler Selection and Atomizer Selection both have interactions with the most people. The two individuals with Boiler Selection and Atomizer Selection as their primary tasks will be the meta-team leaders (B and I). A certain amount of iterations will be unavoidable due to the coupled nature of Boiler Selection and Atomizer Selection. Person B and Person I will meet every week to share information from their teams. Viscosity Requirement, Overall System Flow Rate, and Fuel Oil Pump Selections have the second most people involved. These tasks interact with the most component selection tasks and require the second most information exchange other than Atomizer Selection and Boiler Selection. The teams selecting components directly connected will share information with the leader responsible for the task who will meet with the leader of the other component, this will occur daily as dictated by the Development Organization Interactions Matrix. Each week the leaders of each task team will meet with the meta-team leader and exchange information. This process shall continue until project completion.

CASE STUDY 5.1 (Continued)

DMM	TASKS	Steam Distribution	Boiler Selection	Steam Heater Selection	Condenser Selection	Water Pump Selections	Economizer Selection	Hotwell Tank Selection	Diesel Engine Requirement	Atomizer Selection	Fuel Oil Tank Selection	Fuel Oil Pump Selections	Viscosity Requirement	Centrifuge Selection	Settling Tank Selection	Overall System Efficiency	Overall System Flow Rate
Person		6	3	8	4	15	5	7	9	10	13	14	16	11	12	1	2
Team Member	A	1	2														
Team Member	B		1							2							
Team Member	C		2	1													
Team Member	D		2		1												
Team Member	E					1											2
Team Member	F		2				1										
Team Member	G					2		1									
Team Member	H								1	2							
Team Member	I		2							1							
Team Member	J										1		2				
Team Member	K											1					2
Team Member	L												1	2			
Team Member	M											2		1			
Team Member	N												2		1		
Team Member	O									2						1	
Team Member	P											2					1

1 → Primary Task 2 → Secondary Task

Figure 5.29: Domain Mapping Matrix (DMM).

CASE STUDY 5.1 (continued)

Note that, sequencing of the DSM rows and columns can have a different form such that the new DSM partition can be different than Figure 5.24. This does not mean that the previous partitioning is wrong – the solution is dependent on the sequencing of the DSM rows and columns. For example, Figure 5.30 is another partitioned solution for the same problem. When we check both partitioned Figure 5.24 and Figure 5.30, they both have the same original relationships shown in Figure 5.23. This means that both solutions are correct. However, Figure 5.24 shows a better solution with fewer "X" marks in the upper triangle.

Task Base DSM Partitioned	TASKS	Steam Distribution	Diesel Engine Requirement	Atomizer Selection	Boiler Selection	Centrifuge Selection	Fuel Oil Pump Selections	Settling Tank Selection	Fuel Oil Tank Selection	Viscosity Requirement	Condenser Selection	Economizer Selection	Hotwell Tank Selection	Steam Heater Selection	Water Pump Selections	Overall System Efficiency	Overall System Flow Rate
TASKS		6	9	10	3	11	14	12	13	16	4	5	7	8	15	1	2
Steam Distribution	6	6															
Diesel Engine Requirement	9		9														
Atomizer Selection	10		X	10	X												
Boiler Selection	3	X		X	3												
Centrifuge Selection	11					11	X			X							
Fuel Oil Pump Selections	14		X			X	14	X	X								
Settling Tank Selection	12		X					12	X	X							
Fuel Oil Tank Selection	13		X	X					13	X							
Viscosity Requirement	16		X	X		X	X	X	X	16							
Condenser Selection	4	X			X						4						
Economizer Selection	5			X	X							5					
Hotwell Tank Selection	7				X						X		7				
Steam Heater Selection	8	X			X									8			
Water Pump Selections	15				X							X	X		15		
Overall System Efficiency	1	X	X	X							X	X		X		1	
Overall System Flow Rate	2	X	X	X	X	X	X			X	X	X		X	X		2

Figure 5.30: New partitioned matrix.

CHAPTER 6

Axiomatic Design (AD)

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 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 were 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 has been designed. In this domain, Process Variables (PV) will be determined which will allow us to implement the design parameters that have been chosen.

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.

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[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.

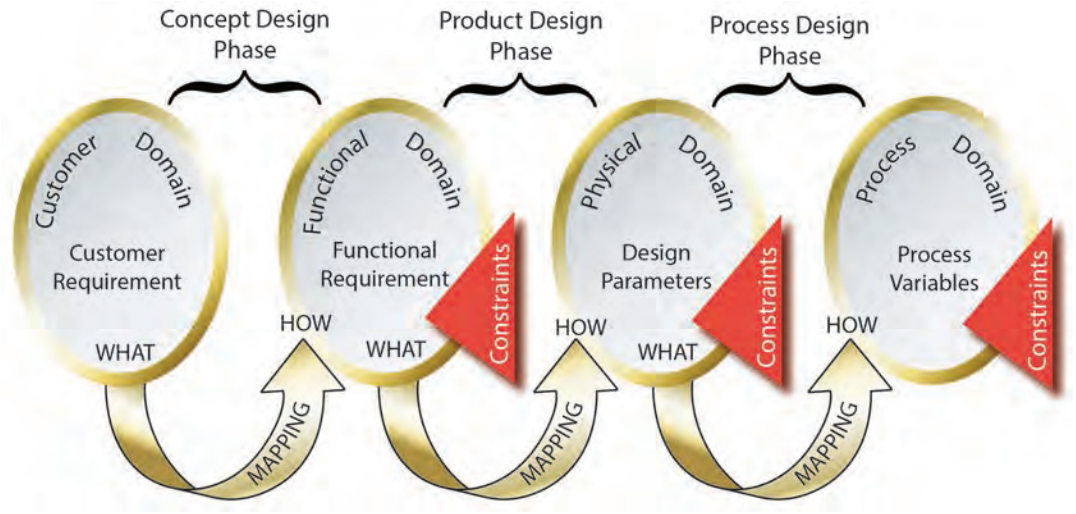


Figure 6.1: Four domains of the design.

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

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

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

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

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 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]

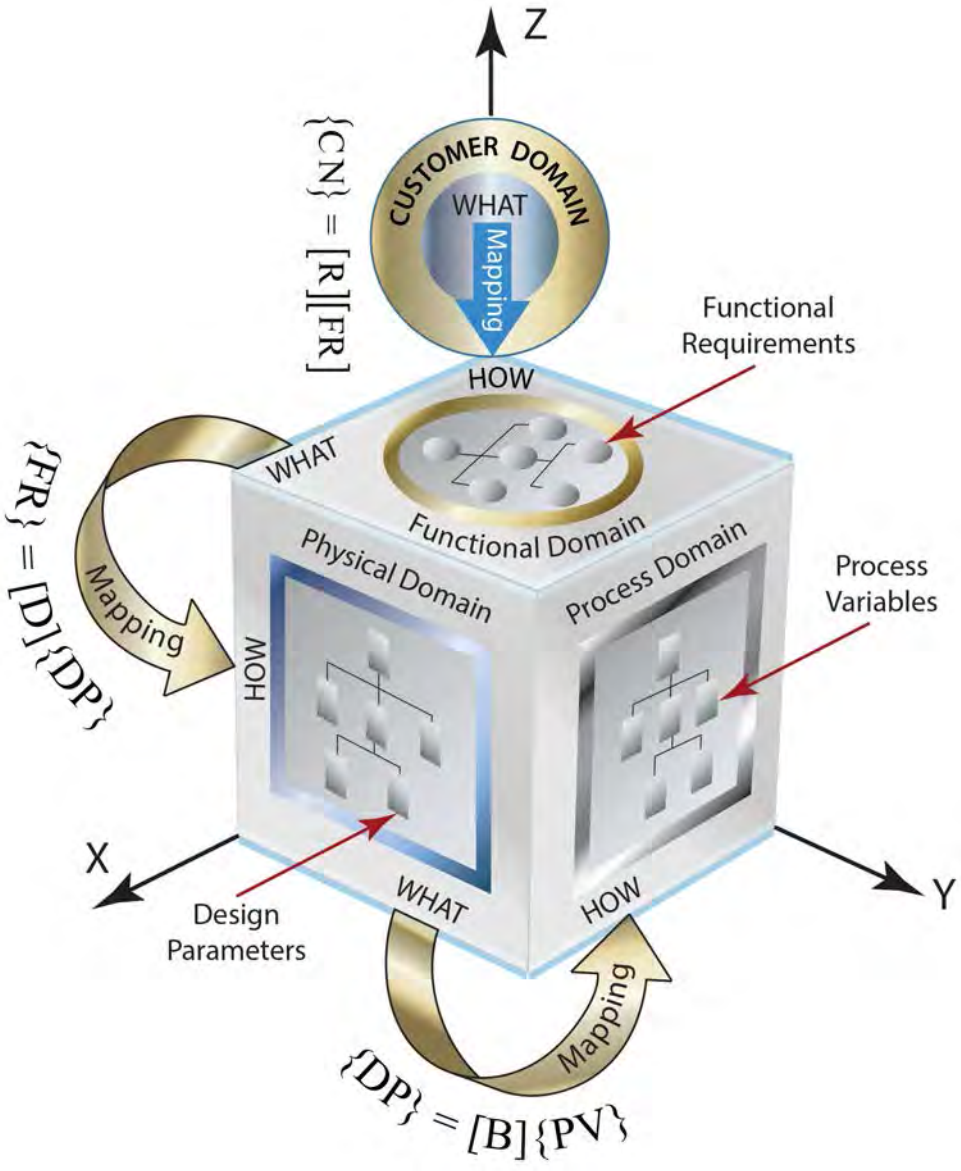


Figure 6.2: Design domains.

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.

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

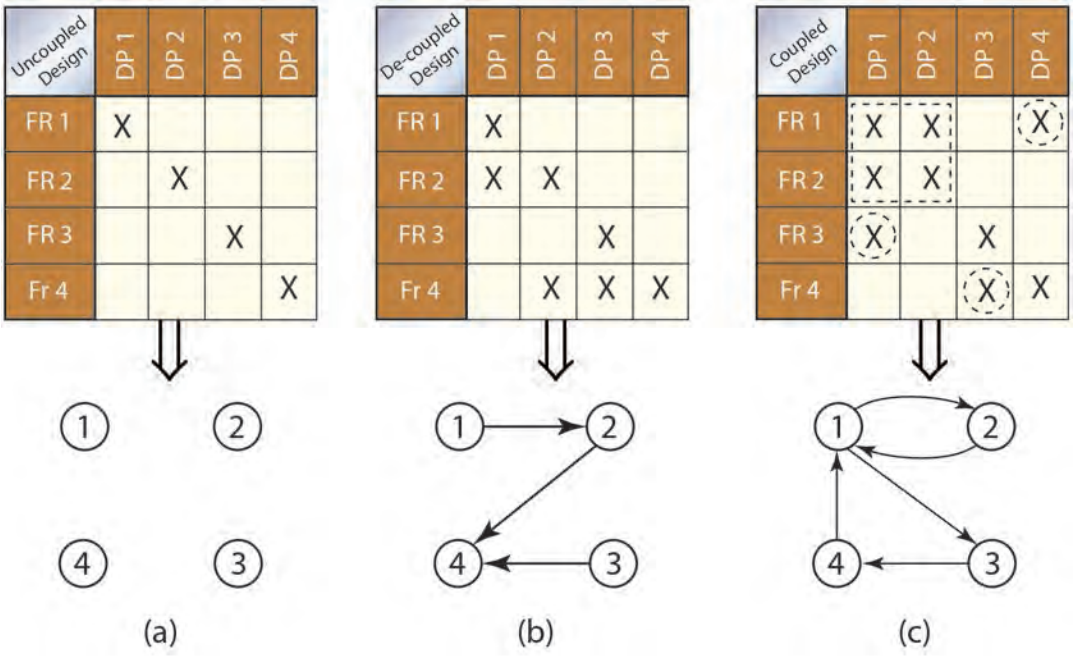


Figure 6.3: (a) Uncoupled design, (b) De-coupled design, (c) Coupled design.

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) representing 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. 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 – minimizing 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.

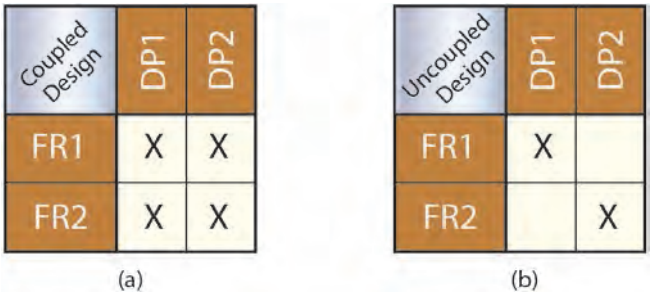


Figure 6.5: (a) Coupled design, (b) Uncoupled design.

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 in the "what" domain and go to the "how" domain.

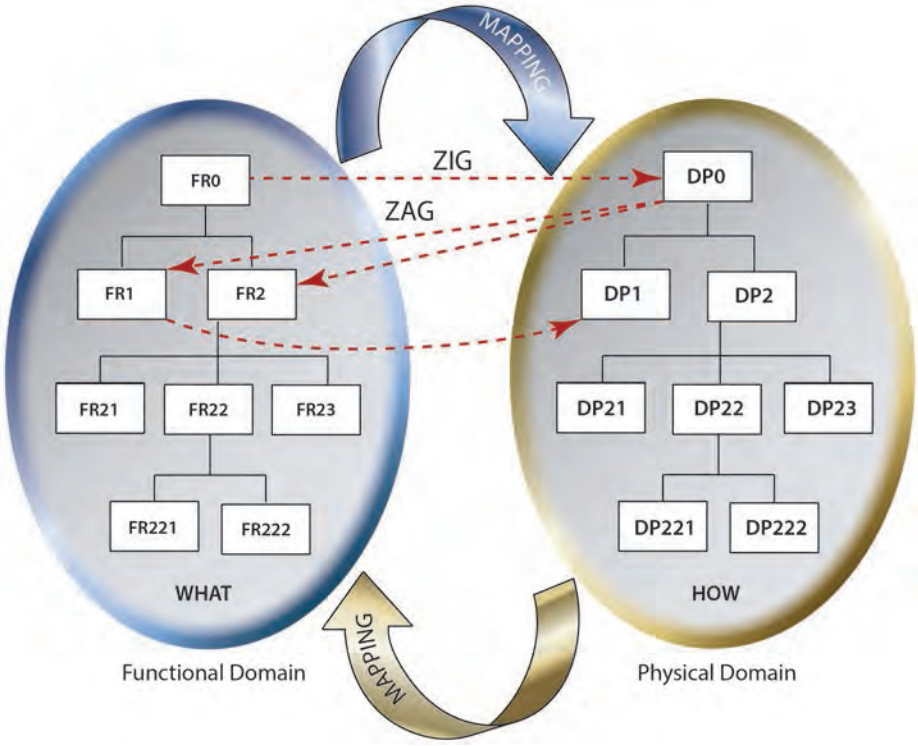


Figure 6.6: Zigzagging to decompose FRs and DPs.

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 concerning 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-sized 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 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 a 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 developed 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.

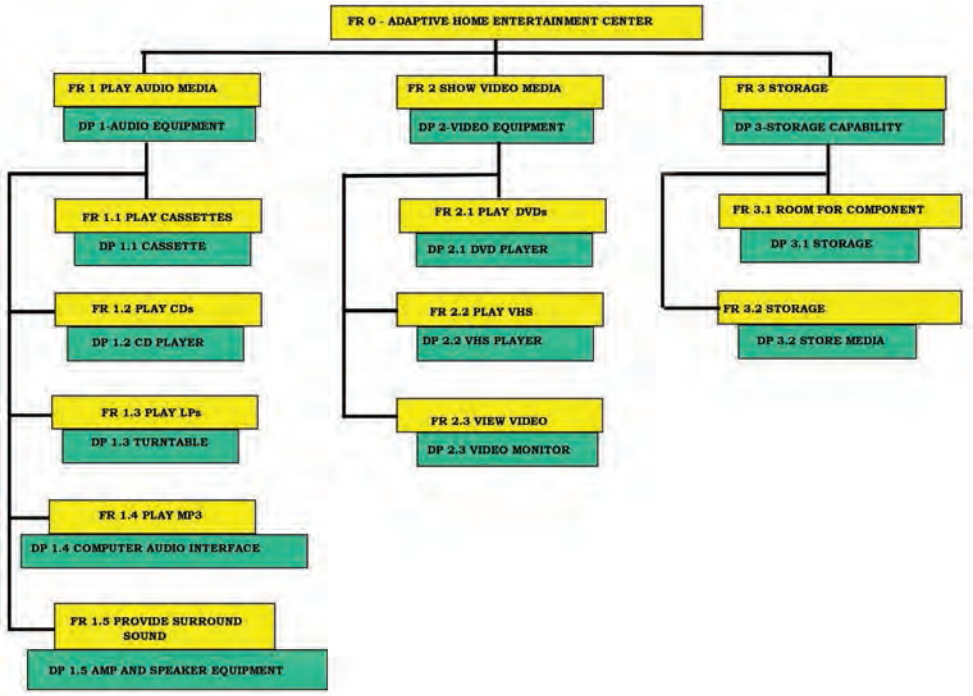


Figure 6.7: Design road map (from reference [a]).

The design team evaluated each of the FRs concerning 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 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)

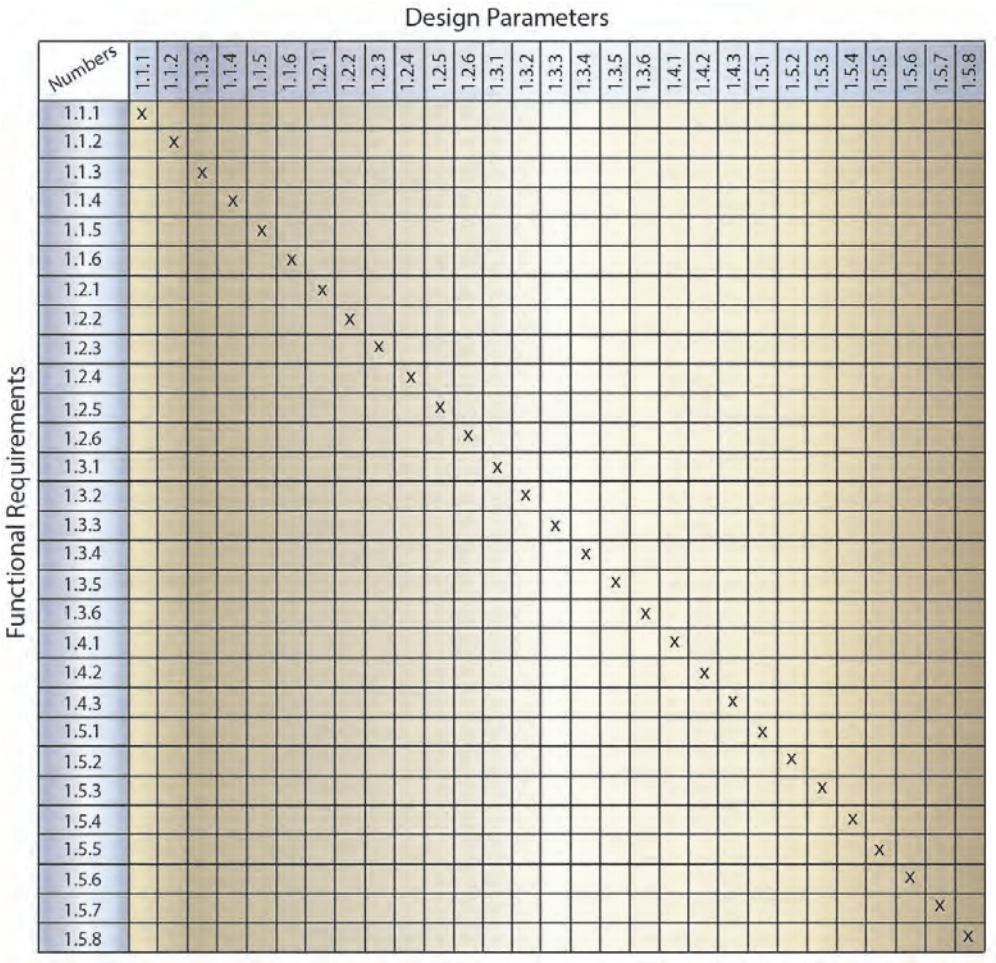


Figure 6.9: First level combined design matrix.

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]).

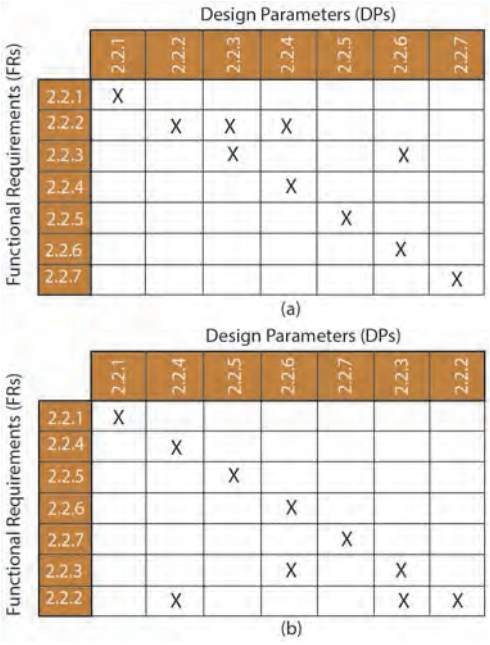


Figure 6.11: Coupled design.

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 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 to further define the program into the clearest possible set of FRs, DPs, and Cs.

CHAPTER 7

Transdisciplinary Design Tools Integration

Integration is a basic law of life; when we resist it, disintegration is the natural result, both inside and outside of us. Thus we come to the concept of harmony through integration.

Norman Cousins

One of the challenges in HR management in general and talent management, in particular, will be to ensure that the tools by which the ideas of talent are delivered are integrated with the tools of management of the organization as a whole with a measurable output.

Tumer & Kalman

7.1 Introduction

Transdisciplinary tools will be covered in this module have been applied in many fields including product development, project management, many engineering disciplines, design of the organization, sustainable development, social issues, environmental issues, and others across many industries including automotive, aerospace, telecom, semiconductor, defense, transportation, energy, healthcare, agriculture, and more – the integration of well-known TD tools such as QFD, TRIZ, ISM, DSM, and AD addressing a wide range of domains will be discussed in this module.

7.2 Transdisciplinary Tools Integration for Product Design

The integrated TD tools can be used in a wide range of domains. This module shows a new framework for integrated TD tools (see Figure 7.1) which has great potential benefits for solving large-scale complex problems.

7.2.1 Integrating QFD and TRIZ

The customer requirements, in general, include contradictions, which are mainly solved by trade-offs or compromises between the two parameters. The TRIZ inventive problem-solving can be used to remove compromises by resolving contradictions in product development – the contradiction resolution is more innovative than any other trade-off solution.

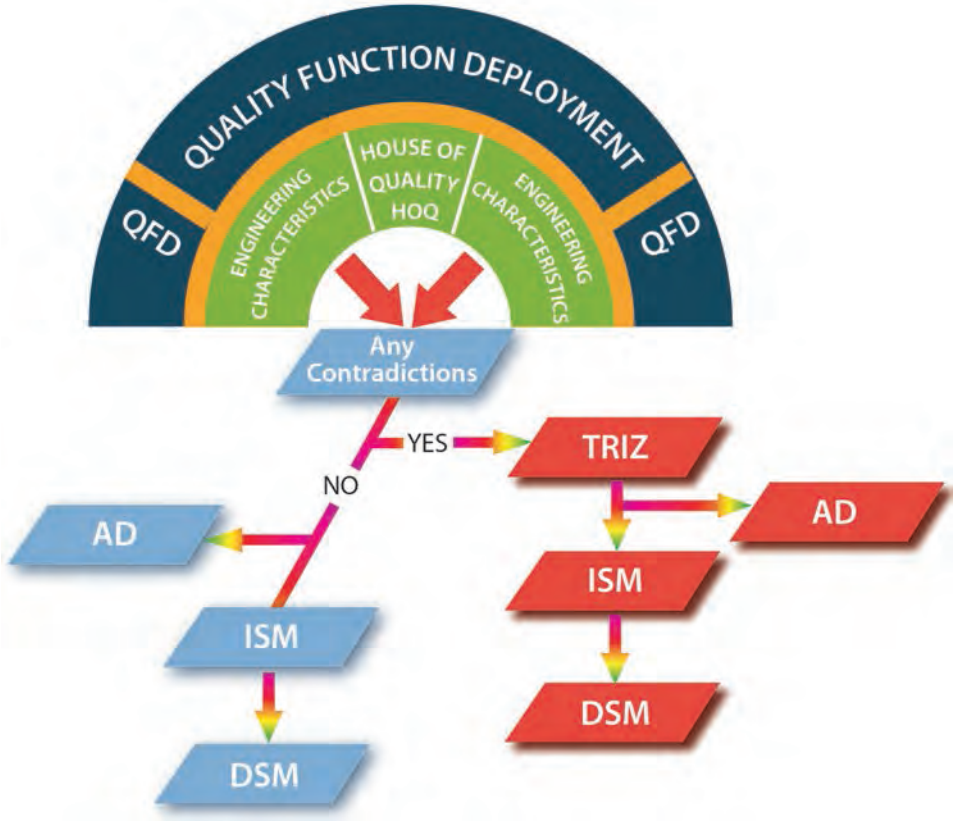


Figure 7.1: Framework of integrated TD tools.

As shown in Figure 7.2, the TRIZ method offers a wide array of applications in QFD.[1] QFD and TRIZ have complementary approaches and different viewpoints for product development and planning. Figure 7.3 illustrates the level of impacts and relationships of QFD and TRIZ on certain requirements of product development.[2]

Hajime et al. developed the Innovative Product Development Process (IPDP), which systematically integrates QFD with TRIZ and enables the effective and systematic creation of technical innovation for new products H. Yamashina, T. Ito and H. Kawada,(2002). Innovative product development process by integrating QFD and TRIZ. *International Journal of Production Research*, vol. 40, no. 5, pp.1031-1050. The integration of TRIZ and QFD capabilities allows not only the satisfaction of the demands of customers but also the design of solutions based on technological systems that provide entirely new experiences use.[3]

[1]Philipp Tursch, Christine Goldmann, Ralf Woll, (2015). Integration of TRIZ into QFD. *Management and Production Engineering Review*, Vol. 6, No. 2, pp. 56–62.

[2]Terninko, J., Zussman, A., & Zlotin, B. (1998). Systematic innovation: an introduction to TRIZ. Boca Raton: CRC Press.

[3]Naveiroa, R. M., Oliveira, V. M., (2018). QFD and TRIZ integration in product development: a Model for Systematic Optimization of Engineering Requirements. Production, Vol. 28.

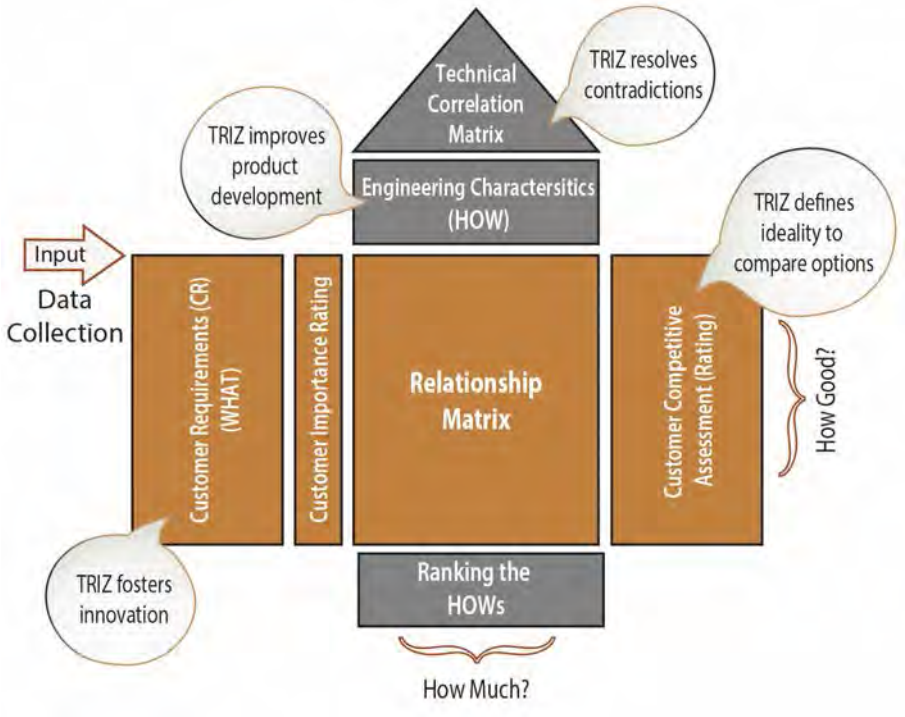


Figure 7.2: TRIZ application in QFD (adapted from reference 1).

Ranking	
Strong Relationship	XXX
Medium Relationship	XX
Weak Relationship	X

	QFD	TRIZ
Customer Satisfaction	XXX	X
Product Quality	XXX	XXX
Profits	XXX	XXX
Market Share	XXX	XXX
Innovation	XX	XXX
Failure Anticipation		XXX
Intellectual Capital Protection		XXX
Technological Prospection		XXX

Figure 7.3: QFD and TRIZ synergy (from reference 2).

The HOQ identifies relationships among requirements and interactions between the engineering characteristics of the product. The TRIZ through contradiction matrix solves the main shortcoming of the QFD method when engineering characteristics conflict with each other. The TRIZ inventive principles may eliminate the conflicts between engineering characteristics that occurred in the HOQ correlation matrix. The steps for finding solutions for conflicting problems that exist in the QFD with TRIZ is the following (see Figure 7.4:

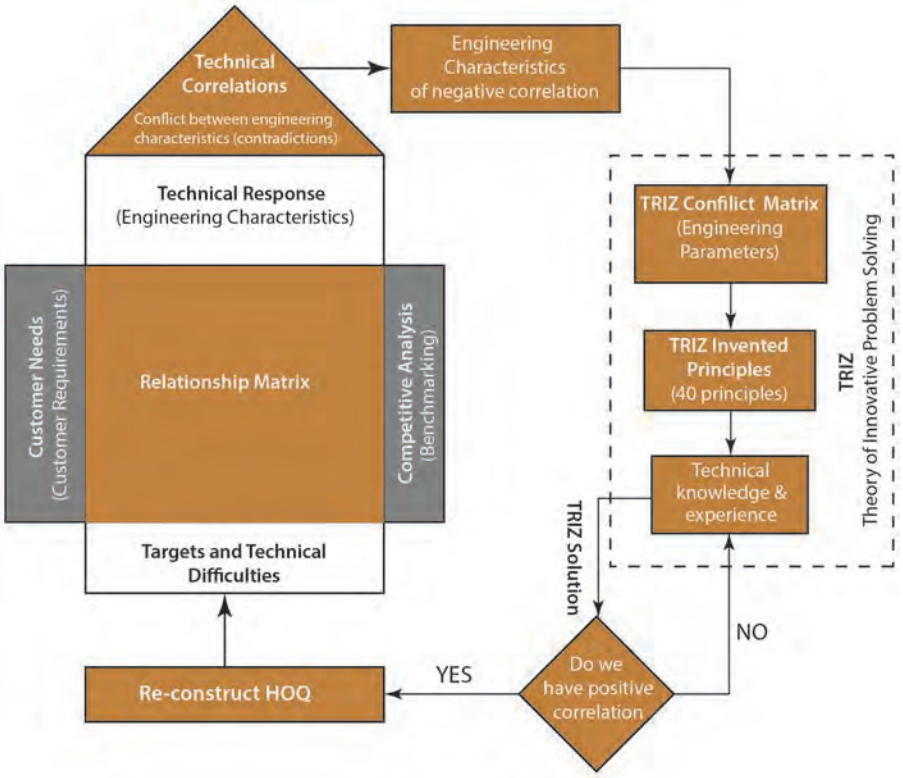


Figure 7.4: Flow chart.

1. Identify the conflicting engineering characteristics (EC) with negative correlation in the HOQ correlation matrix.

2. Identify the EC's type, which one is improving and which one is worsening characteristics.

3. Replace the ECs with corresponding parameters from TRIZ 39 contradiction matrix (Tables 3.1 through 3.6).

4. Using the contradiction matrix tables, identify which of the 40 inventive principles apply to your problem to resolve the contradiction (see Table 3.8 for 40 inventive principles).

5. After brainstorming, adapt the appropriate solution from 40 inventive principles to resolve the conflict among the ECs in the HOQ correlation matrix.

6. Re-construct the HOQ with the new ECs.

EXAMPLE 7.1

Using the TRIZ inventive principles resolve the conflicts among the ECs shown in Figure 7.5.

ANALYSIS

QFD of a simplified example of finger rehab device given in Figure 7.5 shows two negative correlations. In this practical example, the negative correlations between ECs are: (1)"improving support user activity" and "increasing cost", (2)"improving strength" and "increasing weight". We will discuss these two cases as follows.

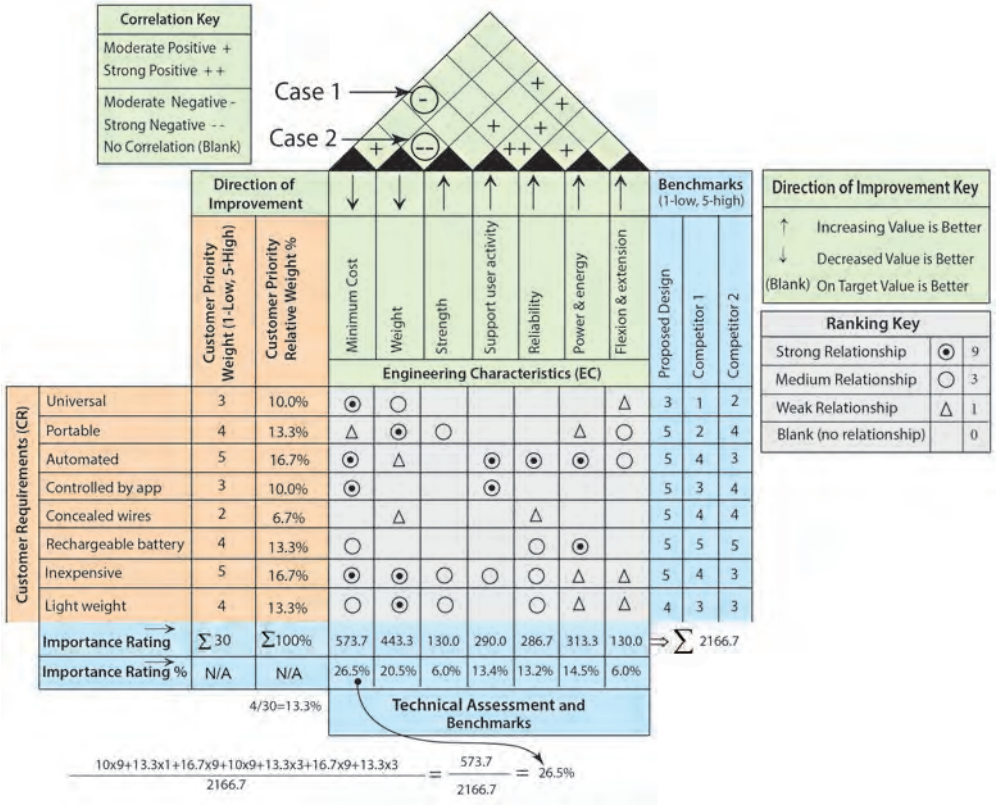


Figure 7.5: Finger rehab device of QFD.

Case 1: The improvement of the "support user activity" causes an increase in production "cost", thus resulting in a moderate negative correlation in the correlation matrix. In this case, "support user activity" is the improving characteristic, and the "cost" of production is the worsening characteristic. In other words, If we want to improve the "support user activity" it will cost more money and time.

EXAMPLE 7.1 (continued)

Many people have difficulty with the issue of cost since cost reduction is a widespread topic throughout the industry. However, many techniques of TRIZ do not deal with cost explicitly.[a]

Darrell Mann (2004) has developed a business matrix similar to the contradiction matrix. His direct cost parameters for the business matrix are as follows:[a]

- R&D Cost
- Production Cost
- Supply Cost
- Support Cost

He also included some of the same parameters used in the TRIZ matrix that cause costs to increase:[a]

- Complexity of the system
- Complexity of control
- System-generated harmful factors
- Time and risk issues for the R&D, production, supply, and support
- Speed of a process
- Duration of action
- Loss of energy, loss of material, loss of information, loss of time
- Reliability
- System-generated harmful factors
- Ease of operation
- Ease of manufacturing
- Ease of repair
- System complexity
- Extent of automation
- Productivity

Using the above information about what causes the cost to increase, we adopt "complexity of device" for "cost of production" and "ease of repair (repairability)" for "support user activity". From the matrix of contradictions, using "Repairability (34)" as the improving characteristic and "complexity of device (36)" worsening characteristic, at the intersection of the two characteristics (see Figure 7.6) the following four potential solutions principles (see Table 3-8) for the contradiction are possible:

[a]Ellen Domb, (2006). How To Deal With Cost-Related Issues In TRIZ. The TRIZ Journal. https://triz-journal.com/deal-cost-related-issues-triz/, accessed July 23, 2020.

EXAMPLE 7.1 (continued)

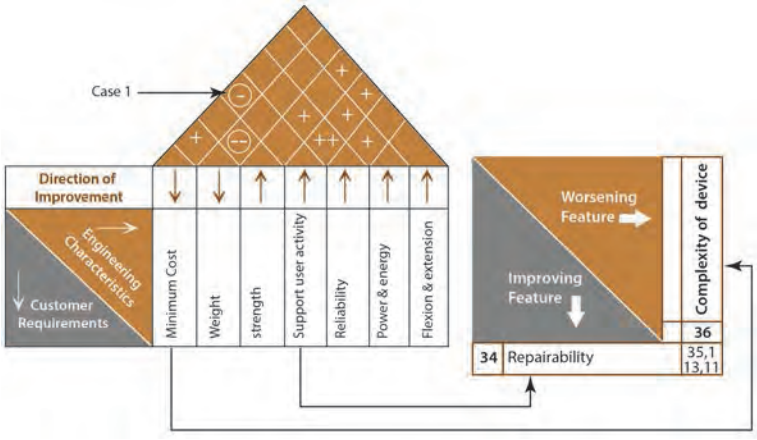


Figure 7.6: TRIZ potential principles solutions.

1. ***Segmentation (1)***
a) Divide an object into independent parts.

- Replace mainframe computers with personal computers.
- Replace a large truck with a truck and trailer.
- Use a work breakdown structure for a large project.

(b) Make an object easy to disassemble.

(c) Increase the degree of fragmentation or segmentation.

2. ***Invertion (the other way around) (13)***
(a) Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).

- To loosen stuck parts, cool the inner part instead of heating the outer part.
- Bring the mountain to Mohammed, instead of bringing Mohammed to the mountain.

(b) Make movable parts (or the external environment) fixed, and fixed parts movable.
(c) Turn the object (or process) upside down.

3. ***Parameter change (35)***

(a) Change an object's physical state (e.g. to a gas, liquid, or solid).
(b) Change the concentration or consistency
(c) Change the degree of flexibility
(d) Change the temperature

4. ***Cushion in Advance (11)***

Prepare emergency means beforehand to compensate for the relatively low reliability of an object.

EXAMPLE 7.1 (continued)

After thorough analysis, principle 1- segmentation of "use a work breakdown structure (WBS) for a large project," will be implemented. A WBS helps to make a large project more manageable. Breaking it down into smaller pieces work can be done simultaneously by different team members, leading to better team productivity. This will save a lot of time and effort, ultimately, saves money, and reduces the production cost.

Case 2: The improvement of the" strength" causes an increase of "weight", thus resulting in a strong negative correlation in the correlation matrix. In this case, strength is the improving characteristic and weight is the worsening characteristic. From the matrix of contradictions, using "strength (14)" as the improving characteristic and "weight (1)" worsening characteristic, at the intersection of the two characteristics (see Figure 7.7) the following four potential solutions principles (see Table 3-8) for the contradiction are possible:

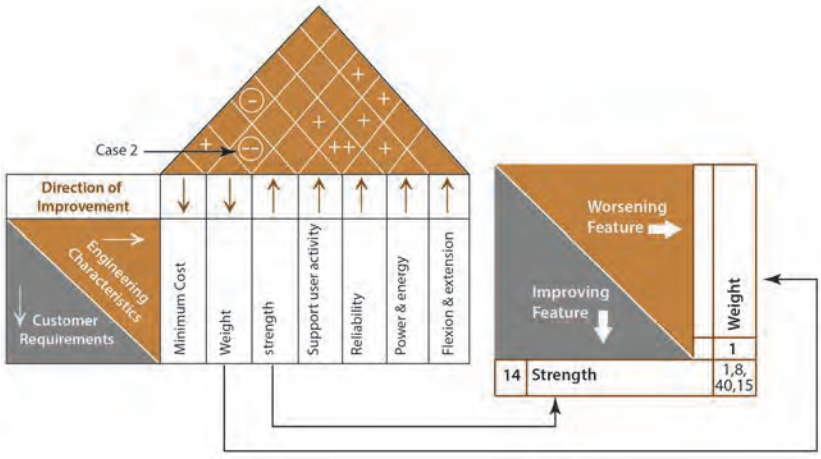


Figure 7.7: TRIZ potential principles solutions.

1. ***Segmentation (1)***

a) Divide an object into independent parts.

- Replace mainframe computers with personal computers.
- Replace a large truck with a truck and trailer.
- Use a work breakdown structure for a large project.

(b) Make an object easy to disassemble.
(c) Increase the degree of fragmentation or segmentation.

2. ***Counterweight (8)***

(a) To compensate for the weight of an object, merge it with other objects that provide lift.
(b) To compensate for the weight of an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy, and other forces).

3. ***Dynamicity (15)***

(a) Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.
(b) Divide an object into parts capable of movement relative to each other.

4. ***Composite material (40)*** – Change from uniform to composite (multiple) materials.

EXAMPLE 7.1 (continued)

For this case, among the other suggested solutions, composite material (40) will lead to a solution. This solution will eliminate the contradiction between weight and strength.

U.S. Department of Energy defines WBS as "A WBS is the cornerstone of effective project planning, execution, controlling, and reporting. All the work contained within the WBS is to be identified, estimated, scheduled, and budgeted. The WBS is the structure and code that integrates and relates all project work (scope, schedule, and cost)."[b]

Therefore, the relationships of the engineering characteristics with this new characteristic (WBS) should be carefully reconsidered to rebuild the HOQ. A similar argument is justifiable for the replacement of "composite material" in the HOQ.

A negative correlation between ECs, mainly "cost of production" and "weight (material)", certainly affects the performance of product design. Thus, these ECs, which have negative correlations are replaced in the HOQ as shown in Figure 7.8.

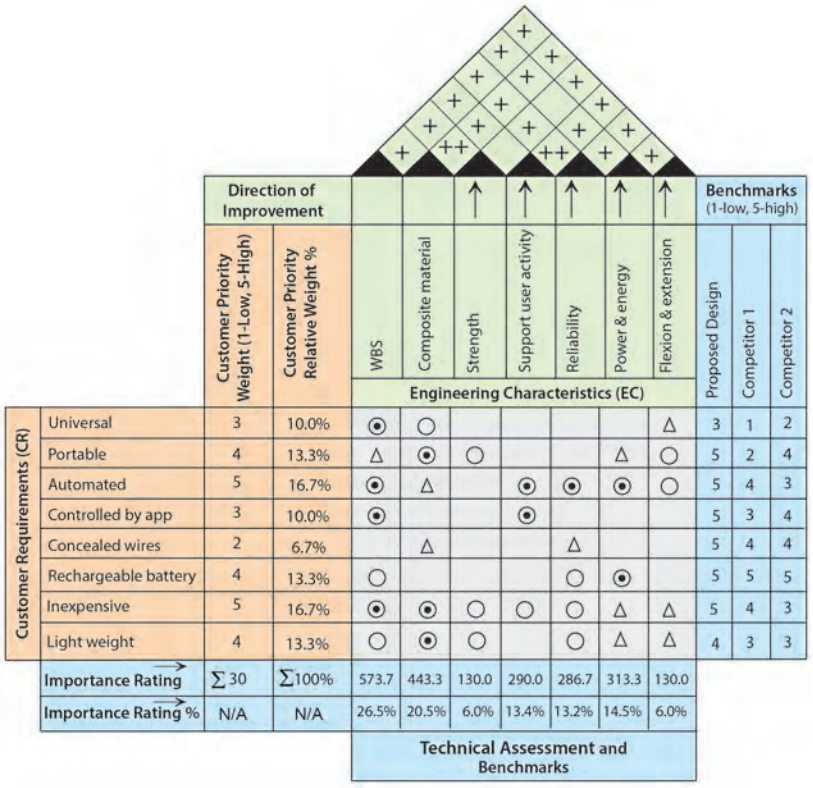


Figure 7.8: New re-build HOQ.

[b]PROJECT MANAGEMENT PRACTICES 1 Work Breakdown Structure (Rev E, June 2003, p.1), https://www4.rcf.bnl.gov/ videbaks/hft/cd1/DOE_guidance_wBS.pdf

7.2.2 Integrating ISM with QFD-TRIZ Results

EXAMPLE 7.2

Integrating ISM from the result of Example 7-1 as shown in Figure 7.9.

ANALYSIS

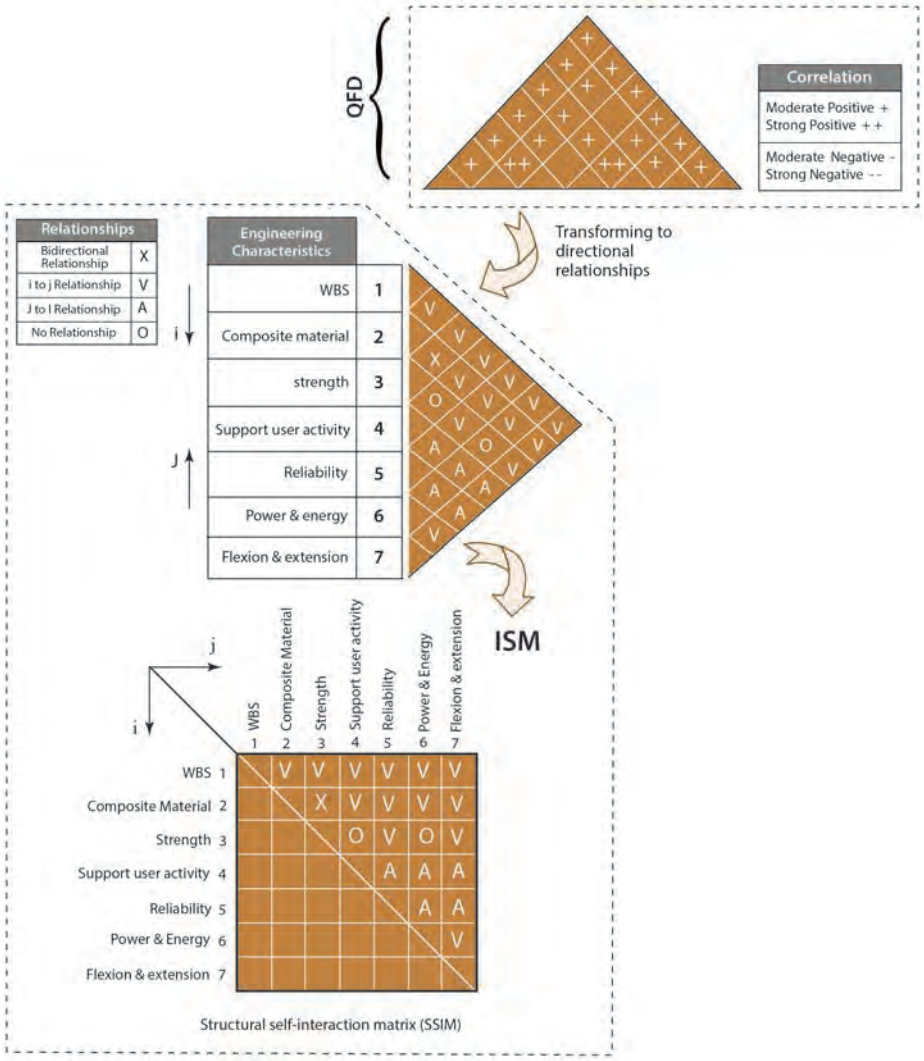


Figure 7.9: Transforming QFD to directional relationships.

EXAMPLE 7.2 (continued)

$R_a =$

		1	2	3	4	5	6	7
WBS	1	1	1	1	1	1	1	1
Composite	2	0	1	1	1	1	1	1
Strength	3	0	1	1	0	1	0	1
Support user activity	4	0	0	0	1	0	0	0
Reliability	5	0	0	0	1	1	0	0
Power & Energy	6	0	0	0	1	1	1	1
Flexion & extension	7	0	0	0	1	1	0	1

Figure 7.10: Adjacency matrix.

$R_f =$

		1	2	3	4	5	6	7	Driving Power
WBS	1	1	1	1	1	1	1	1	7
Composite	2	0	1	1	1	1	1	1	6
Strength	3	0	1	1	1	1	1	1	6
Support user activity	4	0	0	0	1	0	0	0	1
Reliability	5	0	0	0	1	1	0	0	2
Power & Energy	6	0	0	0	1	1	1	1	4
Flexion & extension	7	0	0	0	1	1	0	1	3
Dependence		1	3	3	7	6	4	5	$\sum = 29$

Figure 7.11: Final reachability matrix.

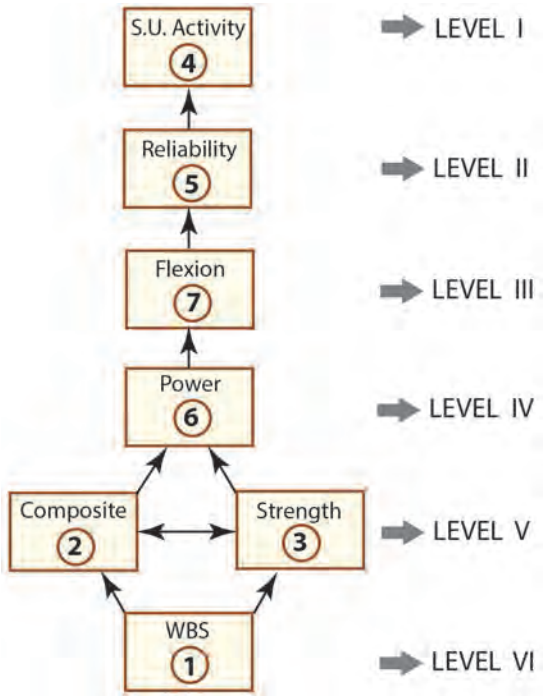


Figure 7.12: Digraph.

EXAMPLE 7.2 (continued)

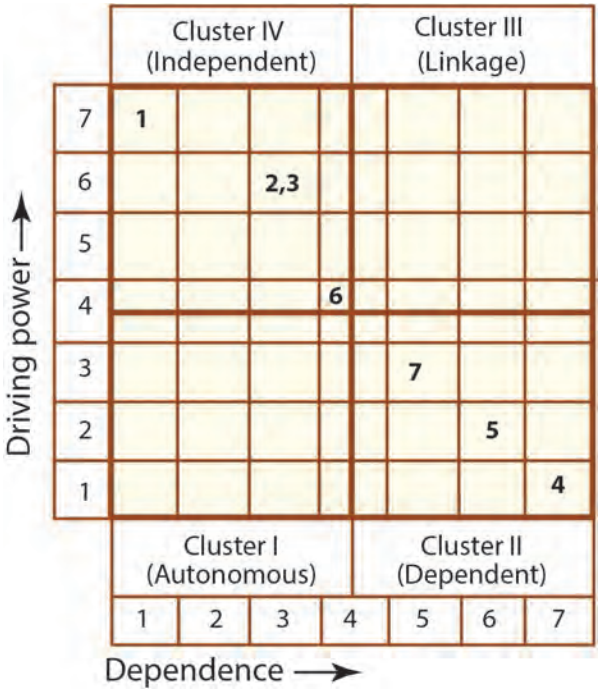


Figure 7.13: MICMAC analysis.

7.2.3 Integrating ISM Result with DSM

EXAMPLE 7.3

Integrating DSM from the results of Example 7-2 as shown in Figure 7.14 and Figure 7.15.

ANALYSIS

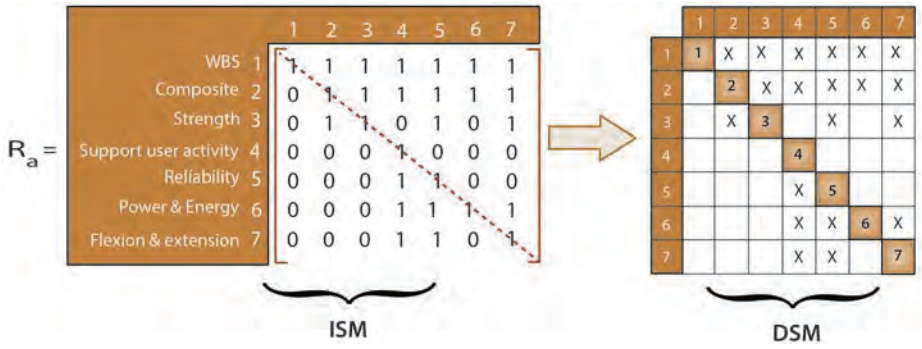


Figure 7.14: Transforming ISM to DSM.

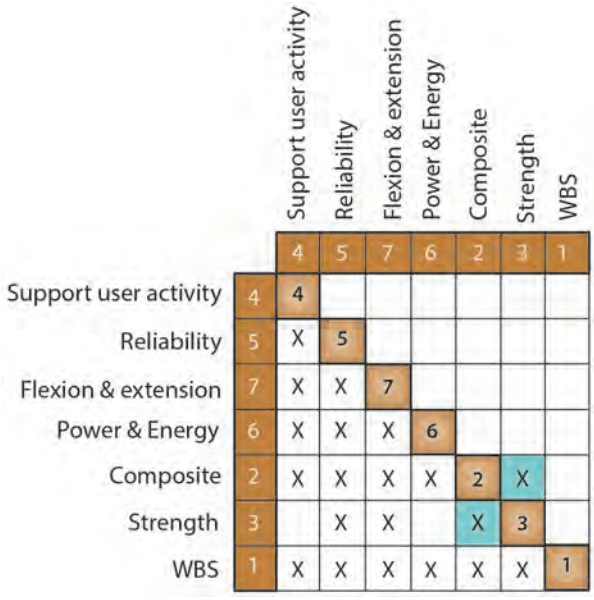


Figure 7.15: Partitioned DSM.

7.3 Integrating QFD, TRIZ, and AD for Product Design

QFD will not help us to describe details of functions and design parameters required to satisfy customer needs or to determine the functional requirements and design parameters without conflicting with each other. Therefore, QFD requires the use of other tools, such as TRIZ to resolve the conflicts in engineering characteristics or functional requirements and axiomatic design to determine the minimum set of design characteristics while satisfying the independence axiom – FRs should be independent of each other.

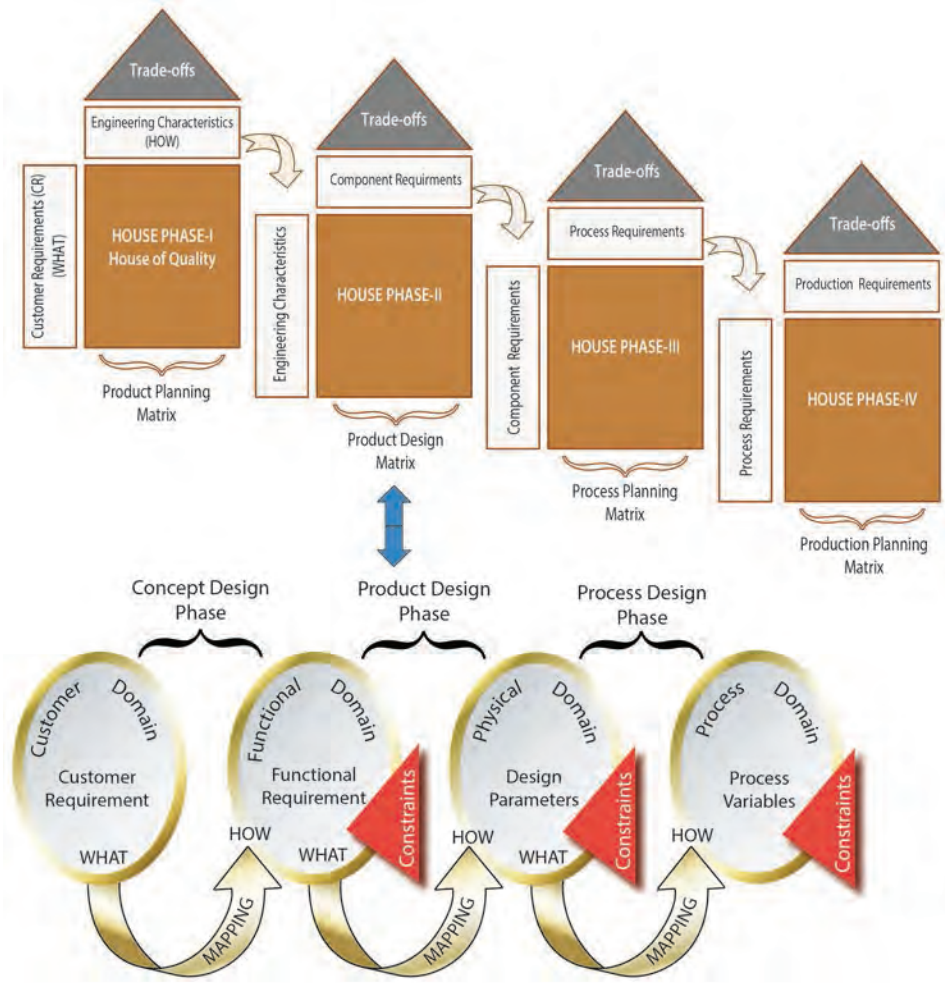


Figure 7.16: Framework of integrated TD tools.

As shown in Figure 7.16, both AD and QFD Phase II form the design process as a mapping between domains, and both the QFD's relationship matrix and the AD's design matrix serve the same purpose: mapping from WHAT to HOW. Usually, QFD focuses on customer needs but not on the product's architecture which is important for new product development (NPD). On the other hand, AD considers the customer needs as QFD does, but AD does not have a methodical process of converting the customer needs into functional

requirements.[4] Figure 7.17 shows the development of conceptual architectural design steps for QFD-TRIZ-AD integration.

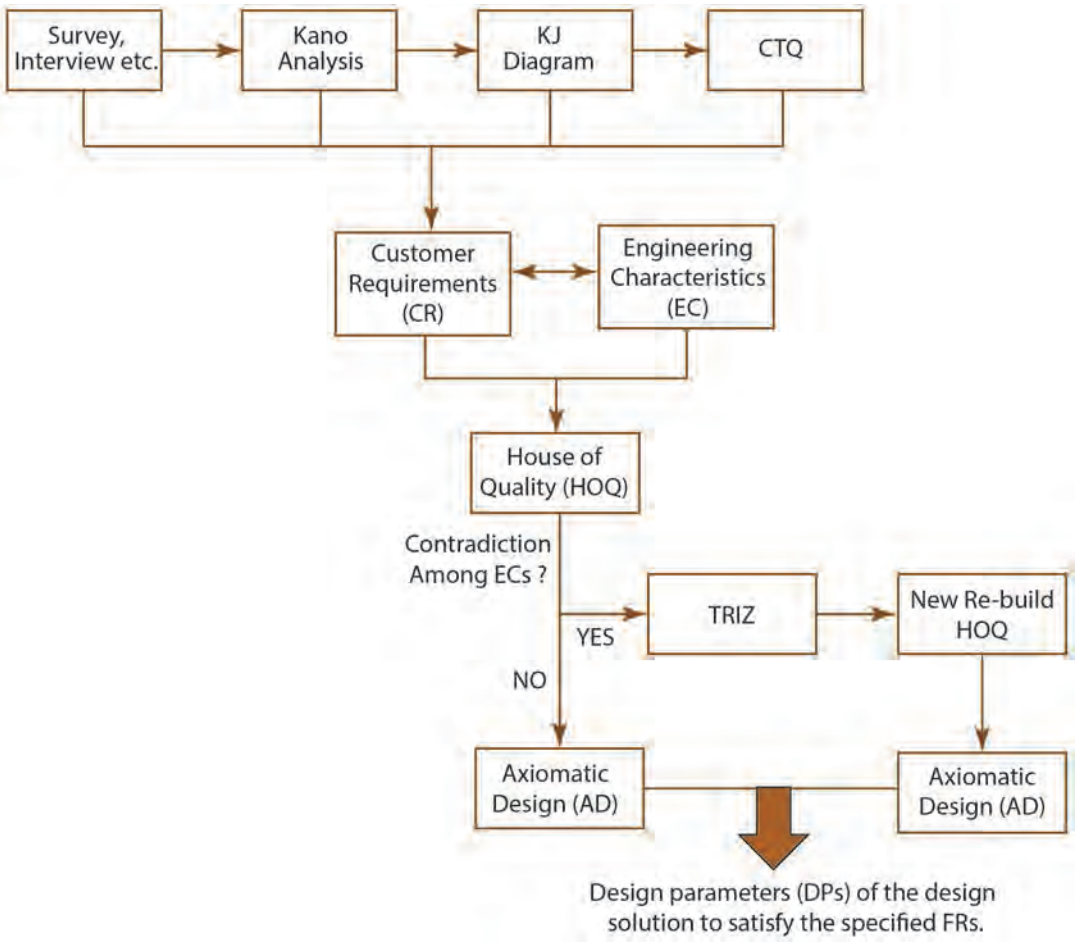


Figure 7.17: Conceptual architectural design steps for QFD-TRIZ-AD integration.

[4]Gilbert, L. R.; Omar, M. A.; Farid, A. 2016. Axiomatic design in large systems: an application of quality function deployment and axiomatic design to the conceptual design of temporary housing stakeholders. Springer, 216–240.

CASE STUDY 7.1

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

SOLUTION

As shown in Figure 7.17, the first step is to develop a list of the customers' requirements (CRs). To define the customer needs, each member of the design team performed a survey of the people who fit the chosen customer profile. Through the survey, after understanding and defining what the customer requirements are, the design team developed the HOQ. After contradictions among the engineering characteristics are resolved (TRIZ has been applied) the high-level functional requirements are identified (see Figure 7.18).

FR1: Product shall be capable of flexion & extension

FR2: Product shall be capable of supporting user activity

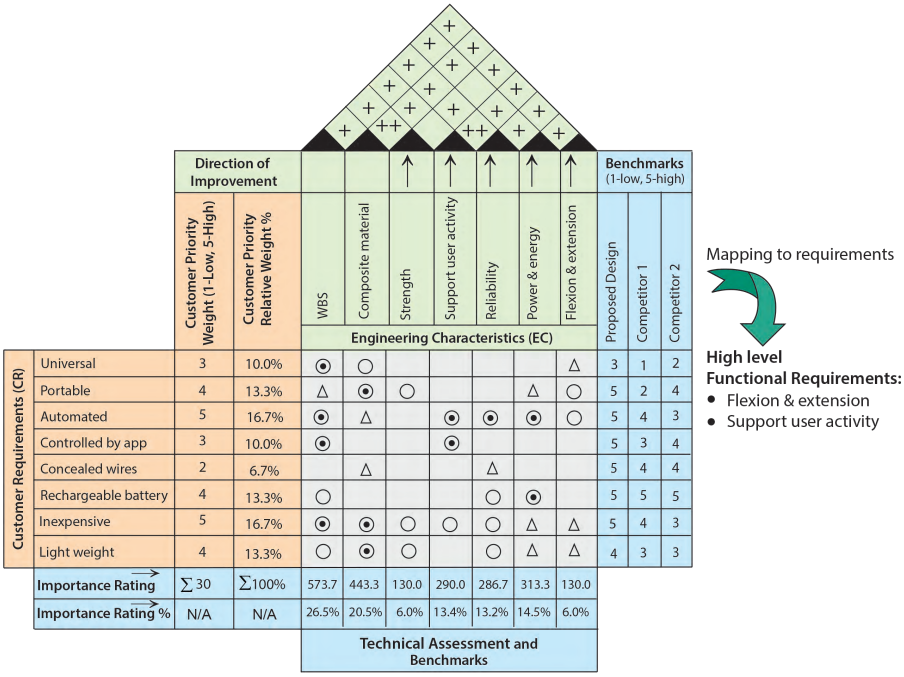


Figure 7.18: Mapping to requirements.

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 further decomposition by using AD zigzag methodology.

CASE STUDY 7.1 (continued)

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

DP1: Soft robotic

DP2: Activity monitoring tool

The DPs that are selected to fulfill the high-level FRs provide some insights about the finger rehab device. Formulation of the design matrix for this initial level of decomposition is shown in matrix Eq. 7.1. The design matrix shown in Eq. 7.1 should be formulated for each level to avoid violating the Independence Axiom.

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{7.1}$$

Eq. 7.1 reveals that the design is uncoupled at the top level and the independence axiom is not violated. This initial step determined the starting point for the further decomposition into additional levels of FRs. A road map for the levels of decomposition is shown in Figure 7.19.

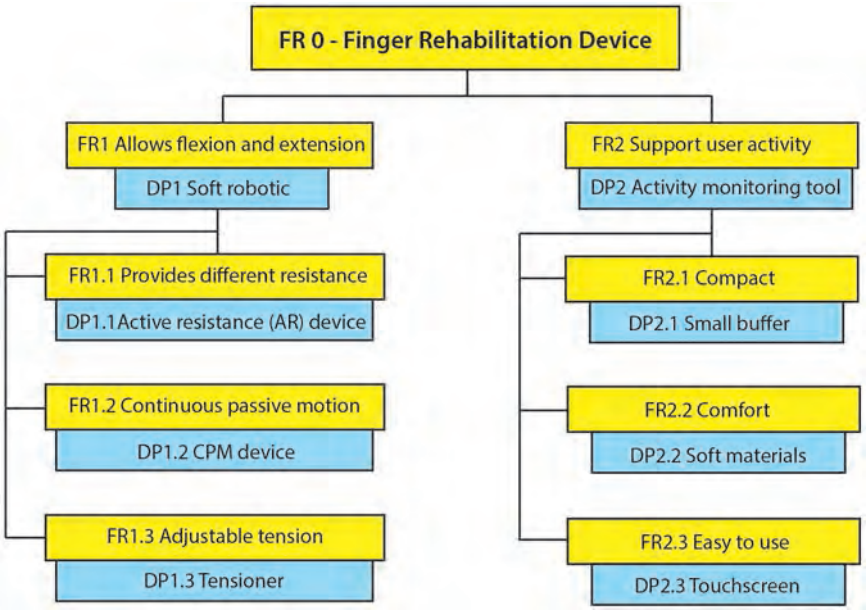


Figure 7.19: Design rod map.

CASE STUDY 7.1 (continued)

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

FR1.1: Provides different resistance

FR1.2: Continuous passive motion (CPM)

FR1.3: Adjustable tension

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

DP1.1: Active resistance (AR) device

DP1.2: CPM device

DP1.3: Adjustable tensioner

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

$$\begin{Bmatrix} FR1.1 \\ FR1.2 \\ FR1.3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1.1 \\ DP1.2 \\ DP1.3 \end{Bmatrix} \tag{7.2}$$

Eq. 7.2 shows that the design is uncoupled at the second level and the independence axiom is not violated. Figure 7.20 shows the remaining part of the decomposition of the high-level functional requirement of FR1.

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

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

Figure 7.20: Decomposition of FR1.

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CASE STUDY 7.1 (continued)

Figure 7.21 shows the decomposition of the high-level functional requirement of FR2.

FR2 Support user activity		DP2.1	DP2.2	DP2.3		
Compact	FR2.1	X			Small buffer	(10)
Comfort	FR2.2		X		Soft materials	(11)
Easy to use	FR2.3			X	Touchscreen	(12)
FR2.1 Provides different resistance		DP2.1.1	DP2.1.2	DP2.1.3		
Easy to carry	FR2.1.1	X			Pack with handle	(13)
Portable	FR21.2		X		Modular parts	(14)
Light weight	FR2.1.3			X	Composite material	(15)
Comfort	FR2.2	DP2.2.1	DP2.2.2			
Prevents swelling	FR2.2.1	X			Ice pad	(16)
Easy flexion of PIP or DIP joints	FR2.2.2		X		Wire-Foam and pad	(17)
Easy to use	FR2.3	DP2.3.1	DP2.3.2			
Consistent	FR2.31	X			Software	(18)
Automated	FR2.32		X		Automation Integrator	(19)

Figure 7.21: Decomposition of FR2.

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CASE STUDY 7.1 (continued)

Figure 7.22 shows the combined design matrix of all of the levels of FRs and DPs. It represents an uncoupled design. That is, each FR is satisfied by only one DP.

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

Figure 7.22: Combined design matrix.

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About the Authors

Dr. Atila Ertas, Professor of Mechanical Engineering, received his master's and Ph.D. from Texas A&M University. He was a Senior Research Fellow of the IC^2 Institute at the University of Texas Austin (until 2020), a Fellow of the American Society of Mechanical Engineers (ASME), a Fellow of the Society of Design and Process Science (SDPS), and a Fellow and an honorary member of The Academy of Transdisciplinary Learning & Advanced Studies (ATLAS). He is also an honorary member of the International Center for Transdisciplinary Research (CIRET), in France. Dr. Ertas has earned both national and international reputations in engineering design. Dr. Ertas is the author of several books and more than 200 technical papers that cover many engineering technical fields. His books include The Engineering Design Process, (John Wiley & Sons, co-authored with J. Jones, 1993 and 1996); Prevention through Design (PtD): Transdisciplinary Process, (National Institute for Occupational Safety and Health, 2010); Engineering Mechanics and Design Applications: Transdisciplinary Engineering Fundamentals, (CRC Press, Taylor & Francis Group, 2011); Transdisciplinarity: Bridging Natural Science, Social Science, Humanities & Engineering, (ATLAS Publication, 2011); Transdisciplinary Theory & Practice, (co-edited with Basarab Nicolescu, TheATLAS Publications, 2013); Transdisciplinary Education, Philosophy, & Applications, (TheATLAS Publications, co-edited with Basarab Nicolescu, 2014); Convergence: Transdisciplinary Knowledge & Approaches to Education and Public Health, (ATLAS Publications, co-edited with Basarab Nicolescu and Sarah Gehlert, 2016); Transdisciplinarity Engineering Design Process, (John Wiley & Sons, Inc., New York, 2018); Being Transdisciplinary, (ATLAS Publications, co-edited with Basarab Nicolescu and Raymond Yeh, 2019); Conducting Transdisciplinary Research, (ATLAS Publications, co-edited with Basarab Nicolescu and Raymond Yeh, 2021). Under his supervision, more than 200 MS and Ph.D. graduate students have received degrees.

Utku Gulbulak, Ph.D., received his BS degree in Mechanical Engineering from Middle East Technical University, Turkey in 2014 and his Ph.D. in Mechanical Engineering at Texas Tech University in 2020. His primary research interest is the parametric design of artificial heart valves using multiphysics modeling and machine learning. His secondary research interest is the impact of transdisciplinary education on the engineering discipline.