Integration of Failure Modes and Effects Analysis (FMEA) in the Engineering Design Process

A Thesis in the Department of

Concordia Institute for Information Systems Engineering (CIISE)

Presented in partial fulfillment of the requirements for the degree of

Master of Applied Science (Quality Systems Engineering) at

Concordia University

Montreal, Quebec, Canada

August 2013

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

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Entitled: **Integration of Failure Modes and Effects Analysis (FMEA) in the Engineering Design Process**

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Quality Systems Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

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Hua-wei Wen

Failure modes and effects analysis (FMEA) is one of the most practical design tools implemented in the product design to analyze the potential failures and to improve the design. The practice of FMEA is diversified and different approaches are proposed by different organizations and researchers from one application to another. Yet, the question is how to systematically utilize the features of FMEA along with the design process. This thesis aims to integrate different types of FMEA in the design process, which is considered as the mapping between customer requirements, product functions, and design components. These three design elements are the foundation of the integration model proposed in this thesis.

The objective of this thesis is to develop an integration approach of FMEA in the design process. Particularly, an integration framework is developed to integrate FMEA and design process. Then, a step-by-step FMEA-facilitated design process is proposed to apply FMEA along with the design process. In the end, a detailed case study of a smartphone model is conducted to demonstrate and verify the proposed methodology. The expectedly benefits of the proposed methodology are the consistency of failure analysis information, and the utilization of the failure analysis information from one stage to the later stages of the design process.

Keywords: Engineering design process, Failure modes and effects analysis (FMEA), Failure analysis, Smartphone

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Chapter 1: Introduction

1.1. Background and Motivation

Failure modes and effects analysis (FMEA) is a design tool to analyze and control the potential impacts from failures (Anleitner 2010). Through the practice of FMEA, it is expected to anticipate the possible failures from a product or system before it is actually implemented. In such a way, engineers can improve the design by deliberately controlling the causes of failures or limiting their negative effects. One key benefit to implement FMEA in product design is due to the "Factor of 10 rule" that early design improvements can substantially minimize the expensive cost of modifications at the later stages of product development (Carlson 2012, pp. 5-6).

Notably, the origin of FMEA comes from the industrial initiative, particularly from military and automotive industries. In this sense, the procedure of FMEA can be very practical towards a particular industrial sector. Yet, significant adapting efforts are required if we want to use the same procedure from one application to another application. Consequently, different standards related to FMEA have been proposed from various organizations such as the military standard of United States (MIL-P-1629), Society of Automotive Engineers (SAE: ARP5580), and International Organization for Standardization (ISO/TS 16949).

In contrast to FMEA, academic researchers have devoted significant efforts in the research of engineering design in the past few decades. The results can be found in some notable texts by Pahl et al. (2007), Dieter and Schmidt (2009), and Ulrich and Eppinger (2012). Intuitively, a design may be mainly referred to the artifact (physical structure or software) that is perceived by the users directly. Yet, these texts of engineering design have emphasized the significance of functions to describe the artifact as part of the design process. That is, the design information (e.g., requirements and functions) is essential before a design concept is developed.

In this thesis, the design process is considered the mapping process between design elements. Three types of design elements are particularly considered in this thesis: customer requirements, product functions and design components. Customer requirements are considered as the input information indicating the needs of customers, and they are usually obtained and organized in a marketing department through the market research activity. Product functions indicate the intents of the design without stating the specific solutions. For example, if I want to eat the food in the can, the function can be described as “open the can”. Notably, there can be various ways to open the can. Design components are referred to the specific design solutions that are implemented to achieve the product functions. For example, an “electric can opener from Company ABC” can be one design component to achieve the function “open the can”.

In brief, this thesis considers the design process as the mapping of "requirements → functions → components". This mapping has the reference to the methodology of Quality Function Deployment (QFD) in quality management and Axiomatic Design (AD) in engineering design. Particularly, QFD can involve several mapping matrices from customer requirements to engineering characteristics and then to part characteristics (Hauser and Clausing 1988). In AD, the mapping framework has been proposed for four design domains: customer, functional, physical and production (Suh 1990).

By considering FMEA as one design tool, the research question of this thesis is how to utilize the features of FMEA systematically in a design process. The academic efforts in engineering design have provided a solid foundation about some key design concepts such as requirements, functions and components. The research effort of this thesis is to interpret these design concepts systematically in the context of FMEA. In such a way, the practice of FMEA can be carried along with the design process. Expectedly, the information of failure analysis (from FMEA) can be utilized at the later stages of the design process. This practice can promote the consistency of the failure information among different teams in product development.

1.2. Research Approach and Objectives

The research approach has two aspects. The first aspect is related to the design process. In this aspect, it is required to specify the definition of design elements and how these design elements are related to each other. This provides the foundation for the integration effort with FMEA. The second aspect is related to FMEA. In this aspect, the key is to clearly define the contents of failure modes with respect to design elements. Once the failure modes are specified in a design context, the procedure of FMEA can be adapted in the design process for risk analysis.

To demonstrate and verify the research of this thesis, the smartphone of a specific model will be used. In this research, the hardware pieces of the smartphone are physically decomposed and studied for their functionalities. Then, the design elements of the smartphone are captured, and the proposed FMEA procedure is carried out for demonstration and verification. The details of the smartphone study are treated as one research deliverable of this thesis.

The goal of this research is to develop an integration approach of FMEA in the design process. To achieve this goal, three objectives are specified for this thesis.

- ❖ Objective #1: Develop an integration framework so that both FMEA and the design process can be integrated in a consistent manner.
- ❖ Objective #2: Develop the FMEA-facilitated design process that consists of a step-by-step process to apply FMEA along the design process.

- Objective #3: Conduct a detailed case study of a smartphone model to demonstrate and verify the methodology

1.3. Thesis Organization

The remaining chapters of the thesis are organized as follows. In Chapter 2, the literatures related to FMEA are reviewed and also the research gaps related to this thesis is highlighted. In Chapter 3, an integration framework is proposed by specifying the design elements and the contents of failure modes in the design process. Besides, a simple example from the Smartphone case study is carried in the end of Chapter 3 to demonstrate the integration model. In Chapter 4, a step-by-step methodology is proposed, and it guides the use of FMEA along with the design process. In Chapter 5, a case study from the specific model of a Smartphone is used to demonstrate and discuss the utility of the proposed methodology. In Chapter 6, the discussion of the benefits that we observed and the contributions clarified in the case study are presented. In the end, the conclusion of this thesis is provided in Chapter 7.

Chapter 2: Literature Review

2.1. Development of FMEA in Industry Practice

The origin of FMEA can be traced back to the military standard of United States in 1949 (MIL-P-1629), and the procedure at that time was titled "Failure Mode, Effects and Criticality Analysis" (FMECA). This military standard has been revised in 1980 (Military 1980). According to the forward of this standard, the purpose of FMECA is to identify the failure modes for assessing the "feasibility and adequacy" of the design and supporting the design decision accordingly. Beyond the military applications, FMECA has also been applied for space missions. One famous example is that National Aeronautics and Space Administration (NASA) has applied FMECA for the Apollo program for analyzing the "system unreliability and crew safety problems" (NASA 1966). The major difference between FMEA and FMECA is that FMECA additionally involves a criticality analysis. For each failure mode, criticality analysis considers the expected failure, mode ratio of unreliability and probability of loss. More details can be found in Carlson (2012).

The wide use of FMEA and similar techniques in civil systems can be found in the automotive industry. The Society of Automotive Engineers (now known as SAE International) has introduced the FMEA standard in 2001 (coded as ARP5580) (SAE 2001). As noted in Carlson (2012, chapter 1) and Bertsche (2008, chapter 4), the Ford Motor Company has been the first automobile manufacturer in the late 1970s applying FMEA, and FMEA remains one important tool in reliability analysis. In addition, FMEA has been recognized as one important tool in quality engineering as it is part of the body of knowledge to the Black Belt Certification (ASQ 2013; Creveling et al. 2003). International Organization for Standardization (ISO) has also managed relevant techniques in one standard, ISO/TS 16949 (Duckworth and Moore 2010, p. 51). This indicates the evidence about the popularity and usefulness of FMEA in industrial practice. Beyond the aerospace and mechanical systems, other industrial sectors have also reported the application of FMEA for reliability and quality analysis such as healthcare (De Rosier et al. 2002) and software (Reifer 1979).

According to the military standards, the techniques of FMEA originally targets for design improvement. That is, by identifying the potential failure modes during the design stage, we can minimize the impacts from these failure modes by modifying the original design. This practice can reduce the overall cost as compared to the modifications at the later stages of the product development process. This domain of FMEA has been termed as “Design FMEA” (Anleitner 2010). When FMEA becomes familiar in the industrial practice, engineers have adapted and extended the FMEA techniques to other domains. Three examples of different FMEA domains are listed and briefly explained as follows.

- Process FMEA (Teng and Ho 1996): the Process FMEA is used to analyze the risks related to the manufacturing operations.

- ❖ Concept FMEA (Carlson 2012, pp. 347-348): the Concept FMEA is used to assess the safety and reliability of the design concepts during the multi-criteria selection process.
- ❖ Social Responsibility FMEA (Duckworth and Moore 2010): the Social Responsibility FMEA is used to evaluate a company's operations in view of social responsibility. In such a way, failure modes are referred to poor impacts to the society and environment as a whole. It is intended to improve the social responsibility performance so that the company can explore alternative ways for the solutions for better society and environment.

After accumulating the experience of using FMEA in industrial practice, some practitioners propose a systematic FMEA methodology to construct the fundamental principles. Anleitner (2010) has proposed the deductive design FMEA method that rigorously specifies the inputs and outputs of each procedural step. Carlson (2012, p. 18) has also constructed the relationship diagram between Design FMEA and Process FMEA by systematically linking the required input and output information.

Based on this review, two observations about FMEA in industrial practice are made. Firstly, originated from the design domain, the application of FMEA has been extended to other domains in product development. From a manufacturer viewpoint, risks are not isolated. Such extension provides an opportunity to integrate the information of risks across different domains (e.g., from customer requirements to design and manufacturing). Secondly, early FMEA procedures tend to provide practical but somewhat ad-hoc guidelines. Thus, the actual outcomes from FMEA can vary significantly from one project to another. Recent efforts have focused on formalizing the FMEA procedure to promote the utility of FMEA in the actual practice. The research of this thesis basically corresponds to these two observations by integrating the requirements, functions and components in a framework for conducting FMEA.

2.2. FMEA in Academic Research

In academic research, one research direction related to FMEA is to enhance the features of FMEA for more comprehensive risk and failure analysis in product development. Stone et al. (2005) proposed the function-failure design method (FFDM) to support the use of FMEA in the conceptual design stage. The fundamental technique behind FFDM is to utilize the notion of functions to systematically define failure modes in engineering design. Chao and Ishii (2007) proposed the error-proofing method by adapting FMEA to prevent design errors, which are classified into six categories: knowledge, analysis, communication, execution, change and organization. FMEA was applied to guide engineers to explore the potential errors in these categories through the question-asking techniques.

One specific issue of FMEA research is to tackle the accuracy and appropriateness of the risk priority number (RPN). In brief, RPN is the product (i.e., by multiplication) of three numerical rankings: occurrence of risks, severity of risks and control of risks. The higher ranking values indicate worse risk situations, and RPN is used to prioritize the failure modes due to their risk situations. Then, the fundamental issue of RPN is that the same value of RPN can essentially represent different risk situations. For example, if the RPN value is equal to 600, we actually cannot determine whether the risk situation is (1) high occurrence and low severity or (2) low occurrence and high severity. It is because all numerical rankings are simply aggregated into one value (i.e., RPN).

To address this specific issue of FMEA, several researchers have proposed more detailed approaches to compute RPN and prioritize failure modes. Pillay and Wang (2003) used fuzzy sets and rules to infer and prioritize the risk situations, and their approach allowed users to define more specific scenarios of risks for particular contexts. Kmenta and Ishii (2004) used the probability and cost as the common basis to estimate and prioritize the risk situations in a more precise manner. Chang and Cheng (2011) used the fuzzy ordered weighted averaging (OWA) that allowed weighting factors and human imprecision in the assessment of risk situations. Bradley and Guerrero (2011) developed a data-elicitation technique integrated with the interpolation algorithm to support the risk assessment in FMEA. Chang et al. (2013) proposed an exponential risk priority number (ERPN) for providing more unique numerical values mapped to various risk situations.

This thesis will not address the issue of RPN. Instead, this thesis focuses on the methodology development for integrating FMEA in the design process. More discussion will be provided in the next sub-section.

2.3. Research Gaps related to this Thesis

From the discussion of FMEA in industrial practice (i.e., Section 2.1), it is stated that the application of FMEA becomes more popular in industry. As FMEA often requires the effort of a team, the FMEA procedure needs to be more rigorous and systematic for better communication and ensuring quality outcomes. Some latest texts such as Anleitner (2010) and Carlson (2012) have supported the direction of FMEA development in industry. In addition, it has been observed that FMEA has been extended for the risk analysis in different stages of product development (e.g., process FMEA and requirement FMEA). Such an extension effort remains active for supporting the organization of the product development process. In these views, this thesis is intended to contribute to the methodology development for the systematic practice of FMEA in different stages of the design process.

From the discussion of FMEA in academics (i.e., Section 2.2), while this thesis does not provide new approaches for handling RPN, it extends the research works of Stone et al. (2005) and Chao and Ishii (2007) by integrating more design elements in the practice of FMEA. Particularly, the design process of this thesis is modeled as a flow from customer requirements to design functions and components (i.e., requirements → functions → components). Essentially, this kind of design flow is similar to the methodology of Quality Function Deployment (QFD) (Suh 1990) or Axiomatic Design (AD) (Hauser and Clausing 1988). To our knowledge, integrating FMEA with these three types of design elements has not been found in literature.

Chapter 3: Integration Framework

The purpose of this chapter is to develop the integration model that provides a platform joining the information from the design and FMEA domains. The information related to the design and FMEA domain is first discussed separately. The integration is based on the definition of failure modes based on the design elements. At the end of this chapter, the smartphone example will be used to demonstrate and examine the integration concept.

3.1. Basic Elements in Engineering Design

The design process in engineering has not yet been standardized among researchers and practitioners, and thus various terms and design processes can be found from literature (Carlson 2012; Creveling et al. 2003; Pahl et al. 2007). In this thesis, three foundational and representative elements in engineering design are considered: requirements, functions and components.

Requirements are referred to the ultimate needs that are used to examine the product's goodness. In the field of quality engineering, requirements are mainly referred to customer needs, where the concept of customers can involve multiple aspects, and some examples are listed in the following.

- ❖ The customers who pay for the product
- ❖ The clients who use the product
- ❖ The governmental policies and regulations

❖ The environmental requirements

Generally, requirements can be viewed as the external and somewhat non-technical expectations that are required to the products. Product failures can be claimed if the requirements of a product cannot be met. This highlights the significance of requirements in engineering design.

The concept of functions in engineering design may come from the philosophy "Form Follows Functions" in architecture (Pahl et al. 2007). The basic idea of functions is to distinguish between "what" and "how" in design. Particularly, "what" describes the basic purposes (or functions) of the design, e.g., separating a piece of paper into two piece. Then, "how" describes the solutions to achieve these purposes, i.e., use a scissor as one solution to separate a piece of paper. The significance of the function concept is that multiple solutions are possible to achieve the same function. For example, in addition to using a scissor, we can use a ruler or our hands to separate the same piece of paper. At this point, the concept of functions can help engineers to creatively think of various solutions without committing to any solutions too quickly.

In this research, the function concept based on functional basis for design (Stone et al. 2000) is used. Particularly, a function is expressed in a phrase structure "verb + noun" to emphasize the "action" to be carried in a function. Furthermore, each action can be viewed as a transfer function that converts some input into some output. For example, “separate a piece of paper into two” is a function with an input “one piece of paper” and an output “two pieces of paper”. The inputs and outputs are further classified into three types: material, information and energy. Also, functions can be decomposed by describing how some sub-functions are required to achieve a high-level function. At the point, a product can be described by as a set of sub-functions that are purposely connected to deliver its major functions. To organize the sub-functions, a functional block diagram is commonly used in practice. Further details of functional design and analysis can be found in Kossiakoff et al. 2011.

Components are referred to the solutions that are chosen to satisfy particular function(s) or sub-function(s). Note that this research is confined to the scope of conceptual design. Thus, a component is generally a concept that is defined by Ulrich and Eppinger (2012, p. 98) as “an approximate description of the technology, working principles, and form of the product”. For example, suppose that a scissor is chosen as the “component” to separate a piece of paper. Then, the scissor concept here only approximately implies the use of two blades for cutting, and further engineering details are required for implementation (e.g., size of scissor, blade materials, etc.) Yet, the choice of a concept confines the direction of engineering efforts, and it is often considered a crucial decision towards the success of a design (Ulrich and Eppinger 2012).

After explaining the meaning of requirements, functions and components, this research focuses on the organization of these three types of elements along the product development process. The first step of the organization is to itemize these elements explicitly as the design information of a product. Let R, F and C be the set of requirements, functions and components, respectively, and these items are further denoted as follows.

- Requirements: $R = \{r_1, r_2, \ldots, r_m\}$, where m is the total number of requirements
- Functions: $F = \{f_1, f_2, \ldots, f_n\}$, where n is the total number of functions
- Components: $C = \{c_1, c_2, \ldots, c_p\}$, where p is the total number of components

In addition to the design information, FMEA targets for the failure information of a product. The next section will define and discuss the basic elements of FMEA.

3.2. Basic Elements of FMEA

Though FMEA is originated from a military standard (Military 1980), the practice of FMEA becomes diversified by incorporating various documentation styles and ranking schemes (Carlson 2012). Nevertheless, there are some basic elements that characterize the fundamental principles of FMEA. In this research, these basic elements are failure modes, causes and effects.

Based on Carlson (2012, p. 28), a failure mode can be defined as "the manner in which the product or operation failure to meet the requirements". In this sense, a failure mode should be a plain description of the failure without stating the reasons behind it or the impacts after it. In the context of engineering design, a failure mode can be referred any dissatisfaction related to requirements, functions and components. Towards the integration efforts, one important idea of this research is that a failure mode should be defined based on the known requirements, functions and component of the design. This idea provides the guidance for engineers to prepare the FMEA documents logically related to the design context.

The casual analysis in the study of engineering failures is always a challenging task, and fault tree analysis (FTA) is often identified as one common tool for this kind of tasks (O'Connor 2012). Compared to FTA, FMEA does not particularly focus on the casual relationships of failures. Instead, FMEA suggests identifying the causes and effects associated with each failure mode. Particularly, the causes are the possible reasons that can lead to the happening of the failure mode, and the effects represent the negative impacts if the failure mode is materialized. In this case, the causes and effects are basically connected by failure modes only without involving the chain effects between causes and effects.

For example, when engineers make failure analysis of a phenomenon "a user cannot take photo", the analysis process in FTA may look like Figure 1, a top-down analysis method to clarify and find the answers (i.e. root causes). In FTA, all the events under the phenomenon being studied are viewed as possible causal factors. In the meantime, one event can be a result of another event in the lower level or a reason for the other event in the upper level, and therefore the causal relationships of failures are broke down. Besides, one causal factor is possibly rooted out in different branches in FTA. From Figure 1, we can find that "camera module is damaged" is the upper event of the causal factor "lack of R/C components for protection", and it is also a causal factor for the event "camera module cannot be executed." Also, "camera module is damaged" can be a root out under the analysis branch of "Design factors" or under the branch of "Manufacture factors".

In contrast, the cause-failure mode-effect chain is clearer in FMEA. In the similar case, the failure mode is identified as "Camera module is damaged" if the analyzed items in FMEA is components, the possible causes is "lack of R/C components for protection" and "Incorrect circuit design"; the possible effect is "Camera module cannot be executed". Similarly, if the analyzed item in the FMEA is functions, the failure mode is "Camera module cannot be executed", and the causes is identified as "Camera module is damaged", "Lack of power supply", "Incorrect patter", or so on; the effect is identified as "A user cannot take photos". Instead of considering "what if" continuously to build up the effect results or to ask "why" continuously to find out the root causes, engineers focus on the direct effects and the causes of the failure modes corresponding to the analyzed items in FMEA.

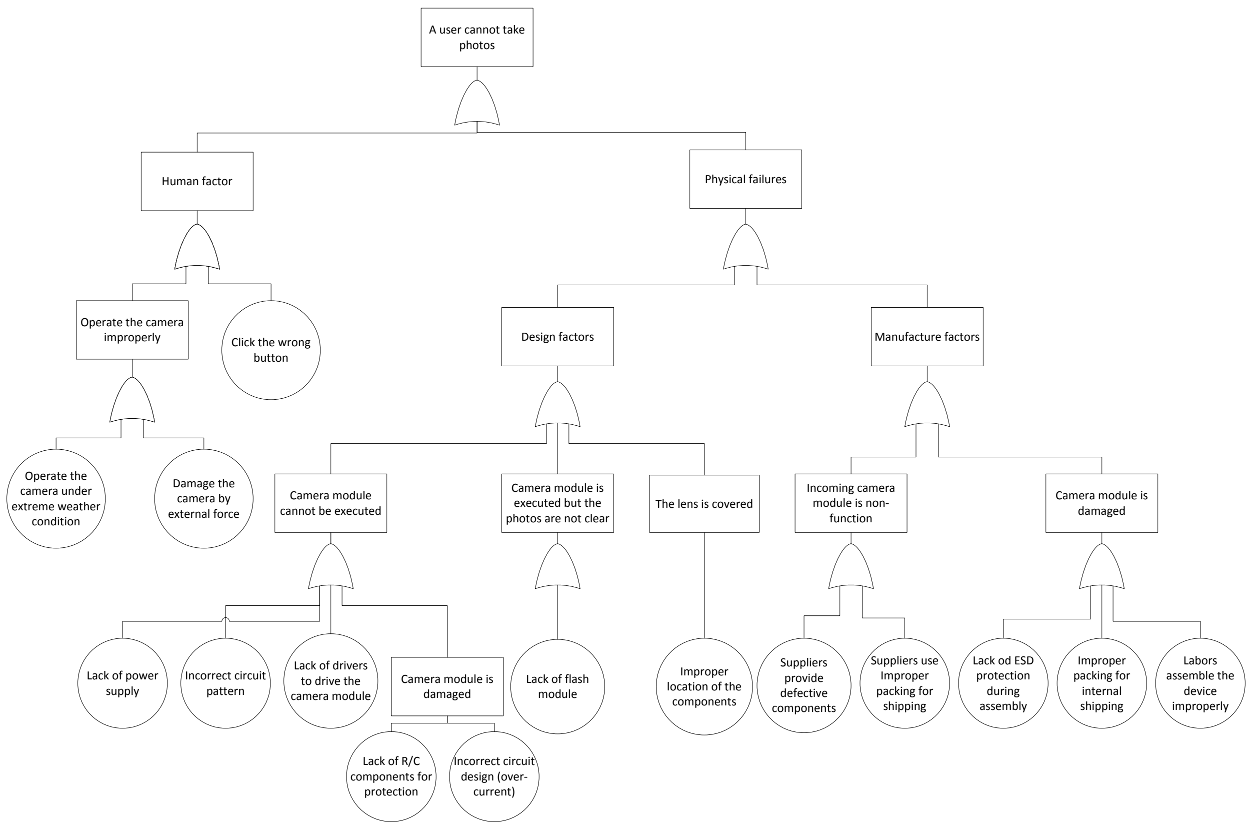

Figure 1 Fault tree analysis (FTA) diagram example

After explaining the meaning of failure modes, causes and effects, this research focuses on the organization of these three types of elements along the product development process. The first step of the organization is to itemize these elements explicitly as the failure information of a design. Let *FM*, *CA* and *EF* be the set of failure modes, causes and effects, respectively, and these items are further denoted as follows.

- ❖ Failure modes: $FM = \{fm_1, fm_2, \ldots, fm_q\}$, where q is the total number of failure modes
- ❖ Causes: $CA = \{ca_{ij}\}$, where ca_{ij} is the jth cause of the ith failure mode
- ❖ Effects: $EF = \{ef_{ik}\}$, where ef_{ik} is the kth effect of the ith failure mode

In FMEA, the definition of failure modes is the key to investigate the corresponding causes and effects. The next section will discuss the definition of failure modes based on design information.

3.3. Definition of Failure Modes from Design Elements

The research effort of this thesis is about integrating the design process with the practice of FMEA. The heart of this integration lies in the definition of failure modes based on the design information. From Section 3.1, three design elements (i.e., requirements, functions and components) have been classified to form the information basis. At the same time, a failure mode can be viewed as "the manner" in which the product fails. Then, the basic principle here is to define the failure mode for each types of design elements by classifying their typical "failure manners".

When product requirements are considered as customer needs, the corresponding failure modes can be generally viewed as failing to meet the requirements. More specifically, there can be five different manners (or modes), in which failures can take place related to requirements. These modes are listed and explained as follows.

- ❖ Absence: the requirement is totally not met
- ❖ Incompleteness: the requirement is only met partially
- ❖ Intermittence: the requirement cannot be smoothly met
- ❖ Incorrectness: the requirement is met incorrectly
- ❖ Improper occurrence: the requirement is met at the wrong time

For example, consider that one requirement of the smartphone example is “have an internet connection at all times”. Then, the engineers can investigate in which manners this requirement can fail, and three possible failure modes can be identified as follows.

- ❖ Absence: the smartphone cannot support internet connection
- ❖ Intermittence: users experience frequent interruptions with internet connection
- ❖ Improper occurrence: it takes long time to connect to the internet

Note that engineers only investigate the failure modes that are reasonable to the requirement’s context. We can skip some modes that may not be too meaningful for a particular requirement. For example, it is found that “incompleteness” is not too meaningful concerning “internet connection” and thus it is not considered as one failure mode. At the point, the value of the five modes (e.g., absence, incompleteness, etc) is to provide the guideline for engineers to carry FMEA systematically.

Similarly, the functions are expressed in a phrase structure "Verb + Noun" and thus the failure modes of functions are viewed as the negative phrases structures compared to the active verbs used in expressing the function. Furthermore, while we emphasize the verbs in the function description, the failure modes are considered as any negation from its original description. In this thesis, we categorized the failure modes of functions into five types.

- ❖ Malfunction: the function is not executed
- ❖ Interference: the function execution is interfered
- ❖ Decayed: declined function performance; the function execution doesn't reach the standard after a certain of time
- ❖ Incompleteness: the function is partly executed
- ❖ Incorrectness: the function is incorrectly executed

For example, if the function "display images" is being studied, two failure modes are possibly identified by engineers.

- ❖ Malfunction: the smartphone does not display images
- ❖ Interference: the image display is interfered

The failure modes of the component in this thesis are specified for electronic components because the case study object is a smartphone. The electronic components are sensitive to the design criteria and any design details may have effects on the components' performance. Yet, only the most serious failure modes which stop components from performing the designed functions are considered in this thesis, and we categorized them as below.

- Damaged: components loss abilities to achieve the functions
- Loss of efficiency: the components perform functions less efficiently than its technical specifications
- EMI: the components emit radiation
- Non-compatible: a component's specification is non-compatible to perform the function properly

For example, a GSM transceiver is studied and the engineers possibly identify three failure modes listed below.

- Damaged: the GSM transceiver is damaged (might be burned out or discharged)
- Loss of efficiency: the GSM transceiver has difficulty to access GSM network even when it is powered
- EMI: the GSM transceiver emits the radiation

The symbols are used to denote the failure modes for each type of design elements, respectively.

- FM_a = the ath failure mode (e.g., FM_1)
- FM_a^{ri} = the ath failure mode of the ith requirement (e.g., FM_1^{r1})
- FM_a^{fj} = the ath failure mode of the jth function (e.g., FM_1^{f1})
- FM_a^{ck} = the ath failure mode of the kth component (e.g., FM_1^{c1})

3.4. Integration Model

Based on the elements of engineering design and FMEA, the integration model of this research is shown in Figure 2. In this graphical model, the boxes represent the design elements, and the ovals represent the FMEA elements. Particularly, the single-head arrows connecting the design elements indicate the flow of a design process from requirements to functions and components. The double-head arrows between design elements and failure modes show the dependency about how the design elements are used to define the failure modes of a product (i.e., the discussion in Section 3.3). Furthermore, the curved arrows belong to FMEA, and they indicate the causes and effects related to the failure models. Notably, the integration model in Figure 2 has not been found in literature and is considered one contribution of this research.

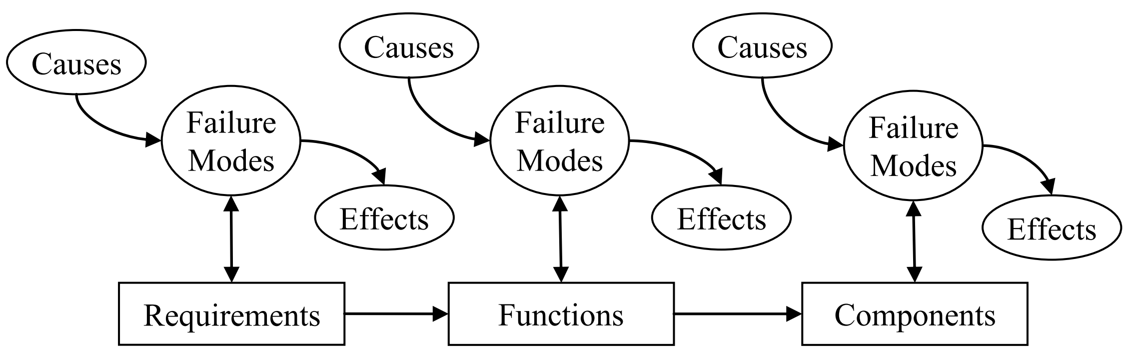

Figure 2 Integration model

Different formats and contents of FMEA exist nowadays depending on the usage timing and situations (Carlson 2012). The common FMEA applied in engineering industry is the design FMEA. In the design FMEA, as indicated in the name, it is applied during design development process, and the analyzed items are generally the functions or components. Researchers propose methodologies to apply FMEA as early as possible in the conceptual design stage in order to design out the potential causes of failure modes to lower down the risk and quality cost (Stone et al. 2005). However, it barely connects different FMEAs. As well-known, FMEA is a tedious and time consuming process (Hunt et al. 1995), and thus engineers hardly apply several FMEAs in one project especially when the development time is limited to as short as possible for an engineering product such as a smartphone. As a result, the integration model developed in this research aims to extend the existing knowledge about FMEA to connect different FMEA documents. The integration model enables engineers to apply FMEA in different key stage of design development mentioned in Section 3.1 based on the part of the efforts put in the previous analysis. That is, when engineers deploy functions based on requirements, the integration model enables engineers use part of the efforts from requirement FMEA analysis to function FMEA analysis. The FMEA connect with each other make sure the analysis consistent, especially the risk rating number. The most important requirements remain important and the identified critical failures remain critical throughout the product development process. At the point, it helps engineers prioritize and select the components corresponding to the analysis. Furthermore, the integration model also enables engineers make documentation of FMEAs and it potentially helps engineers to modify and reuse the FMEA documents in the future for product redesign and reengineering.

3.5. Smartphone Demonstration

A common requirement for a smartphone is used as a start point to demonstrate the methodology. Noted the complete case study is in Chapter 5.

Firstly, engineers collect and define the requirements and features to be designed in the product. Assume there is one requirement "R_1: have an internet connection at all time". The failure modes and effects are then identified respectively in the following.

R_1: have an internet connection at all time

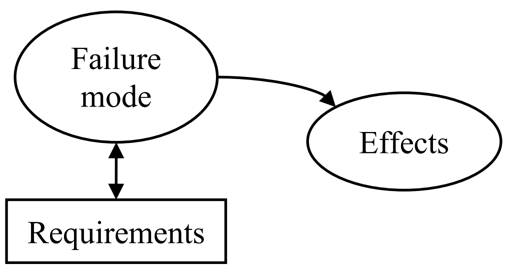

Figure 3 Schematic diagram of requirements domain analysis

Failure modes of R_1:

- ❖ FM_1^{r1}: the smartphone cannot connect to internet
- ❖ FM_2^{r1}: the users experience frequent interruptions of internet connection
- ❖ FM_3^{r1}: it takes long time to connect to the internet

Effects and causes of requirement failure modes:

EF_{11}^{r1}: the users will change the smartphone

EF_{21}^{r1}: the users might complain it and try to fix the problem

EF_{31}^{r1}: the users might accept it or tolerate it

Secondly, engineers need to deploy functions and also identify the failure modes and effects respectively.

Deploy function and identify the failure modes of functions:

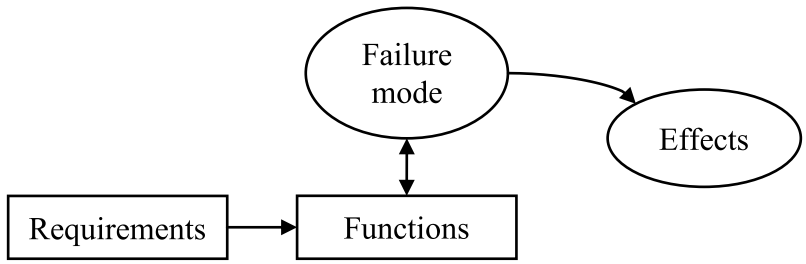

Figure 4 Schematic diagram of function domain analysis

$R_1 \rightarrow F_1$: Receive internet signal, F_2: Transmit internet signal

Failure modes and corresponding effects of F_1:

- FM_1^{f1}: The smartphone doesn't receive internet signal
- FM_2^{f1}: It takes too much time to receive internet signal
- EF_{11}^{f1}: the users cannot connect to the internet
- EF_{21}^{f1}: the users have to wait and be patient to connect to the internet

Failure modes and corresponding effects of F_2:

- FM_3^{f2}: The smartphone doesn't transmit internet signal
- FM_4^{f2}: It takes too much time to transmit internet signal
- EF_{12}^{f2}: the users cannot connect to the internet
- EF_{22}^{f2}: the users have to wait and be patient to connect to the internet

When the engineers deploy the functions from requirements and relate requirements and functions, the effects of function failures modes are the guide for the engineers to analyze the causes of requirements failure modes. In other words, functions are deployed to satisfy requirements and thus any failure modes of functions might affect the completion of requirements. The schematic diagram is showed in Figure 5. The dotted line represents the two elements are related in the integration model.

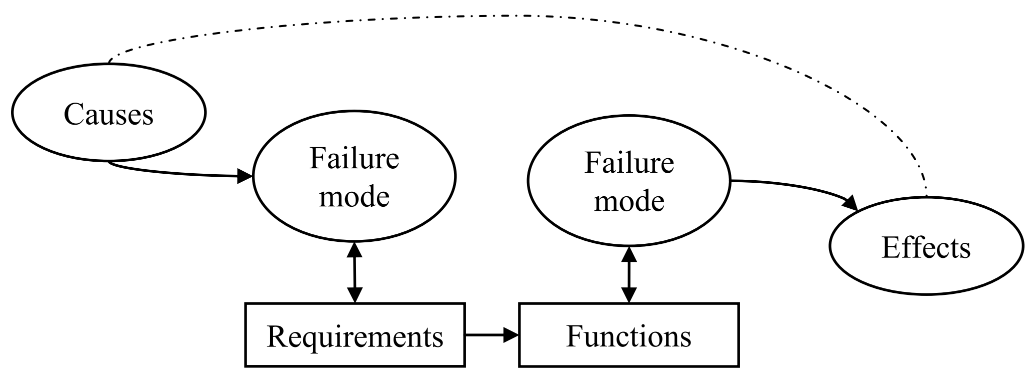

Figure 5 Schematic diagram of the relation between requirements and functions in the integration model

Thirdly, engineers define the components to achieve functions and make failure analysis accordingly.

<u>Define components and identify the failure modes and effects:</u>

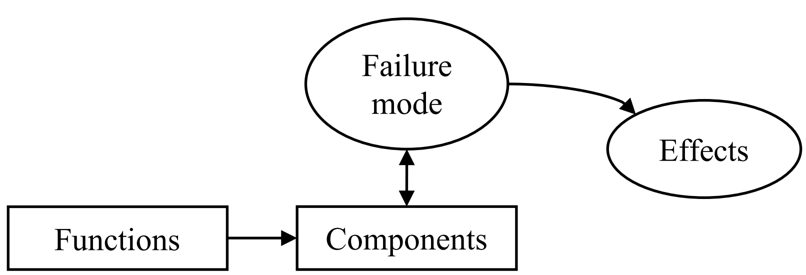

Figure 6 Schematic diagram of components domain analysis

F_1: Receive internet signal → C_1: Wi-Fi antenna, C_2: GSM transceiver

F_2: Transmit internet signal→ C_1: Wi-Fi antenna, C_2: GSM transceiver

Failure modes and corresponding effects of C_1:

- FM_1^{c1}: Wi-Fi antenna loses efficiency
- FM_2^{c1}: GSM transceiver is damaged
- EF_{11}^{c1}: the smartphone meets difficulty to connect to Wi-Fi network
- EF_{21}^{c1}: the smartphone is unable to connect to GSM network

Failure modes and corresponding effects of C_2:

- FM_3^{c2}: GSM transceiver loses its efficiency
- FM_4^{c2}: GSM transceiver emits radiation
- EF_{11}^{c2}: the smartphone is unable to connect to GSM network
- EF_{21}^{c2}: the signal display is interred (e.g. users see or hear noise signal)

Similar to the elements relations between requirements and functions, the failures of components affect the achievement of functions because the components are selected to be the solutions for functions description. The schematic diagram is showed in Figure 7.

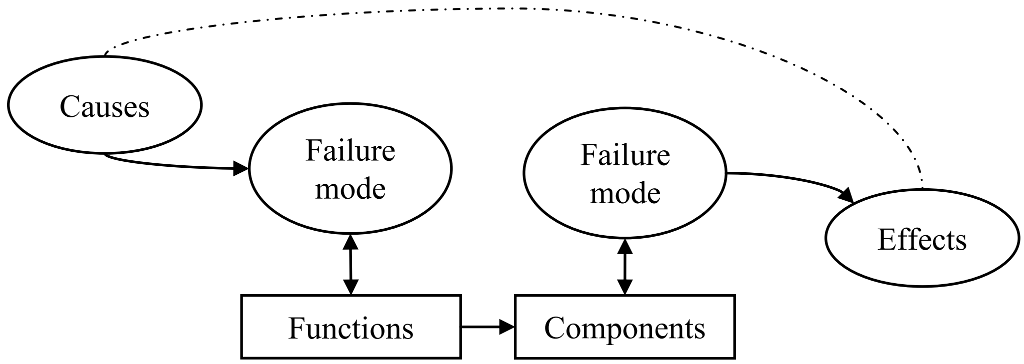

Figure 7 Schematic diagram of the relation between functions and components in the integration model

At the point, we have showed how the integration model benefits in FMEAs. The cause analysis is not a brainstorming process but a systematically analysis process when the design elements (e.g. requirements, functions, and components) are linked closely with each other and it's the goal in the product development process.

Chapter 4: FMEA-Facilitated Design Process

The purpose of this chapter is to propose the methodical procedure for facilitating the practice of FMEA in the design process. Firstly, the three-phase design process is provided based on the three elements in engineering design (i.e., requirements, functions and components). Based on this design process, a methodical procedure is developed that incorporates the FMEA practice. The benefits of the methodical procedures will be discussed at the end of this chapter.

4.1. Three-Phase Design Process

The three-phase design process focuses on the acquirement of the design information as part of the design efforts. Particularly, the design information in this research is referred to the design requirements, functions and components. Notably, the development of this design information is similar to the mapping process from the customer domain to the functional domain and then to the physical domain in axiomatic design (Suh 2001). The research work here emphasizes how to acquire the information of requirements, functions and components systematically. The three phases of the process are labeled and listed as follows.

- ❖ Phase 1: Identification of requirements
- ❖ Phase 2: Deployment of product functions
- ❖ Phase 3: Definition of product components

4.1.1. Identification of requirements

In Phase 1, the major duty is to identify the list of customer requirements that can characterize the directions of product development. The significance of requirements has been well studied in quality engineering and six-sigma management (Evans and Lindsay 2005). At this point, market research has traditionally played an important role to collect and analyze the customers' expectations, needs, perceptions, and preferences. Typical techniques from market research include formal survey, focus group, and internet monitoring (Bradley 2010).

Besides, the insights from designers and engineers are also important according their knowledge and experiences. Meeting customer expectations is often considered the minimum required to reach the bottom line of customer satisfaction. To be competitive, it is necessary to delight customers by going beyond the expectation, and therefore engineers' insights about the industry tendency and challenge are critical in identifying the requirements. Particularly, the insights of engineers are important to determine the exciters / delighters in the Kano classification system (Evans and Lindsay 2005). In addition, the insights of engineers make sure the results of market research can be translated into technical aspects without deviation.

Furthermore, the information of existing products can help the identification of requirements. By studying the existing products from the competitors in the same industry, we can compare the technical performance, product features and other characteristics. This technique is so-called competitive benchmarking that is common for setting realistic and competitive goals in product development (Stapenhurst 2009).

The expected output of phase 1 is a list of requirements that characterize the directions of product development. To get this point, method of quality function decomposition (QFD) matrix is used. QFD is a focused methodology for carefully listening to the voice of customer and then effectively responding to those needs and expectations (Evans and Lindsay 2005). Several different types of matrices are developed for different purposes of practicing QFD, such as requirements matrix, design matrix, product characteristic matrix, and so on. For the purpose of requirements identification here, the requirements matrix is used to transform the customer requirements to design requirements, which is illustrated in the Figure 8.

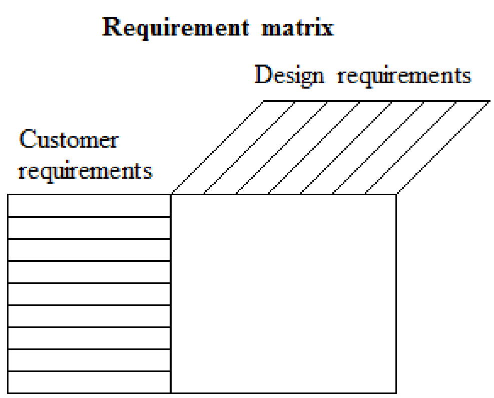

Figure 8 Requirement matrix

4.1.2. Deployment of product functions

Based on the list of requirements, product functions are deployed to indicate the engineering goals that are expected in the product. The deployment of product functions can be viewed as translating the descriptions of a product from customer languages into engineering languages. In product development, this process is similar to the design matrix in QFD, which involves the mapping between requirements to engineering characteristics (ASQ 2004). Yet, it should be noted that engineering characteristics in QFD are referred to some measurable quantities that are relevant to the satisfaction of customer requirements. Functions in this research (discussed in Section 3.2) are different by definition.

To deploy the functions based on requirements, we can use some question-asking techniques that are not uncommon in conceptual design. Given below are two possible questions that are useful to deploy functions from requirements.

- What are the expected inputs and outputs if the requirement is satisfied? The conversion process between inputs and outputs can be described as function(s).
- What actions of the product need to be carried out in order to satisfy the requirement? The actions here can be expressed as the "verbs" of the functional descriptions.

After deploying the product functions, two specific outputs are expected: a set of functions and the mapping between requirements and functions. Referring to

Section 3.1, the set of functions is denoted as $F = \{f_1, f_2, \ldots, f_n\}$. The mapping can be expressed in a matrix denoted as $RF = \{rf_{ij}\}$, where rf_{ij} is equal to one if the jth function is necessary to satisfy the ith requirement. Otherwise, rf_{ij} is equal to zero.

4.1.3. Definition of product components

Based on the list of functions, product components are defined to specify the particular solutions to achieve the functions. A design concept is generally obtained after defining the components that address all the product functions. Then, the definition of product components can be viewed as the process of concept generation in engineering design. Various techniques have been proposed for concept generation such as brainstorming, morphological chart and axiomatic design (Suh 2001).

In this research, the information of functions is one important input to stimulate the definition of components. Particularly, the inputs and outputs of each function help engineers imagine what engineering components are able to achieve such conversion. Ulrich and Eppinger (2012, chapter 7) have introduced various search techniques for concept generation such as searching the patents and engineering handbooks. In addition, they have suggested some strategies for getting design ideas in the thinking such as "make analogies" and "wish and wonder".

Defining the components for achieving the functions can be viewed as a creative process in design. The adjective "creative" here implies that we do not have an automated path that can always lead to successful designs. Among some design best practices (Stapenhurst 2009), engineers are suggested to focus on the functional descriptions in view of the necessary inputs and outputs. This helps them to clarify what exactly needs to be achieved in the products.

After defining the components, two specific outputs are expected: a set of components and the mapping between functions and components. Referring to Section 3.1, the set of components is denoted as $C = \{c_1, c_2, \ldots, c_p\}$. The mapping can be expressed in a matrix denoted as $FC = \{fc_{jk}\}$, where fc_{jk} is equal to one if the kth component is required to achieve the jth function. Otherwise, fc_{jk} is equal to zero.

Notably, the aim of this section is not to propose a new design process. The design information of requirements, functions and components has been discussed abundantly in the literature of engineering design and product development (Pahl et al. 2007). In this view, the purpose of this section is to generally discuss how we obtain the design information in this research and specify the outputs that are required in the methodical integration with FMEA.

4.2. FMEA Evaluation Schemes in the Design Process

Risk Priority number (RPN) is numerical ranking of the risk on each potential failure mode, made up of the arithmetic product of the three elements: severity of the effect, likelihood of occurrence of the cause, and likelihood of detection of the cause. (Carlson 2012, chapter 3). The severity is given associated with the most serious effect based on the scheme. The occurrence associates with the chance a failure mode may occur. The detection is given based on the control plan, and it associates with the chance a cause may be detected by the control method. The schemes are specific to the companies, projects or products (e.g., the scaling table may vary depending on the usage.) In this section, the evaluation scheme of these three numerical ranking are provided in Table 1, Table 2, and Table 3. To give the assessing number to each element, engineers followed by the evaluation scheme tables in general. In the next section, a reasoning method is developed to obtain these evaluated ranking systematically.

Definition of symbols:

- S = severity ranking
- O = occurrence ranking
- D = detection ranking
- RPN = (S x O x D)

Table 1 FMEA evaluation scheme for occurrence

Rank	Occurrence
9-10	Frequency ≥1 in 20
7-8	Frequency ≥1 in 125
5-6	Frequency ≥1 in 1250
2-4	1 in 100000 ≤ Frequency ≤ 1 in 10000
1	Frequency ≤ 1 in 1000000

(ISO MIL-STD-105E & average sales quantity per model per region)

Table 2 FMEA evaluation scheme for severity

Rank	Severity – Requirement	Severity – Function	Severity – Component
9-10	Safety issue	Safety issue	Safety issue
7-8	The users choose competitors' products	The users meet difficulty to operate the function	Effects on primary function
5-6	The users need to return the device to fix the problem	The users can operate functions but the performance is under standard	Effects only on secondary function
2-4	The users might tolerate the problem and continue to use the product	Isolated defect and doesn't affect function execution	Non-functional effects
1	Invisible to a user (make no difference to a user)	Invisible to users	Invisible to a user

Table 3 FMEA evaluation scheme for control detection

Rank	Detection
9-10	No apparent method to detect
7-8	Controlled by design analysis
5-6	Controlled by following standard design documents
2-4	Controlled by pass/fail or reliability test
1	Controlled by real-life product test (function-simulated test)

4.3. Reasoning of Causes and Effects in FMEA

Definitions of symbols:

- $S(FM_a^{ri})$ = severity ranking of the ath failure mode of the ith requirement
- $S(FM_a^{fj})$ = severity ranking of the ath failure mode of the jth function
- $S(FM_a^{ck})$ = severity ranking of the ath failure mode of the kth component
- $O(FM_a^{ck})$ = occurrence ranking of the ath failure mode of the kth component
- $S(r_i)$ = severity ranking of the ith requirement

- $S(f_j)$ = severity ranking of the jth function
- $S(c_k)$ = severity ranking of the kth component
- $O(r_i)$ = occurrence ranking of the ith requirement
- $O(f_j)$ = occurrence ranking of the jth function
- $O(c_k)$ = occurrence ranking of the kth component
- $D(c_k)$ = detection and control ranking of the kth component

Forward analysis of effects

The reasoning of effects showed below is to obtain the severity of effects of an element (i.e. requirements, functions, and components). The purpose is to prioritize the risk consequence of the element.

- $S(r_i)$ = Maximum of $S(FM_a^{ri})$ (e.g. $S(r_1)$= Max[$S(FM_a^{r1})$)]
- $S(f_j)$ = Maximum of $S(FM_a^{fj})$ (e.g. $S(f_1)$= Max[$S(FM_a^{f1})$)]
- $S(c_k)$ = Maximum of $S(FM_a^{ck})$ (e.g. $S(c_1)$= Max[$S(FM_a^{c1})$)]

The reasoning of effects showed below is to obtain the severity of functions (and components) from requirements (and functions.)

- $S(f_j)$ = Maximum of [$S(r_i)$ of all rf_{ij}] (e.g. if f_1 is deployed to satisfy both r_1 and r_2 , then $S(f_1)$ is the maximum value of $S(r_1)$ and $S(r_2)$)
- $S(c_k)$ = Maximum of [$S(f_i)$ of all fc_{jk}] (e.g. if c_1 is defined to achieve both f_1 and f_2 , then $S(c_1)$ is the maximum value of $S(f_1)$ and $S(f_2)$)

Backward analysis of causes

The reasoning of causes showed below is to obtain the occurrence of causes an element (i.e. requirements, functions, and components). The purpose is to know the chance of occurrence and complete the documentation of FMEAs to prioritize the risk of failure modes.

- O_components → O_functions → O_requirements
- $O(c_k) = \max O(FM_a^{ck})$
- $O(f_j)$ = Maximum of [$O(c_k)$ of all fc_{jk}] (e.g. if f_1 has to be achieved by both c_1 and c_2 , then $O(f_1)$ is the maximum value of $O(c_1)$ and $O(c_2)$)
- $O(r_i)$ = Maximum of [$O(f_i)$ of all rf_{ij}] (e.g. if r_1 has to be satisfied by both f_1 and f_2 , then $O(r_1)$ is the maximum value of $O(f_1)$ and $O(f_2)$)

4.4. Methodical Procedure

A methodical procedure is developed that incorporates the FMEA practice in this section. The procedure aligns with the general FMEA practice but the evaluation rating is supported by the reasoning based on Section 4.3. The procedure is showed as following and a comprehensive case study based on the procedure is done in Chapter 5.

Step 1: identify the requirements and determine their failure modes

- Identify the requirements (based on Section 4.1.1)
- Determine their failure modes (based on Section 3.3)

Step 2: analyze the effects of requirements

- ❖ Analyze the effects of requirements and decide severity (based on Section 4.2)
- ❖ Determine $S(r_i)$ from reasoning by $S(FM_a^{ri})$ (based on Section 4.3)
- ❖ Prioritize the "risk consequences" of requirements

Step 3: deploy the functions and determine their failure modes

- ❖ Deploy the functions (based on Section 4.1.2 plus the risk consequences of requirements from Step 2)
- ❖ Determine their failure modes (based on Section 3.3)

Step 4: analyze the effects of functions

- ❖ Analyze the effects of functions and decide severity (based on Section 4.2)
- ❖ Reasoning $S(f_j)$ by $S(r_i)$ (based on Section 4.3)
  - ➢ Reasoning $S(f_j)$ by $S(r_i)$
  - ➢ Reasoning $S(f_j)$ by $S(FM_a^{fj})$
  - ➢ Determine $S(f_j)$
- ❖ Prioritize the "risk consequences" of functions

Step 5: define the components and complete the FMEA document in the component domain

- ❖ Define the components (based on Section 4.1.3) plus the information from Step 4

- Determine their failure modes (based on Section 3.3)
- Analyze effects and decide severity (based on Section 4.2)
- Determine $S(c_k)$ (based on Section 4.3)
  - Reasoning $S(c_k)$ by $S(f_j)$
  - Reasoning $S(c_k)$ by $S(FM_a^{ck})$
  - Determine $S(c_k)$
- Causes
  - Analyze the causes of components and decide occurrence (based on Section 4.2)
  - Determine $L(FM_a^{ck})$ (occurrence ranking) → determine $L(c_k)$
- Define current control plan and assign detection (based on Section 4.2)
- Complete the FMEA of component

Step 6: complete the FMEA document in the function domain

- Analyze the causes of functions (based on Section 3.4)
- Determine $O(f_j)$ (based on Section 4.3)
- Complete FMEA of functions

Step 7: complete the FMEA document in the requirement domain

- Analyze the causes of requirements (based on Section 3.4)
- Determine $O(r_i)$ (based on Section 4.3)
- Complete FMEA of requirements

Figure 9 below shows where above steps are incorporated in the procedure of FMEA-facilitated design process.

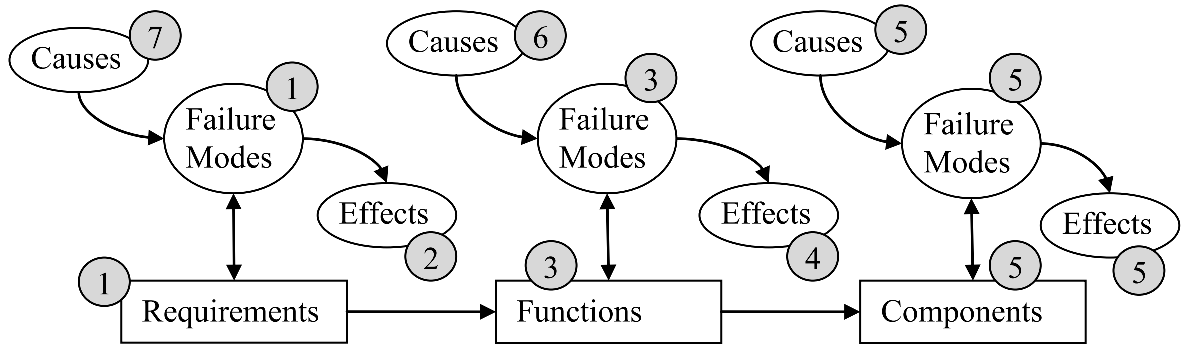

Figure 9 Schematic diagram of the procedure of FMEA-facilitated design process

After completing the FMEA-facilitated design process, benefits of the procedure can be expected in view of the design practice, listed as below.

- ❖ Cascade of the information of effects when performing the "component design" helps engineers prioritize not only the failure mode itself but also the risk of a component, a function, or a requirement. Besides, it motivates the engineers make decisions on "safe" solutions at some critical parts when the components selections are on the basis of the prioritization of the functions risk consequences.
- ❖ Logical development of FMEA documents by the support of reasoning the rating numbers minimize the mental efforts and mistakes. At the same time, the FMEA documents are completed in a relatively shorter time and more accurate results.

- The documentation of the FMEA of functions or the FMEA of requirements is potentially to be used for re-design or re-engineering of the product. The documents provide a guideline for engineers to assess the risk of the similar products with similar requirements or functions.

Chapter 5: Case Study

A step-by-step real-life product case study is presented in this chapter to demonstrate how the dependency model is applied and how it integrates the failure modes and effects analysis documents in the product development process. Three benefits are showed in the case study. First, one of the main outputs of each phase (e.g. phases defined in Section 4.1) is the risk consequences. Supporting with the method of reasoning the severity, it minimizes the human mistakes during the severity rating activities. Second, the prioritization of risk consequences helps engineers select components and be aware of the design detail to prevent critical failures. Third, by the method of reasoning the occurrences of causal factors, it helps engineers do the documentation of the efforts put in the requirements and function analysis, and it is potentially re-used for the product redesign.

In this research, design information is referred to the design requirements, functions and components. Thus, the case study is presented based on the sequence of these three design information: requirements domain, functions domain and components domain.

5.1 Requirements Domain

In the requirements domain, the main object is to prioritize the customer needs and the features which are going to delight and surprise the users. In the case study, we started from listing five common customer requirements for the smartphones in the market nowadays. After a series of analyses and reasoning the severity rating value, we got the output of requirements domain: a list of requirements and a list of prioritized risk consequences of requirements. They are the inputs to deploy the functions in the next domain.

5.1.1 Identification of the requirements

First, five most common customer requirements are listed as below.

- I can check and use my emails whenever I need it
- I need videoconference to keep connective for my job
- I like to listen to music sometimes
- I like to have digital agenda and notebook with me
- I like to keep in touch with friends through different social networks

The concept of requirement matrix in QFD methodology is used in this thesis to translate customer requirements to design requirements (see Section 4.1.1). The requirement matrix for this case study is showed in Table 4. After the analysis, we got a list of design requirements showed as below.

- R_1: have an internet connection at all time
- R_2: support videoconferencing
- R_3: support playing music
- R_4: support taking notes
- R_5: support sending messages

Table 4 Requirement matrix of smartphone example

	have an internet connection at all time	support videoconferencing	support playing music	support taking notes	support sending messages
I can check and use my emails whenever I need it	x				x
I need videoconference to keep connective for my job	x	x			
I like to listen to music sometimes			x		
I like to have digital agenda and notebook with me				x	
I like to keep in touch with friends through different social networks	x	x			x

5.1.2 Determination of the requirements failure modes

The classical failure manners can be classified because the failure modes are considered and defined as the negation of the requirement description. In Section 3.3, modes of possible requirement failures are classified into five categories, and here the worksheet is used to check each possible mode one by one. The list of requirements failure modes is identified as below.

- ❖ FM_1^{r1}: the smartphone cannot connect to internet
- ❖ FM_2^{r1}: the users experience frequent interruptions of internet connection
- ❖ FM_3^{r1}: it takes long time to connect to the internet
- ❖ FM_4^{r2}: the smartphone doesn't support videoconferencing
- ❖ FM_5^{r2}: the smartphone only supports part of the functions required in videoconferencing

- FM_6^{r2}: the users experience interruptions of image or voice transfer during videoconferencing
- FM_7^{r3}: the smartphone cannot play music
- FM_8^{r3}: the smartphone can only play specific music files
- FM_9^{r4}: the users cannot take notes by the smartphone
- FM_{10}^{r4}: the users cannot take notes (e.g. some texts are unable to edit)
- FM_{11}^{r4}: the users meet difficulties to take notes correctly (i.e. The users see incorrect notes which are different from the ones edited)
- FM_{12}^{r5}: the users cannot send messages
- FM_{13}^{r5}: the users meet difficulties to send complete messages (e.g. some texts are unable to edit)
- FM_{14}^{r5}: the users meet difficulties to send correct messages (some texts are different from the ones that users edited)

Table 5 Worksheet for identifying the failure modes of requirements

		Absence	Incompleteness	Intermittence	Incorrectness	Improper occurrence
R_1	Have an internet connection at all times	X		X		X
R_2	Support video-conference	X	X	X		
R_3	Support playing music	X	X			
R_4	Support taking notes	X	X		X	
R_5	Support sending messages	X	X		X	

5.1.3 Effect analysis of the requirements failure modes

The effect analysis of the requirements failure modes is on the basis of the point of view of users' experiences because the requirements are identified to delight the customers. Besides, the severity values are given based on the severity evaluation scheme table (see Section 4.2), which is as same as the process in the classical FMEA methodology, and the result is presented in Table 6.

Notably, how we predicted the users' reactions in a reasonable manner when we analyzed the effects of the failure modes of requirements? Keep in mind that the design requirements are from customer requirements which were collected from the market survey plus the engineers insights. As a result, the importance of these requirements is categorization and prioritization during market research. For example, if a requirement is considered as a must for all the users, such as having internet connection, the absence of this requirement is considered as a critical issue with a severity value 8. On the other hand, if a requirement is important for some users but may not be a must for other users, such as supporting of taking notes, the absence of this requirement is viewed as serious (because it is still listed in the requirement list) but not critical, and thus we gave it a severity value 5.

The step follows by the effect analysis is to apply the concept of reasoning of effects (see Section 4.3) after we marked all the severity values (See Table 6). The first approach of reasoning of severity is defined as the maximum severity value among all the failure modes of that requirement (i.e. $S(r_i)$ = Maximum of $S(FM_a^{ri})$). For example, the requirement R_1 "having an internet connection at all times" has three possible failure modes and each of them has one effect. Their severity values are 8, 6, 4 respectively, and thus the reasoned severity value of R_1 is 8 (e.g. $S(r_1)$ is 8.) The reasoned severity values of each requirement are listed as below.

- ❖ $S(r_1) = \max S(FM_a^{r1})=8$
- ❖ $S(r_2) = \max S(FM_a^{r2})=8$
- ❖ $S(r_3) = \max S(FM_a^{r3})=3$
- ❖ $S(r_4) = \max S(FM_a^{r4})=5$
- ❖ $S(r_5) = \max S(FM_a^{r5})=7$

Table 6 Effects analysis of requirement failure modes

Failure modes (FM) of requirements	Effects of requirements FM	Severity
The smartphone cannot support internet connection	The users will change smartphone	8
The users experience frequent interruptions with internet connection	The users might complain it and try to fix the problem	6
It takes long time to connect to the internet	The users might accept it or tolerate it	4
The smartphone cannot support video-conference	The users will change smartphone	8
The smartphone only supports part of the functions required in video-conference	The users will complain it and try to fix the problem	6
The users experience interruptions of image or voice transfer during video-	The users might complain it	6

conferencing		
The smartphone cannot play music	The users might accept or tolerate it	3
The smartphone can only play specific music formats	The users might not care about it and adapt it	3
The users cannot take notes by the smartphone	The users might complain it	4
The users cannot take all the notes desired, some texts is unable to edit	The users might complain it and try to fix the problem.	5
The users meet difficulty to take notes correctly (i.e. The users see incorrect notes different from the ones edited)	The users might complain it and try to fix the problem.	5
The users cannot send messages	The users might change smartphone.	7
The users meet difficulty to send complete messages, some texts is unable to edit	The users will complain and try to fix the problem	6
The users meet difficulty to send correct messages (some texts is different from edited)	The users will complain and try to fix the problem	6

5.1.4 Prioritization of the requirements risk consequences

From the severity value assigned to each effects of requirement failure mode, it is obviously which requirement failure mode has higher risk and on which we need to pay more attentions. In general, each company has their own standard in selecting the critical ones according to the value of the severity value. In this case study, we point out the ones with severity greater than or equal to 7. The prioritization is to help engineers deploy the functions and make effect analysis accordingly (e.g. if time is limited, the followed FMEA may only focus on the critical requirements on the top of the prioritization list.)

The main requirements (Select the ones with $S(r_i)$ greater than or equal to 7):

- ❖ R_1: have an internet connection at all time
- ❖ R_2: support videoconferencing
- ❖ R_5: support sending messages

The requirements failure modes on which engineers need to pay more attention:

- ❖ The smartphone cannot support internet connection (SEV=8)
- ❖ The smartphone cannot support video-conference (SEV=8)
- ❖ The users cannot send messages (SEV=7)

5.2 Function Domain

In the function domain, two main inputs are the list of requirements and the list of prioritized risk consequences of requirements. A *RF* matrix is made to show the mapping between requirements and functions after deploying the functions from requirements. Then, in the effect analysis, we obtained $S(f_j)$ by two different approaches based on Section 4.3. One approach is obtaining $S(f_j)$ from the severity value assigned by the evaluation scheme table (see Section 4.2). The other approach is obtaining $S(f_j)$ from reasoning of severity values of relevant requirements (see Section 4.3). From the comparison of these two $S(f_j)$ values from different reasoning approaches, the more accurate severity values are decided and assigned eventually to the corresponding effects of function failure modes.

5.2.1 Deployment of functions

The input of the list of requirements helps us deploy functions (see Section 4.1.2). With the question-asking technique and the experience of engineers, a set of functions are listed as below. Accordingly, the mapping between requirements and functions is presented in *RF* matrix (See Table 7). In the *RF* matrix, rf_{ij} is equal to one represents that the *j*th function is necessary to satisfy the *i*th requirement. Otherwise, rf_{ij} is equal to zero.

Deployment of functions:

- R_1: Have an internet connection at all time
  - Receive internet signal
  - Transmit internet connection request
- R_2: support videoconferencing
  - Capture video
  - Capture sound
  - Process image signal
  - Process sound signal
  - Display image signal
  - Display sound signal
  - Transport sound signal to other device
  - Connect to Internet/network

- R_3: support playing music
  - Display sound signal
  - Process sound signal
  - Transport sound signal to other device
- R_4: support taking notes
  - Input texts
  - Process texts
  - Display texts
  - Store edited files
- R_5: support sending messages
  - Input texts
  - Process texts
  - Display texts
  - Connect to internet/network

Thus, we got a list of functions.

- F_1: Receive internet signal
- F_2:Transmit internet signal
- F_3:Capture video
- F_4:Capture sound
- F_5:Process image signal
- F_6:Process sound signal
- F_7:Display image signal
- F_8:Display sound signal

- F_9:Transport sound to other device
- F_{10}:Input texts
- F_{11}:Process texts
- F_{12}:Display texts
- F_{13}:Store edited files

Table 7 *RF* matrix of the mapping between requirements and functions

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}
R_1	1	1	0	0	0	0	0	0	0	0	0	0	0
R_2	1	1	1	1	1	1	1	1	1	0	0	0	0
R_3	0	0	0	0	0	1	0	1	1	0	0	0	0
R_4	0	0	0	0	0	0	0	0	0	1	1	1	1
R_5	1	1	0	0	0	0	0	0	0	1	1	1	0

5.2.2 Determination of the function failure modes

Using the worksheet with the failure modes of functions defined in Section 3.3, we reviewed each possible mode and then got a list of function failure modes. The worksheet is showed in Table 8.

- FM_1^{f1}: The smartphone doesn't receive internet signal
- FM_2^{f1}: It takes too much time to receive internet signal
- FM_3^{f2}: The smartphone doesn't transmit internet signal
- FM_4^{f2}: It takes too much time to transmit internet signal
- FM_5^{f3}: The smartphone doesn't capture video
- FM_6^{f4}: The smartphone doesn't capture sound
- FM_7^{f5}: The smartphone doesn't process image signal

- FM_8^{f5}: It takes too much time to process image signal
- FM_9^{f6}: The smartphone doesn't process sound signal
- FM_{10}^{f7}: The smartphone doesn't display image signal
- FM_{11}^{f7}: The image display is interfered
- FM_{12}^{f8}: The smartphone doesn't display sound signal
- FM_{13}^{f8}: The sound display is interfered
- FM_{14}^{f9}: The smartphone doesn't transport sound to other device
- FM_{15}^{f10}: It doesn't input texts (no reaction after users entered texts)
- FM_{16}^{f10}: After certain of time, it doesn't input texts
- FM_{17}^{f10}: Some texts cannot be input
- FM_{18}^{f10}: The input texts are different from users' action
- FM_{19}^{f11}: The smartphone cannot process texts
- FM_{20}^{f11}: It takes too much time to process texts
- FM_{21}^{f12}: The smartphone cannot display texts
- FM_{22}^{f12}: The texts display is interfered
- FM_{23}^{f13}: The smartphone cannot store edited files

Table 8 Worksheet for identifying the failure modes of functions

		Malfunction	Interference	Decayed	Improper occurrence	Incompleteness	Incorrectness
F_1	Receive internet signal	X			X		
F_2	Transmit internet signal	X			X		
F_3	Capture video	X					

F_4	Capture sound	X					
F_5	Process image signal	X			X		
F_6	Process sound signal	X					
F_7	Display image signal	X	X				
F_8	Display sound signal	X	X				
F_9	Transport sound to other device	X					
F_{10}	Input texts	X		X		X	X
F_{11}	Process texts	X			X		
F_{12}	Display texts	X	X				
F_{13}	Store edited files	X					

5.2.3 Effect analysis of function failure modes

The effect of function failure modes is on the point of view that how it affects the requirement satisfaction (see the integrated dependency model presented in Section 4.4.) And according to the evaluation scheme table (see Section 4.2) and with the support reference of the prioritized risk consequences of requirements, the severity value of each effect is marked preliminarily (e.g. the prioritized risk consequences of requirements provide engineers an overview on the impacts of the potential failure modes). The complete analysis is showed in Table 9.

Table 9 Effect analysis of function failure modes

Functions	Failure modes (FM) of functions	Effects of functions FM	Severity
F_1	The smartphone doesn't receive internet signal	The users cannot connect to internet	8
	It takes too much time to receive internet signal	The users have to wait some time to connect to internet	5

F_2	The smartphone doesn't transmit internet signal	The users cannot connect to internet	8
	It takes too much time to transmit internet signal	The users have to wait some time to connect to internet	5
F_3	The smartphone doesn't capture video	The users cannot make videoconferencing	7
F_4	The smartphone doesn't capture sound	The users cannot make phone calls	8
F_5	The smartphone doesn't process image signal	The users cannot take photos or see any images on the screen	8
	It takes too much time to process image signal	The users have to wait to see the processed result showed on the screen	3
F_6	The smartphone doesn't process sound signal	The users cannot make phone calls or listen to music	8
F_7	The smartphone doesn't display image signal	The users see nothing on the screen	8
	The image display is interfered	The users see extra lines or dots on the screen	6
F_8	The smartphone doesn't display sound signal	The users cannot make phone calls or listen to music	8
	The sound display is interfered	The users hear noise	6
F_9	The smartphone doesn't transport sound to other device	The users cannot use their own device (such as earphone) to hear the sound	3
F_{10}	It doesn't input texts (no reaction after users enter texts)	The users cannot enter texts	8
	After certain time, it doesn't input texts	The users might meet difficulties to enter texts after certain time	5
	Some texts cannot be input	The users cannot enter all the texts desired	8
	The input texts are	The users cannot enter texts	8

	different from users' action	correctly	
F_{11}	The smartphone cannot process texts	The users see nothing on the screen	8
	It takes too much time to process texts	The users have to wait to see the processed result showed on the screen	3
F_{12}	The smartphone cannot display texts	The users see nothing on the screen	8
	The texts display is interfered	The users see extra lines or dots on the screen	6
F_{13}	The smartphone cannot store edited files	The users might lose files	7

5.2.4 Reasoning of severity $S(f_i)$

According to Section 4.3, the severity value can be reasoned by two approaches:

- ❖ Reasoning from $S(r_i)$: $S(f_j)$ = Maximum of [$S(r_i)$ of all rf_{ij}]
- ❖ Reasoning from $S(FM_a^{fj})$: $S(f_j)$ = Maximum of $S(FM_a^{fj})$

The severity evaluation scheme table provides a general idea about the impact of the function failure modes. Meanwhile, it is necessary to take consideration on the severity of requirement failure modes because the reason we deployed functions is to satisfy the requirements.

First approach (e.g. $S(f_j)$ = Maximum of [$S(r_i)$ of all rf_{ij}]:

We already knew $S(r_i)$ from Section 5.1.3 , and we also know the mapping between requirements and functions from Table 7. By applying the reasoning of severity, we got the $S(f_j)$ from the first approach and showed them in the Table 10.

Table 10 Severity of functions by reasoning from $S(r_i)$

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}
$S(f_j)$	8	8	8	8	8	8	8	8	8	7	7	7	5

Second approach (e.g. $S(f_j) = \max S(FM_a^{fj})$):

We have preliminarily marked severity values to all the effects of function failure modes in Table 9. From the reasoning of $S(f_j) = \max S(FM_a^{fj})$, we got the $S(f_j)$ from the second approach and showed them in the Table 11.

Table 11 Severity of functions by reasoning from $S(FM_a^{fj})$

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}
$S(f_j)$	8	8	7	8	8	8	8	8	3	8	8	8	7

Comparing the $S(f_j)$ obtained from two approaches, we noted that the severity value of function "Transport sound to other device" (F_9) is obviously different. How does it happen? Let's go back to review the analysis process.

In the effect analysis of function failure modes (See Table 9), function "transport sound to other device" might have one failure modes which is the malfunction (e.g. the function cannot be executed), and its effect is that the user cannot use their own device such as earphone to hear the sound. It doesn't sound too serious because the smartphone is still able to play the sound and thus the severity value was given as 3 (i.e. According to the evaluation scheme table, it is an isolated problem that does not affect executing the function of playing the sound.) Yet, if we take a closer look at the function deployment process and the relations between requirements and functions, we also have to consider that having privacy during making videoconferencing is an important aspect especially the failure mode "The smartphone only supports part of the functions required in video-conference" was listed as critical failure modes on the top of prioritization list of risk consequences of requirements. Viewed on this point, the severity of effect of unable to transport sound to other device should be marked at least more serious than others.

To make sure the severity value doesn't be mistakenly assigned less serious, we compared the Table 10 and Table 11, the bigger value was treated as the relatively more accurate value. The modified severity of effects of function failure modes is showed in Table 12. By referring to the severity of functions, it is obviously the functions with bigger severity values are the main functions the engineers need to pay more attention.

Table 12 Modified severity of functions

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}
$S(f_j)$	8	8	8	8	8	8	8	8	8	8	8	8	7

Noted the severity values in FMEA only provide an idea about which failure mode is relatively more serious or less serious and thus the values' absolute values have no meaning in the analysis unless it is compared with others. Therefore, when we modified one value, it was necessary to review other values to make sure the "tendency" and "relative relationship" still exist. Thus, meanwhile we modified the severity value in the effect analysis (Section 5.2.3) by taking reference of Table 10, and the modified effect analysis of function domain is showed in the Table 13.

Table 13 Modified effect analysis with severity values in function domain

Functions	Failure modes of functions	Effects of functions FM	Severity
F_1	The smartphone doesn't receive internet signal	The users cannot connect to internet	8
	It takes too much time to receive internet signal	The users have to wait some time to connect to internet	5
F_2	The smartphone doesn't transmit internet signal	The users cannot connect to internet	8
	It takes too much time to transmit internet signal	The users have to wait some time to connect to internet	5
F_3	The smartphone doesn't capture video	The users cannot make videoconferencing	8
F_4	The smartphone doesn't capture sound	The users cannot make phone calls	8
F_5	The smartphone doesn't process image signal	The users cannot take photos or see any images on the screen	8
	It takes too much time to process image signal	The users have to wait to see the processed result showed on the	3

		screen	
F_6	The smartphone doesn't process sound signal	The users cannot make phone calls or listen to music	8
F_7	The smartphone doesn't display image signal	The users see nothing on the screen	8
	The image display is interfered	The users see extra lines or dots on the screen	6
F_8	The smartphone doesn't display sound signal	The users cannot make phone calls or listen to music	8
	The sound display is interfered	The users hear noise	6
F_9	The smartphone doesn't transport sound to other device	The users cannot use their own device (such as earphone) to hear the sound	8
F_{10}	It doesn't input texts (no reaction after users entered texts)	The users cannot enter texts	8
	After certain of time, it doesn't input texts	The users might meet difficulties to entered texts after certain of time	6
	Some texts cannot be input	The users cannot enter all the texts desired	8
	The input texts are different from users' action	The users cannot enter texts correctly	8
F_{11}	The smartphone cannot process texts	The users see nothing on the screen	8
	It takes too much time to process texts	The users have to wait to see the processed result showed on the screen	5
F_{12}	The smartphone cannot display texts	The users see nothing on the screen	8
	The texts display is interfered	The users see extra lines or dots on the screen	6
F_{13}	The smartphone cannot store edited files	The users might lost files	7

5.2.5 Prioritization of the function risk consequences

From the modified severity value showed in Table 13, the risk consequences of functions are prioritized and listed as below. Similar to Section 5.1.4, the engineers are free to choose the critical ones to monitor depending on the projects. In this case study, we listed the functions and their failure modes with the severity greater than or equal to 7.

The main functions (Select the ones with $S(f_j)$ greater than or equal to 7):

In this case study, all the functions are treated as main functions because all the $S(f_j)$ are greater than or equal to 7. The list below is the relatively more serious ones and therefore we treated them as prioritized functions.

The most important function ($S(f_j)$ is 8):

- ❖ F_1: Receive internet signal
- ❖ F_2: Transmit internet signal
- ❖ F_3: Capture video
- ❖ F_4: Capture sound
- ❖ F_5: Process image signal
- ❖ F_6: Process sound signal
- ❖ F_7: Display image signal
- ❖ F_8: Display sound signal
- ❖ F_9: Transport sound to other device

Notably, the prioritized risk consequences of functions and requirements should be matched with each other because the functions are deployed from the requirements. If the results are not matched, the engineers have to review the analysis process.

For their failure modes, we listed the failure modes with severity value greater than or equal to 7.

The most critical ones: (SEV=8)

- ❖ The smartphone doesn’t receive internet signal
- ❖ The smartphone doesn’t transmit internet signal
- ❖ The smartphone doesn’t capture video
- ❖ The smartphone doesn’t capture sound
- ❖ The smartphone doesn’t process image signal
- ❖ The smartphone doesn’t process sound signal
- ❖ The smartphone doesn’t display image signal
- ❖ The smartphone doesn’t display sound signal
- ❖ The smartphone doesn’t transport sound to other device

Also critical ones that need to pay more attention on: (SEV=7)

- ❖ It doesn’t input texts (no reaction after users entered texts)
- ❖ Some texts cannot be input
- ❖ The input texts are different from users’ action
- ❖ The smartphone cannot process texts
- ❖ The smartphone cannot display texts

Before moving on to the next domain in the case study, notably, as so far we have already showed the two benefits that how the dependency model helps to minimize the mistakes of human factors and how it helps save time when engineers are giving the severity value. Even though the mistake may be avoided by reviewing each effect analysis one by one carefully, it will take much more time.

5.3 Component Domain

In the component domain, the main input is the function list. After defining the components to achieve the functions, the design concept is now ready to define the solutions for each function. Similarity to the function domain, the reasoning approaches also help engineers make effect analysis. What we should not forget is that the purpose of performing FMEA is to prevent serious failures and to do quality management. In other words, the main output of the component domain is not only a design concept but also a control plan. Based on this point, we also make causes analysis and define the control plan to complete the FMEA document for components.

5.3.1 Definition of the components

To define the components, we have two inputs: a list of functions and a list of risk consequences prioritization of functions. The definition of components is the particular solutions to achieve the functions, and thus the components are defined one by one based on the list of functions. Particularly, the function description and the knowledge from engineers help us to imagine what components are required. For example, to achieve the function "receive internet signal", the engineers knows there are two main internet signals: one is from Wi-Fi and another one is from GSM, and therefore the product might need Wi-Fi antenna or GSM transceiver or both of them to achieve the function.

The components are defined in Table 14 by taking reference of the smartphone that we disassembled (e.g. the complete component list is displayed in Appendix 1). For example, different components are available to achieve the function of input texts nowadays such as capacitive touchscreen, resistive touchscreen, keyboard, or so on. In this case study, we defined the component to satisfy the function of input texts as keyboard from the real-life product on hand. Besides, a *FC* matrix is showed in Table 15 to present the mapping between functions and components. In the *FC* matrix, fc_{jk} is equal to one represents that the *k*th component is defined to achieve the *j*th function. Otherwise, fc_{jk} is equal to zero.

Table 14 Components and their corresponding functions to achieve

	Functions	Components (sub-systems)
F_1	Receive internet signal	Wi-Fi antenna GSM transceiver
F_2	Transmit internet signal	Wi-Fi antenna GSM transceiver
F_3	Capture video	Camera module
F_4	Capture sound	Microphone
F_5	Process image signal	Graphic processing unit (GPU)

		Central processing unit (CPU)
F_6	Process sound signal	Audio Codec Audio processing unit (APU) CPU
F_7	Display image signal	LCD display module
F_8	Display sound signal	Headphone, speaker
F_9	Transport sound to other device	Audio jack
F_{10}	Input texts	Keyboard module, scroll key module
F_{11}	Process texts	CPU
F_{12}	Display texts	LCD display module
F_{13}	Store edited files	ROM, RAM, expansion slot

Table 15 Mapping between functions and components (*FC* matrix)

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}
F_1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
F_2	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
F_3	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
F_4	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
F_5	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
F_6	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
F_7	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
F_8	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0
F_9	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
F_{10}	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0
F_{11}	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
F_{12}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
F_{13}	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1

5.3.2 Determination of components failure modes

Failure modes of components are already defined in Section 3.3. Here, we used the worksheet to review each possibility, and the result is displayed in Table 16. In the product design, it is assumed and it is suggested to assume the raw materials (i.e. components or sub-systems in the case study) all function well and meet their specifications because the manufacturing, processing or shipping process are not controllable at this stage of conceptual design development. If engineers focus too much on the uncontrollable failure modes and causes, the FMEAs won't benefit in the design to improve the product quality because the analysis tend to blame the suppliers or manufacturers but not make quality improvement on the design itself.

The failure modes of components are listed as below.

- FM_1^{c1}: Wi-Fi antenna loses efficiency
- FM_2^{c2}: GSM transceiver is damaged
- FM_3^{c2}: GSM transceiver loses its efficiency
- FM_4^{c2}: GSM transceiver emits radiation
- FM_5^{c3}: Camera module is damaged
- FM_6^{c3}: Camera module's driver is not compatible
- FM_7^{c4}: Microphone is damaged
- FM_8^{c4}: Microphone's driver is not compatible
- FM_9^{c5}: GPU is damaged
- FM_{10}^{c5}: GPU emits radiation
- FM_{11}^{c5}: GPU and operating system (OS) is not compatible
- FM_{12}^{c6}: CPU is damaged
- FM_{13}^{c6}: CPU emits radiation
- FM_{14}^{c6}: CPU and OS is not compatible
- FM_{15}^{c7}: Audio Code is damaged
- FM_{16}^{c7}: Audio Code is not compatible with drivers

- FM_{17}^{c8}: APU is damaged
- FM_{18}^{c8}: APU emits radiation
- FM_{19}^{c8}: APU and OS is not compatible
- FM_{20}^{c9}: LCD display module is damaged
- FM_{21}^{c10}: Headphone is not compatible with its driver
- FM_{22}^{c11}: Speaker is not compatible with its driver
- FM_{23}^{c12}: Audio jack is damaged
- FM_{24}^{c13}: Keyboard is damaged
- FM_{25}^{c13}: Keyboard module loses its efficiency
- FM_{26}^{c14}: Scroll key module loses its efficiency
- FM_{27}^{c15}: ROM emits radiation
- FM_{28}^{c16}: RAM emits radiation
- FM_{29}^{c17}: Expansion slot is damaged

Table 16 Worksheet of components failure modes

		Damaged	Loss of efficiency	EMI	Non-compatible
C_1	Wi-Fi antenna		X	X	
C_2	GSM transceiver	X	X	X	
C_3	Camera module	X			X
C_4	Microphone	X			X
C_5	Graphic processing unit (GPU)	X		X	X
C_6	Central processing unit (CPU)	X		X	X
C_7	Audio Codec	X			X
C_8	Audio processing unit (APU)	X		X	X
C_9	LCD display module	X			

C_{10}	Headphone				X
C_{11}	Speaker				X
C_{12}	Audio jack	X			
C_{13}	Keyboard module	X	X		
C_{14}	scroll key module		X		
C_{15}	ROM			X	
C_{16}	RAM			X	
C_{17}	Expansion slot	X			

5.3.3 Effect analysis of the components failure modes

Effect of components failure modes focus on the impacts of functions achievement, the mapping is showed in the integrated model in Section 4.4. For example, if a Wi-Fi antenna loses efficiency (e.g. doesn't function as wrote in the specification), it might have an effect that the smartphone meet difficulty to connect to Wi-Fi network. The severity value is assigned based on the evaluation scheme table defined in Section 4.2, and the effect analysis is showed in Table 17.

Table 17 Effect analysis of components failure modes

Components	Failure modes (FM) of components	Effects of components FM	Severity
C1	Wi-Fi antenna loses efficiency	The smartphone meets difficulty to connect to Wi-Fi network	7
C2	GSM transceiver is damaged	The smartphone cannot connect to GSM network	8
	GSM transceiver loses its efficiency	The smartphone meets difficulty to connect to GSM network	7
	GSM transceiver emits radiation	Signal output display might be interfered	4
C3	Camera module is	The smartphone cannot get	7

	damaged	images	
	Camera module's driver is not compatible	The smartphone cannot get images	7
C4	Microphone is damaged	The smartphone cannot get sounds from users	8
	Microphone's driver is not compatible	The smartphone cannot get sounds from users	8
C5	GPU is damaged	The smartphone cannot process image signal	8
	GPU emits radiation	The signal output display might be interfered	4
	GPU and operating system (OS) are not compatible	The smartphone cannot process image signal	8
C6	CPU is damaged	The smartphone cannot execute any function	8
	CPU emits radiation	The signal output display might be interfered	4
	CPU and OS are not compatible	The smartphone cannot execute any function	8
C7	Audio Code is damaged	The smartphone cannot process sound signal	8
	Audio Code is not compatible with drivers	The smartphone cannot process sound signal	8
C8	APU is damaged	The smartphone cannot process sound signal	8
	APU emits radiation	The signal output display might be interfered	4
	APU and OS is not compatible	The smartphone cannot process sound signal	8
C9	LCD display module is damaged	The smartphone cannot display images/texts	8
C10	Headphone is not compatible with its driver	The smartphone cannot display sounds	8
C11	Speaker is not compatible with its driver	The smartphone cannot display sounds	8
C12	Audio jack is damaged	Sound signal cannot be transported to other devices	6

C13	Keyboard is damaged	The users cannot input texts/instruction by keyboard	8
	Keyboard module loses its efficiency	The users meet difficulty to input texts/instruction	5
C14	Scroll key module loses its efficiency	The users meet difficulty to input texts/instruction	5
C15	ROM emits radiation	The signal output display might be interfered	4
C16	RAM emits radiation	The signal output display might be interfered	4
C17	Expansion slot is damaged	The smartphone has limited storage capacity	3

5.3.4 Reasoning severity $S(c_k)$

Two reasoning approaches are used to get severity of components failure modes based on Section 4.3.

- Reasoning from $S(f_j)$: $S(c_k)$ = Maximum of [$S(f_i)$ of all fc_{jk}]
- Reasoning from $S(FM_a^{ck})$: $S(c_k)$ = Maximum of $S(FM_a^{ck})$

The first approach considers that the components are defined to achieve function description and therefore the severity of components failure modes can be derived from the severity of the function and the mapping between functions and components. The second approach considers the severity valueing from the evaluation scheme table defined in Section 4.2.

First approach (e.g. $S(c_k)$ = Maximum of [$S(f_j)$ of all fc_{jk}]:

We got the $S(f_j)$ in Table 12 in Section 5.2.1, and the mapping between functions and components is showed in Table 15. By the reasoning of severity, the $S(c_k)$ is presented in Table 18.

Table 18 Severity of components by reasoning from $S(f_j)$

Components	$S(c_k)$	Components	$S(c_k)$
C_1	8	C_{10}	8
C_2	8	C_{11}	8
C_3	8	C_{12}	8
C_4	8	C_{13}	7
C_5	8	C_{14}	7
C_6	8	C_{15}	6
C_7	8	C_{16}	6
C_8	8	C_{17}	6
C_9	8		

Second approach (e.g. $S(c_k)$ = Maximum of $S(FM_a^{ck})$):

The severity values are preliminarily marked in Table 17 based on the evaluation scheme table defined in Section 4.2. By the reasoning of severity from it, we got the $S(c_k)$ and they are displayed in Table 19.

Table 19 Severity of components by reasoning from $S(FM_a^{ck})$

Components	$S(c_k)$	Components	$S(c_k)$
C_1	7	C_{10}	8
C_2	8	C_{11}	8
C_3	7	C_{12}	6
C_4	8	C_{13}	8
C_5	8	C_{14}	5
C_6	8	C_{15}	4
C_7	8	C_{16}	4

C_8	8	C_{17}	3
C_9	8		

From the comparison of the $S(c_k)$ reasoned by two approaches, obviously some effects of components failure modes are under estimated in Table 17. For example, the damaged expansion slot (C_{17}) has an effect "the smartphone has limited storage capacity", if engineers don't consider it has negative effect on the function description "store edited files", the severity rating will be low based on the evaluation scheme table. It may not be totally wrong if other components (e.g. ROM and RAM) support this function both work perfectly, and it is the reason that on the effect analysis, the defect of expansion slot is not marked as serious effect. But when don't have control or confidence that other components are without any defects, it is better we assume the function need this component to be executed. Thus, the modified severity of components is showed in Table 20.

As mentioned in function domain, we also modified the severity values based on the Table 20, and the modified effect analysis is displayed in Table 21.

Table 20 Modified severity of components

Components	$S(c_k)$	Components	$S(c_k)$
C_1	8	C_{10}	8
C_2	8	C_{11}	8
C_3	8	C_{12}	8
C_4	8	C_{13}	8
C_5	8	C_{14}	7
C_6	8	C_{15}	6
C_7	8	C_{16}	6
C_8	8	C_{17}	6

C_9	8		

Table 21 Modified effect analysis with severity values in component domain

Components	Failure modes	Effects	SEV
C1	Wi-Fi antenna loses efficiency	The smartphone meets difficulty to connect to Wi-Fi network	8
C2	GSM transceiver is damaged	The smartphone cannot connect to GSM network	8
	GSM transceiver loses its efficiency	The smartphone meets difficulty to connect to GSM network	7
	GSM transceiver emits radiation	Signal output display might be interfered	6
C3	Camera module is damaged	The smartphone cannot get images	8
	Camera module's driver is not compatible	The smartphone cannot get images	8
C4	Microphone is damaged	The smartphone cannot get sounds from users	8
	Microphone's driver is not compatible	The smartphone cannot get sounds from users	8
C5	GPU is damaged	The smartphone cannot process image signal	8
	GPU emits radiation	The signal output display might be interfered	6
	GPU and operating system (OS) are not compatible	The smartphone cannot process image signal	8
C6	CPU is damaged	The smartphone cannot execute any function	8
	CPU emits radiation	The signal output display might be interfered	6
	CPU and OS are not compatible	The smartphone cannot execute any function	8
C7	Audio Code is damaged	The smartphone cannot process sound signal	8
	Audio Code is not	The smartphone cannot	8

	compatible with drivers	process sound signal	
C8	APU is damaged	The smartphone cannot process sound signal	8
	APU emits radiation	The signal output display might be interfered	6
	APU and OS are not compatible	The smartphone cannot process sound signal	8
C9	LCD display module is damaged	The smartphone cannot display images/texts	8
C10	Headphone is not compatible with its driver	The smartphone cannot display sounds	8
C11	Speaker is not compatible with its driver	The smartphone cannot display sounds	8
C12	Audio jack is damaged	Sound signal cannot be transported to other devices	8
C13	Keyboard is damaged	The users cannot input texts/instruction by keyboard	8
	Keyboard module loses its efficiency	The users meet difficulty to input texts/instruction	7
C14	Scroll key module loses its efficiency	The users meet difficulty to input texts/instruction	7
C15	ROM emits radiation	The signal output display might be interfered	6
C16	RAM emits radiation	The signal output display might be interfered	6
C17	Expansion slot is damaged	The smartphone has limited storage capacity	6

5.3.5 Cause analysis of components failure modes

Based on Section 3.2, the cause analysis in FMEA has to be the controllable and improvable causes that are capable being eliminated or monitored by engineers. View on this point, for every cause of component failure modes, the reason for the causal factor existence is the improper design. Thus, we listed some common possible design failures as below.

- Improper calculation of dimension, tolerance or shape
- Improper component selection, including materials and specifications.
- Improper circuit analysis
- Lack of components or required protection
- Inconsideration of operation conditions in real life

The cause analysis mainly depends on engineers' experience and knowledge. The above list is only a reference for engineers to review and assess the possibility in a certain failure mode. In the real situation, it is still suggested engineers write down the causes in a clear manner. For example, the Wi-Fi antenna loses efficiency is analyzed to be caused by shielding (i.e. the component Wi-Fi antenna works complying with its specification and the signal coverage is good and strong. Nevertheless, the component (may be a frame) between the signal coverage and the antenna shields the signal and prevent the Wi-Fi antenna receiving the signal.) It belongs to the improper component selection (i.e. the thickness of the frame may be too thick that is over the Wi-Fi antenna's capacity). Another possible cause is the static electricity from the users and it can be categorized into the design failure of inconsideration of operation conditions in real life and as well as improper component selection (the material of the frame is too sensitive to the static electricity and affects the components inside the frame). The reason that engineers should think from the possible design failures and write down in a clear description is that it is clearer for the record and it is easier for engineers to assess the occurrence.

After the cause analysis, the occurrence value is given preliminarily based on the evaluation scheme table defined in Section 4.2. (See Table 22)

Table 22 Cause analysis of components failure modes

Failure modes of components	Causes of components FM	Occurrence
Wi-Fi antenna loses efficiency	Shielded	6
	Static electricity	6
GSM transceiver is damaged	Electrostatic discharge (ESD)	4
GSM transceiver loses its efficiency	Shielded	6
GSM transceiver emits radiation	Lack of proper EMI shielding	4
Camera module is damaged	ESD	4
	Overcurrent	4
Camera module's driver is not compatible	Improper components selection	2
Microphone is damaged	ESD	4
Microphone's driver is not compatible	Improper components selection	2
GPU is damaged	ESD	4
	Overcurrent	4
GPU emits radiation	Lack of proper EMI shielding	4
GPU and operating system (OS) are not compatible	Improper components selection	2
CPU is damaged	ESD	4
	Overcurrent	4
CPU emits radiation	Lack of proper EMI shielding	4
CPU and OS are not compatible	Improper components selection	2
Audio Code is damaged	ESD	4
	Overcurrent	4
Audio Code is not compatible with drivers	Improper components selection	2
APU is damaged	ESD	4
	Overcurrent	4
APU emits radiation	Lack of proper EMI shielding	4
APU and OS are not compatible	Improper components selection	2

LCD display module is damaged	Overcurrent	3
	External force	3
Headphone is not compatible with its driver	Improper components selection	2
Speaker is not compatible with its driver	Improper components selection	2
Audio jack is damaged	Insensitive contact (improper component selection or improper tolerance design)	1
Keyboard is damaged	External force	3
Keyboard module loses its efficiency	Improper tolerance design	5
	Improper component selection	4
Scroll key module loses its efficiency	Dimension mismatch	5
	Improper component selection	4
ROM emits radiation	Lack of proper EMI shielding	4
RAM emits radiation	Lack of proper EMI shielding	4
Expansion slot is damaged	External force	1

5.3.6 Reasoning of causes of components failure modes

The reasoning of causes of components failure modes is defined as $O(c_k)$ = max $O(FM_a^{ck})$ in Section 4.3. The reasoned $O(c_k)$ are listed in Table 23.

Table 23 Reasoned occurrence of components failures modes

Components	$L(c_k)$	Components	$L(c_k)$
C_1	6	C_{10}	2
C_2	6	C_{11}	2
C_3	4	C_{12}	1
C_4	4	C_{13}	5
C_5	4	C_{14}	5
C_6	4	C_{15}	4
C_7	4	C_{16}	4

C_8	4	C_{17}	1
C_9	3		

5.3.7 Decision of control plan and detection

One of the valuable outputs of FMEA is the quality control plan. After the cause and effect analysis for the component failure modes and relevant severity and occurrence ranking, the engineers get basic ideas about the failure modes. The occurrence and the severity values provide a guideline for designers to decide the control methods. If these two rating values are both high, it is necessary for engineers to decide a control method with low detection.

One type of control plan is eliminating the causal factor, such as setting the dimension tolerance by following a guideline (might be an internal document such as SOP in a company) to prevent dimension miscalculation. The other type of the control plan is detecting the causal factor, such as performing function test.

Nevertheless, it is relatively harder to define the control method because the case study focuses on the early design stage (i.e. conceptual design). In other words, the engineers may suggest that the component needs to be checked by functional test in order to monitor the possible failure modes, but the functional test machine will not be made in the conceptual design. Yet, the engineers can still write down the current control method and rate them based on Section 4.2 to assess overall risk by the risk priority value (RPN). (See Table 24)

5.3.8 Completion of FMEA for components

After all the preparing work in Section 5.3, we had all the materials on hands to complete the document of FMEA for component. The completion of FMEA for components is one of the milestones in the product development process. The FMEA for components provides a guideline for engineers to consider the components specification selection and the proper quality control plan to prevent critical failures. The critical failures mean the critical ones that we prioritized in requirements and functions domains.

With the supporting document of the prioritized risk consequences of functions, the engineers are able to review design concept. In other words, engineers are able to define a component or components as a solution of a functional description easily. However, it doesn't give engineers more information on selecting the specification of components or the design details such as component location and relations with other components. For example, the engineers may put Wi-Fi antenna and GSM transceiver in the smartphone design to provide the feature of internet connection to the users, but without careful thinking about how serious the impact is when the component failure modes occurred or how it may affect the users, the engineers may not pay much attention on these components. The well-known examples are antennagate happened on iPhone 4 and similar issue happened on HTC legend.

It doesn't mean that the integration of FMEA and design development process can prevent such fails, but at least the engineers have more chance to "see" the possible result about the improper design by the supporting documents of prioritized risk consequences. Besides, the integration of FMEAs in the conceptual design makes sure the ratings are consistent throughout the product development process and minimize the mistakes of human factors by reasoning the cause and effects.

Furthermore, engineers are able to review the critical failure modes of components after completing the FMEA for components by RPN. It gives engineers more information to select proper components or to decide the control plan when the design is done. For example, in Table 24, the row with relatively higher RPN is "GSM transceiver is damaged by ESD and it has a high severity effect because the smartphone will be unable to connect to GSM network." In this case, the engineers definitely need to design protection to protect GSM transceiver from ESD in the processes of handling the GSM transceiver component, or to design the method to eliminate the static electricity, or to select a GSM transceiver less sensitive to static electricity.

Table 24 FMEA for components

Components	Failure modes	Effects	S	Causes	O	Control	D	RPN
Wi-Fi antenna	Wi-Fi antenna loses efficiency	The smartphone meets difficulty to connect to	8	Shielded	6	Follow design SOP	5	240

		Wi-Fi network						
				Static electricity	6	Follow design SOP	5	240
GSM transceiver	GSM transceiver is damaged	The smartphone cannot connect to GSM network	8	Electrostatic discharge (ESD)	4	None	9	288
	GSM transceiver loses its efficiency	The smartphone meets difficulty to connect to GSM network	7	Shielded	6	Follow design SOP	5	210
	GSM transceiver emits radiation	Signal output display might be interfered	6	Lack of proper EMI shielding	4	Design analysis	7	168
Camera module	Camera module is damaged	The smartphone cannot get images	8	ESD	4	None	9	288
				Overcurrent	4	Follow design SOP	5	160
	Camera module’s driver is not compatible	The smartphone cannot get images	8	Improper components selection	2	Design analysis	7	112
Microphone	Microphone is damaged	The smartphone cannot get sounds from users	8	ESD	4	None	9	288
	Microphone’s driver is not compatible	The smartphone cannot get sounds from users	8	Improper components selection	2	Design analysis	7	112
GPU	GPU is	The	8	ESD	4	None	9	288

	damaged	smartphone cannot process image signal						
				Overcurrent	4	Follow design SOP	5	160
	GPU emits radiation	The signal output display might be interfered	6	Lack of proper EMI shielding	4	Design analysis	7	168
	GPU and operating system (OS) are not compatible	The smartphone cannot process image signal	8	Improper components selection	2	Design analysis	7	112
CPU	CPU is damaged	The smartphone cannot execute any function	8	ESD	4	None	9	288
				Overcurrent	4	Follow design SOP	5	160
	CPU emits radiation	The signal output display might be interfered	6	Lack of proper EMI shielding	4	Design analysis	7	168
	CPU and OS are not compatible	The smartphone cannot execute any function	8	Improper components selection	2	Design analysis	7	112
Audio Code	Audio Code is damaged	The smartphone cannot process sound signal	8	ESD	4	None	9	288
				Overcurrent	4	Follow design SOP	5	160
	Audio Code is not compatible	The smartphone cannot process	8	Improper components selection	2	Design analysis	7	112

	with drivers	sound signal						
APU	APU is damaged	The smartphone cannot process sound signal	8	ESD	4	None	9	288
				Overcurrent	4	Follow design SOP	5	160
	APU emits radiation	The signal output display might be interfered	6	Lack of proper EMI shielding	4	Design analysis	7	168
	APU and OS is not compatible	The smartphone cannot process sound signal	8	Improper components selection	2	Design analysis	7	112
LCD display module	LCD display module is damaged	The smartphone cannot display images/texts	8	Overcurrent	3	Follow design SOP	5	120
				External force	3	None	9	243
Headphone	Headphone is not compatible with its driver	The smartphone cannot display sounds	8	Improper components selection	2	Design analysis	7	112
Speaker	Speaker is not compatible with its driver	The smartphone cannot display sounds	8	Improper components selection	2	Design analysis	7	112
Audio jack	Audio jack is damaged	Sound signal cannot be transported to other devices	8	Insensitive contact (improper component selection or improper tolerance design)	1	Design analysis	7	56
Keyboard module	Keyboard is damaged	The users cannot input	8	External force	3	None	9	243

		texts/instruction by keyboard						
	Keyboard module loses its efficiency	The users meet difficulty to input texts/instruction	7	Improper tolerance design	5	Follow design SOP	5	175
				Improper component selection	4	Design analysis	7	196
Scroll key module	Scroll key module loses its efficiency	The users meet difficulty to input texts/instruction	7	Dimension mismatch	5	Follow design SOP	5	175
				Improper component selection	4	Design analysis	7	196
ROM	ROM emits radiation	The signal output display might be interfered	6	Lack of proper EMI shielding	4	Design analysis	7	168
RAM	RAM emits radiation	The signal output display might be interfered	6	Lack of proper EMI shielding	4	Design analysis	7	168
Expansion slot	Expansion slot is damaged	The smartphone has limited storage capacity	6	External force	1	None	9	54

5.4 Completion of the documentation for functions

In Section 5.4 and Section 5.5, it’s the case study about documentation for FMEAs of functions and requirements based on the analyzed in Section 5.1 – Section 5.3. The documentation of the complete FMEAs of functions or requirements has no direct help in the engineering product development process.

Nevertheless, it will benefit the engineers to check and modify the relative FMEAs when this product is re-designed.

5.4.1 Causes of functions failure modes analysis

Causes of functions failure modes are inspired by the effects of component failure modes. The *FC* matrix (Table 15) provides a mapping between functions and components and from which we know a function is achieved by several components. For example, *F1* is achieved by *C1*, *C2* and *C6*. On this point, the failure of *C1*, *C2* and *C6* might affect *F1*. Thus, we needed to check components *C1*, *C2* and *C6* when we analyzed the possible causes responsible for the failure modes of function *F1*. Based on this principle, we completed the caused analysis in the Table 25.

Table 25 Cause analysis of function failure modes

Functions	Failure modes (FM) of functions	Causes of function FM
F_1	The smartphone doesn't receive internet signal	Wi-Fi antenna loses efficiency
		GSM transceiver is damaged
		GSM transceiver loses its efficiency
		CPU is damaged.
		CPU and OS are not compatible.
	It takes too much time to receive internet signal	Wi-Fi antenna loses efficiency
		GSM transceiver loses its efficiency
F_2	The smartphone doesn't transmit	Wi-Fi antenna loses

	internet signal	efficiency
		GSM transceiver is damaged
		GSM transceiver loses its efficiency
		CPU is damaged.
		CPU and OS are not compatible.
	It takes too much time to transmit internet signal	Wi-Fi antenna loses efficiency
		GSM transceiver loses its efficiency
F_3	The smartphone doesn't capture video	Camera module is damaged
		Camera module's driver is not compatible
		CPU is damaged.
		CPU and OS are not compatible.
F_4	The smartphone doesn't capture sound	Microphone is damaged
		Microphone's driver is not compatible
		CPU is damaged.
		CPU and OS are not compatible.
F_5	The smartphone doesn't process image signal	GPU is damaged.
		GPU and OS are not compatible.
		CPU is damaged.
		CPU and OS are not compatible.
	It takes too much time to process image signal	Improper GPU and CPU selection.
F_6	The smartphone doesn't process sound signal	CPU is damaged.
		CPU and OS are not compatible.
		Audio Code is damaged.
		Audio code is not compatible

		with drivers.
		APU is damaged.
		APU and OS are not compatible.
F_7	The smartphone doesn't display image signal	CPU is damaged.
		CPU and OS are not compatible.
		LCD display module is damaged.
	The image display is interfered	Components emit radiation.
F_8	The smartphone doesn't display sound signal	CPU is damaged.
		CPU and OS are not compatible.
		Headphone is not compatible with its driver.
		Speaker is not compatible with its driver.
	The sound display is interfered	Components emit radiation.
F_9	The smartphone doesn't transport sound to other device	CPU is damaged.
		CPU and OS are not compatible.
		Audio jack is damaged.
F_{10}	It doesn't input texts (no reaction after users entered texts)	CPU is damaged.
		CPU and OS are not compatible.
		Keyboard is damaged.
	After certain of time, it doesn't input texts	Keyboard module loses its efficiency.
	Some texts cannot be input	Keyboard module loses its efficiency.
	The input texts are different from users' action	Keyboard module loses its efficiency.
F_{11}	The smartphone cannot process texts	CPU is damaged.
		CPU and OS are not compatible.

	It takes too much time to process texts	Improper CPU selection.
F_{12}	The smartphone cannot display texts	CPU is damaged.
		CPU and OS are not compatible.
		LCD display module is damaged.
	The texts display is interfered	Components emit radiation.
F_{13}	The smartphone cannot store edited files	CPU is damaged.
		CPU and OS are not compatible.
		Expansion slot is damaged

Notably, we didn't consider components relations in this research and therefore some causes may not be noticed at the first sight for engineers without experience by considering only the functions and components relations. The possible solution is making a component-component (*CC*) matrix to map the relations between components and thus the failure modes of related components are also considered. We recommend it to be done in the future work.

5.4.2 Determine $O(f_j)$

Based on Section 4.3, the occurrence of function is determined by the occurrence of components (i.e. $O(f_j)$ = Maximum of [$O(c_k)$ of all fc_{jk}]). Accordingly, the roccurrence of the causes of functions failure modes is reasoned and showed in Table 26.

Table 26 the reasoned occurrence of causes of functions failure modes

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}
$O(f_j)$	6	6	4	4	4	4	4	4	4	5	4	4	5

Notably, the occurrence of the causes of functions failure modes can be assigned based on the evaluation scheme table if the engineers have experiences on it. Otherwise, $O(f_j)$ is more accurate based on the chance of causes responsible for components failure modes (i.e. $O(c_i)$).

5.4.3 Completion of the FMEA document of functions

The FMEA of functions (See Table 27) is completed based on Table 13, Table 25 and Table 26. For re-design, the components may be changed and thus the causes of function FM are just a reference. But the valuable result by take it as a reference is that the engineers are able to assess the possible occurrence based on it (i.e. the similar design.) The documentation helps engineers maintain the corresponding FMEAs in re-design process. For example, when engineers select resistant-touch screen instead of LCD display module to achieve F_7 (i.e. display signal), the causes that related to LCD display module have to be evaluated. Besides, if engineers have made *CC* matrix, it will also help to do the evaluation over the whole functions' cause analysis.

Table 27 FMEA for functions

F	Failure modes (FM) of functions	Effects of functions FM	S	Causes of function FM	O	RPN
F_1	The smartphone doesn't receive internet signal	The users cannot connect to internet	8	Wi-Fi antenna loses efficiency	6	48
				GSM transceiver is damaged		
				GSM transceiver loses its efficiency		
				CPU is damaged.		
				CPU and OS are not compatible.		
	It takes too much time to receive internet signal	The users have to wait some time to connect to internet	5	Wi-Fi antenna loses efficiency		30
				GSM transceiver loses its efficiency		
F_2	The smartphone doesn't transmit internet signal	The users cannot connect to internet	8	Wi-Fi antenna loses efficiency	6	48
				GSM transceiver is damaged		
				GSM transceiver loses its efficiency		
				CPU is damaged.		
				CPU and OS are not compatible.		
	It takes too much time to transmit internet signal	The users have to wait some time to connect to internet	5	Wi-Fi antenna loses efficiency		30

				GSM transceiver loses its efficiency		
F_3	The smartphone doesn't capture video	The users cannot make videoconferencing	8	Camera module is damaged	4	32
				Camera module's driver is not compatible		
				CPU is damaged.		
				CPU and OS are not compatible.		
F_4	The smartphone doesn't capture sound	The users cannot make phone calls	8	Microphone is damaged	4	32
				Microphone's driver is not compatible		
				CPU is damaged.		
				CPU and OS are not compatible.		
F_5	The smartphone doesn't process image signal	The users cannot take photos or see any images on the screen	8	GPU is damaged.	4	32
				GPU and OS are not compatible.		
				CPU is damaged.		
				CPU and OS are not compatible.		
	It takes too much time to process image signal	The users have to wait to see the processed result showed on the screen	3	Improper GPU and CPU selection.		12
F_6	The smartphone doesn't process sound signal	The users cannot make phone calls or listen to music	8	CPU is damaged.	4	32

				CPU and OS are not compatible.		
				Audio Code is damaged.		
				Audio code is not compatible with drivers.		
				APU is damaged.		
				APU and OS are not compatible.		
F_7	The smartphone doesn't display image signal	The users see nothing on the screen	8	CPU is damaged.	4	32
				CPU and OS are not compatible.		
				LCD display module is damaged.		
	The image display is interfered	The users see extra lines or dots on the screen	6	Components emit radiation.		24
F_8	The smartphone doesn't display sound signal	The users cannot make phone calls or listen to music	8	CPU is damaged.	4	32
				CPU and OS are not compatible.		
				Headphone is not compatible with its driver.		
				Speaker is not compatible with its driver.		
	The sound display is interfered	The users hear noise	6	Components emit radiation.		24
F_9	The smartphone doesn't transport sound to other device	The users cannot use their own device (such as earphone) to hear the sound	8	CPU is damaged.	4	32

				CPU and OS are not compatible.		
				Audio jack is damaged.		
F_{10}	It doesn't input texts (no reaction after users enter texts)	The users cannot enter texts	7	CPU is damaged.	5	35
				CPU and OS are not compatible.		
				Keyboard is damaged.		
	After certain of time, it doesn't input texts	The users might meet difficulties to enter texts after certain of time	5	Keyboard module loses its efficiency.		25
	Some texts cannot be input	The users cannot enter all the texts desired	7	Keyboard module loses its efficiency.		35
	The input texts are different from users' action	The users cannot enter texts correctly	7	Keyboard module loses its efficiency.		35
F_{11}	The smartphone cannot process texts	The users see nothing on the screen	7	CPU is damaged.	4	28
				CPU and OS are not compatible.		
	It takes too much time to process texts	The users have to wait to see the processed result showed on the screen	3	Improper CPU selection.		12
F_{12}	The smartphone cannot display texts	The users see nothing on the screen	7	CPU is damaged.	4	28
				CPU and OS are not compatible.		
				LCD display module is damaged.		

	The texts display is interfered	The users see extra lines or dots on the screen	6	Components emit radiation.		24
F_{13}	The smartphone cannot store edited files	The users might lose files	6	CPU is damaged.	5	30
				CPU and OS are not compatible.		
				Expansion slot is damaged		

5.5 Completion of the documentation for requirements

Similarity to the FMEA of functions, the FMEA of requirements is completed for the documentation purpose.

5.5.1 Analyze the causes of requirements based on Section 4.2

Causes analysis of requirements failure modes can be inspired by the effects of functions failure modes (See Figure 5). We know the mapping between requirements and functions in the *RF* matrix (Table 7) and accordingly we check the possible causes for requirements failure modes from the effects of functions failure modes. For example, *R1* is satisfied by *f1* and *f2*. On this point, the failure of *f1* and *f2* might affect the complement of *r1*. Based on this principle, we completed the cause analysis in the Table 28.

Table 28 cause analysis of requirements failure modes

Failure modes (FM) of requirements	Causes of requirements FM
The smartphone cannot support internet connection	- Doesn't receive internet signal - Doesn't transmit internet signal
The users experience frequent interruptions with internet connection	The function is not executed perfectly (meet the standard)
It takes long time to connect to the internet	- Take much time to receive internet signal - Take much time to transmit internet signal
The smartphone cannot support video-conference	- Doesn't receive internet signal - Doesn't transmit internet signal - Doesn't capture video - Doesn't capture sound - Doesn't process image signal - Doesn't process sound signal - Doesn't display image signal - Doesn't display sound signal - Doesn't transport sound
The smartphone only supports part of the functions required in video-conference	- Might not receive internet signal - Might not transmit internet signal - Might not capture video - Might not capture sound - Might not process image signal - Might not process sound signal - Might not display image signal - Might not display sound signal - Might not transport sound
The users experience interruptions of image or voice transfer during video-conferencing	The function is not executed perfectly (meet the standard)
The smartphone cannot play music	- Doesn't process sound signal - Doesn't display sound signal - Doesn't transport sound
The smartphone can only play specific music formats	The function is not executed perfectly (meet the standard)
The users cannot take notes by the smartphone	- Doesn't input texts - Doesn't process texts

	- Doesn't display texts - Doesn't store files
The users cannot take all the notes desired, some texts is unable to edit	- Some texts cannot be input - Input texts are incorrect
The users meet difficulty to take notes correctly (i.e. The users see incorrect notes different from the ones edited)	- Input texts are incorrect
The users cannot send messages	- Doesn't receive internet signal - Doesn't transmit internet signal - Doesn't input texts - Doesn't process texts - Doesn't display texts
The users meet difficulty to send complete messages, some texts is unable to edit	- Some texts cannot be input - Input texts are incorrect
The users meet difficulty to send correct messages (some texts is different from edited)	- Input texts are incorrect

5.5.2 Determine O(r_i)

The occurrence of causes of requirements failure modes is reasoned from the occurrence of causes of functions failure modes based on Section 4.3 (i.e. $O(r_i)$ = Maximum of [$O(f_j)$ of all rf_{ij}]). The reasoned occurrence is showed in Table 29.

Table 29 The reasoned occurrence of causes of requirements failure modes

	R_1	R_2	R_3	R_4	R_5
$O(r_j)$	6	6	4	5	6

5.5.3 Completion of the FMEA document of requirements

In Table 30, a complete FMEA for requirement is showed based on above analysis. In this document, engineers are able to prioritize the risk based on the RPN.

Table 30 FMEA for requirements

R	Failure modes (FM) of requirements	Effects of requirement FM	S	Causes of requirements FM	O	RPN
R_1	The smartphone cannot support internet connection	The users will change smartphone	8	- Doesn't receive internet signal - Doesn't transmit internet signal	6	48
	The users experience frequent interruptions with internet connection	The users might complain it and try to fix the problem	6	The function is not executed perfectly (meet the standard)		36
	It takes long time to connect to the internet	The users might accept it or tolerate it	4	- Take much time to receive internet signal - Take much time to transmit internet signal		24
R_2	The smartphone cannot support video-conference	The users will change smartphone	8	- Doesn't receive internet signal - Doesn't transmit	6	48

				internet signal - Doesn't capture video - Doesn't capture sound - Doesn't process image signal - Doesn't process sound signal - Doesn't display image signal - Doesn't display sound signal - Doesn't transport sound		
	The smartphone only supports part of the functions required in video-conference	The users will complain it and try to fix the problem	6	- Might not receive internet signal - Might not transmit internet signal - Might not capture video - Might not capture sound - Might not process image signal - Might not process sound signal - Might not display image signal - Might not		36

				display sound signal - Might not transport sound		
	The users experience interruptions of image or voice transfer during video-conferencing	The users might complain it	6	The function is not executed perfectly (meet the standard)		36
R_3	The smartphone cannot play music	The users might accept or tolerate it	3	- Doesn't process sound signal - Doesn't display sound signal - Doesn't transport sound	4	12
	The smartphone can only play specific music formats	The users might not care about it and adapt it	3	The function is not executed perfectly (meet the standard)		12
R_4	The users cannot take notes by the smartphone	The users might complain it	4	- Doesn't input texts - Doesn't process texts - Doesn't display texts - Doesn't store files	5	20
	The users cannot take all the notes desired, some texts is unable to edit	The users might complain it and try to fix the problem.	5	- Some texts cannot be input - Input texts are incorrect		25
	The users meet difficulty to take notes correctly (i.e. The users see incorrect notes	The users might complain it and try to fix the problem.	5	- Input texts are incorrect		25

	different from the ones edited)					
R_5	The users cannot send messages	The users might change smartphone.	7	- Doesn’t receive internet signal - Doesn’t transmit internet signal - Doesn’t input texts - Doesn’t process texts - Doesn’t display texts	6	42
	The users meet difficulty to send complete messages, some texts is unable to edit	The users will complain and try to fix the problem	6	- Some texts cannot be input - Input texts are incorrect		36
	The users meet difficulty to send correct messages (some texts is different from edited)	The users will complain and try to fix the problem	6	- Input texts are incorrect		36

Chapter 6: Discussion

As showed in the case study (e.g., Chapter 5), the integration model of FMEA applied along with the engineering design process is implemented using a step-by-step FMEA-facilitated design process methodology that is proposed in Chapter 4. Notable observations from the case study are listed as bellows.

- Observation #1: The information of failure analysis can be utilized at the later stages and ensure the analysis consistent among design teams. (See Section 5.2.4 and Section 5.3.4)

  The practice of reasoning the severity of failure modes in the requirement domain is used as a supporting method for double-checking the severity value assigned to the failure modes in the function domain. The practice promotes the consistency of the failure information even when the failure analyses are done by different teams. Similar logical scenario is also applied from function domain to component domain.

- Observation #2: The practice of prioritizing the risk consequence of requirements and functions helps engineers to select proper components and make better design based on the consideration of corresponding risk consequences. (See Section 5.3.8)

The risk consequences lists gathered from each domain (e.g. requirement domain, function domain and component domain) are used as supporting documents throughout the FMEA. In the end of component selection of before the selection, the engineers are suggested to review the design and risk consequences to ensure the critical situations are considered and avoided. The critical situations indicates the ones impact users the most and which is analyzed in requirement domain.

❖ Observation #3: The completion of FMEA in the components domain promotes the completion of function-FMEA and requirement-FMEA. (See Section 5.4 and Section 5.5) The documentation purpose activities help engineers to maintain the corresponding FMEAs when the product is re-designed or revised in the future.

Even though the integration model enables engineers to implement FMEA along with the engineering design process, we also notice some limitations in the case study. The limitations are the result of lack of inputs of product information and which is pointed out in Section 5.3.7 and Section 5.4.1. The limitations are discussed respectively as following.

❖ Limitation #1: The control plan is decided based on the developer's internal regulation and also on the project budget. Therefore, we have limited information to put inside the case study. (See Section 5.3.7)

This limitation will not exist in the real situation when the FMEA is implemented in a real project development process in industry.

- Limitation #2: The cause of a function failure mode can be inspired by the effect of the corresponding components failure modes. Yet, we didn't consider the components relationship in the case study and thus some causes of function failure modes are not directly observed from the failure analysis of components. (See Section 5.4.1)

  The possible solution to this limitation is that engineers make a mapping between components to know the components relationships, and therefore the possible causes from the "related components" can also be observed and taken into account.

Chapter 7: Conclusion

For decades, FMEA is used in industry and different approaches are proposed and improved by researchers. The practice of FMEA allows engineers to examine the design and control or eliminate the possible causes of failures. In this thesis, an integration framework is developed to integrate FMEA and engineering design process and the goal is to utilize the failure analysis information from one stage to another stage of the design process. To reach this goal, it is necessary to integrate different FMEA documents that are implemented throughout the product development process. In this thesis, the engineering design process is defined by specifying three key design elements: requirements, functions, and components. It is by the reference of QFD and AD methodologies. These design elements are treated as a foundation of the proposed integration model.

This thesis aims to apply FMEA along with the design process, and thus a step-by-step FMEA-facilitated design procedure is proposed. The procedure then is demonstrated and verified by a case study. From the case study, we have three observations and also notice two limitations about the integration model.

The first observation is the information of failure analysis can be utilized at the later stages and it ensures the failure analysis is consistent. The second observation is that the practice or prioritizing the risk consequence of requirements and functions helps engineers to select components and design the product according to the consideration of the risk consequence that the engineers listed in the earlier analysis process. The third observation is the completion of FMEA in the components domain promotes the documentation of the FMEA of functions and FMEA of requirements. Nevertheless, there are two limitations of applying the integration model in the real design practice. The detection assessing value is required in FMEA practice most of time. Yet, this research is unable to capture the real control method due to the lack of information. Instead, we made an assumption on the control and detection part in the FMEA of component domain in Section 5.3.7. Secondly, due to the limitation of time, component relations are not mapped in this thesis. As a result, some causes of function failure modes are unable to be observed by only reviewing the failure analysis of components and the mapping between functions and components. These two limitations are left to be addressed in the future research.

Notably, the contributions of this thesis are pointed out as below.

- ❖ First, the integration of different types of FMEA documents in the product development process, which has not been found in the literature.
- ❖ Second, a step-by-step FMEA-facilitated design process is proposed, and it ensures the consistent of failure analysis among product design process.
- ❖ Third, a real-life product is studied.

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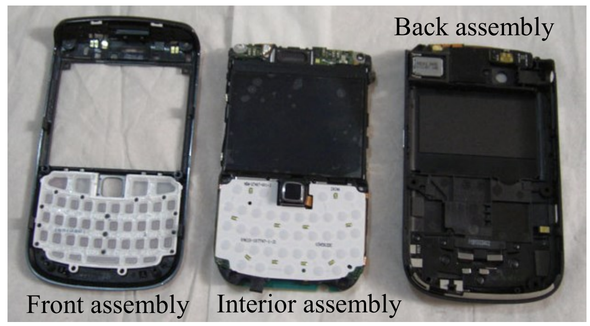
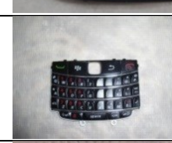
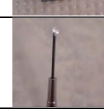
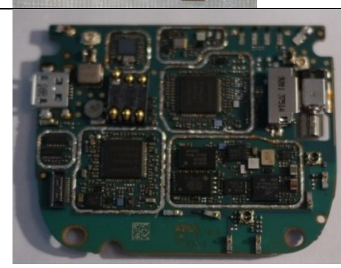
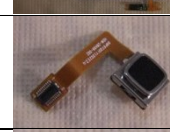
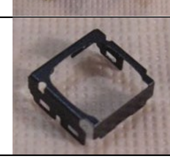
Appendices

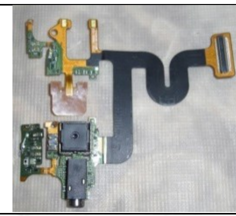
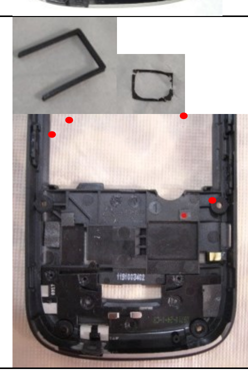
Appendix 1 List of components

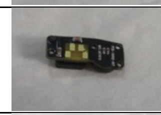
Decomposed product: *BlackBerry Smartphone – Bold 9650*

Systems	**Sub-systems**	**Components**	**Photos**
Front assembly	Frames	Headphone cover	 
		Front main frame	
		Protector pad	
		Liner profile & frame	 
		Down outer profile	
	Input sub-system	Keypad	
		Top key dome-switch pad	
		Top key liner	

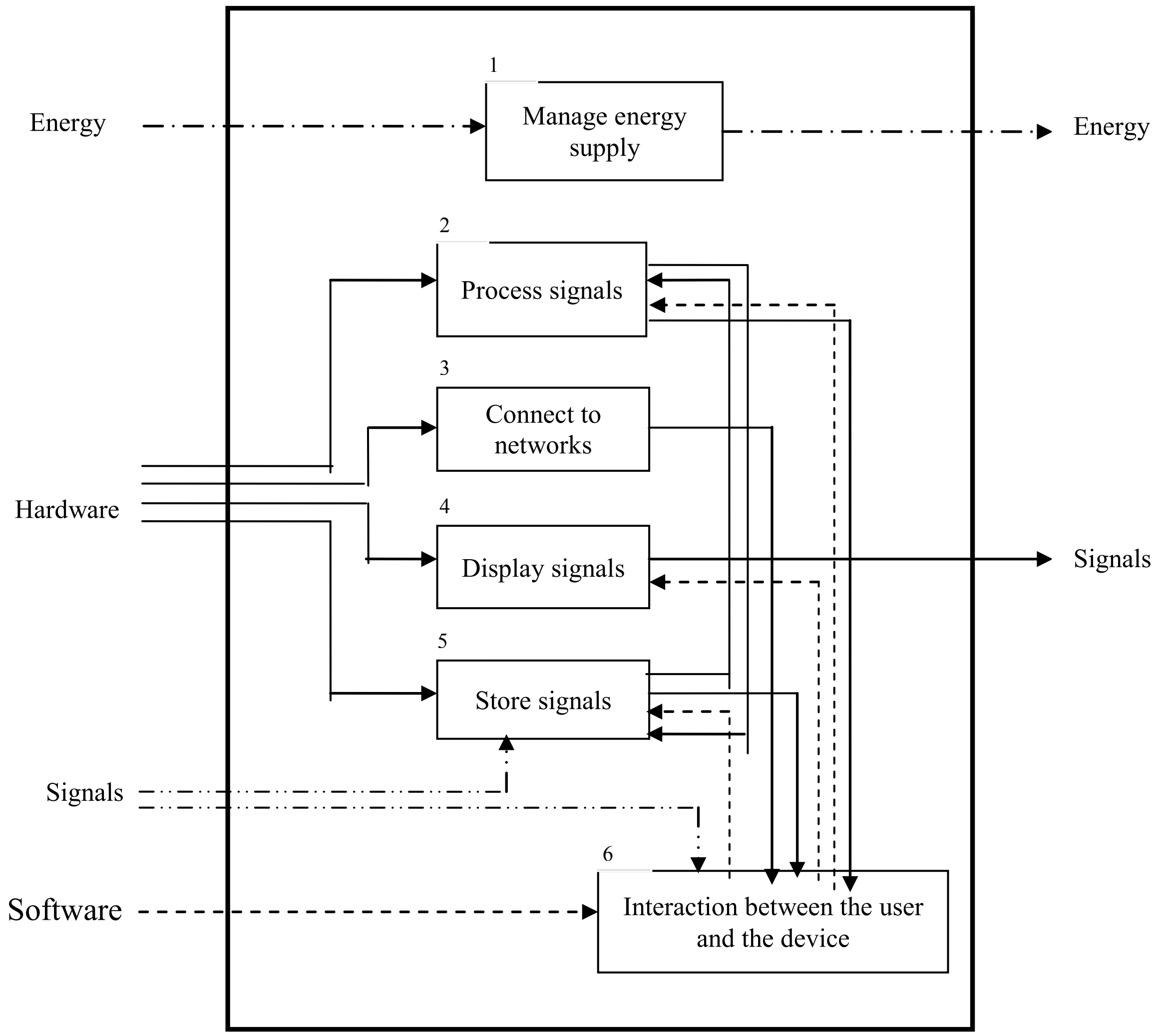
	Signal exchange sub-system	Antenna #1	
Interior assembly	Display module	LCD screen mounted with Connector and circuit board	
	Main board	Micro USB port	
		SIM card connector	
		Connectors	
		Battery	
		Blue-tooth transceiver	
		Audio Codec	
		GPS receiver	
		GSM transceiver	
		Vibrator	
		Micro SD slot	
		Power AMP/multiplexer array	
		CPU	
		GPU	
		APU	
	Input sub-system	Dome-switch pad	
	Scroll Key module	Scroll key mounted on Circuit board (with a connector)	
		Scroll key holder	

	Sound and VGA	Camera module, Audio jack, Connectors, R/C components are mounted on circuit board	
		Headphone speaker	
	Power supply sub-system	Wires and wire holders	
	Protection	EMI gaskets (conductive sponges)	
Back assembly	Frames	Battery cover	
		Trigger	
		Back frame	
		Bottom fixture	
		Liners	

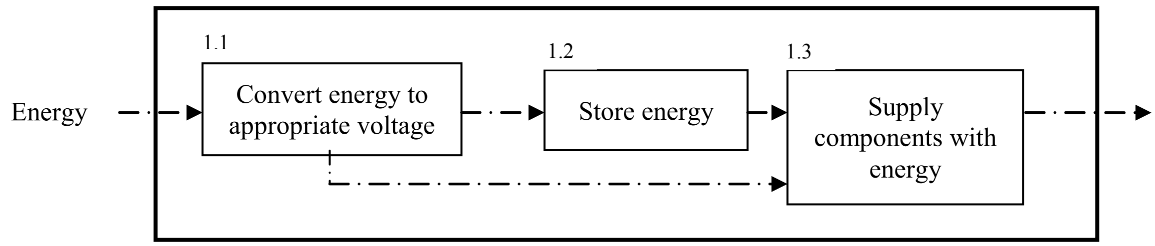
		Conductive layer between Main board and battery	
	Input sub-system	Side buttons	
	Flash module	R/C components mounted on circuit board	
		LED	
	Signal exchange sub-system	Antenna #2	
		Antenna #3	
	Sound-display sub-system	Speaker	

Appendix 2 Functional analysis

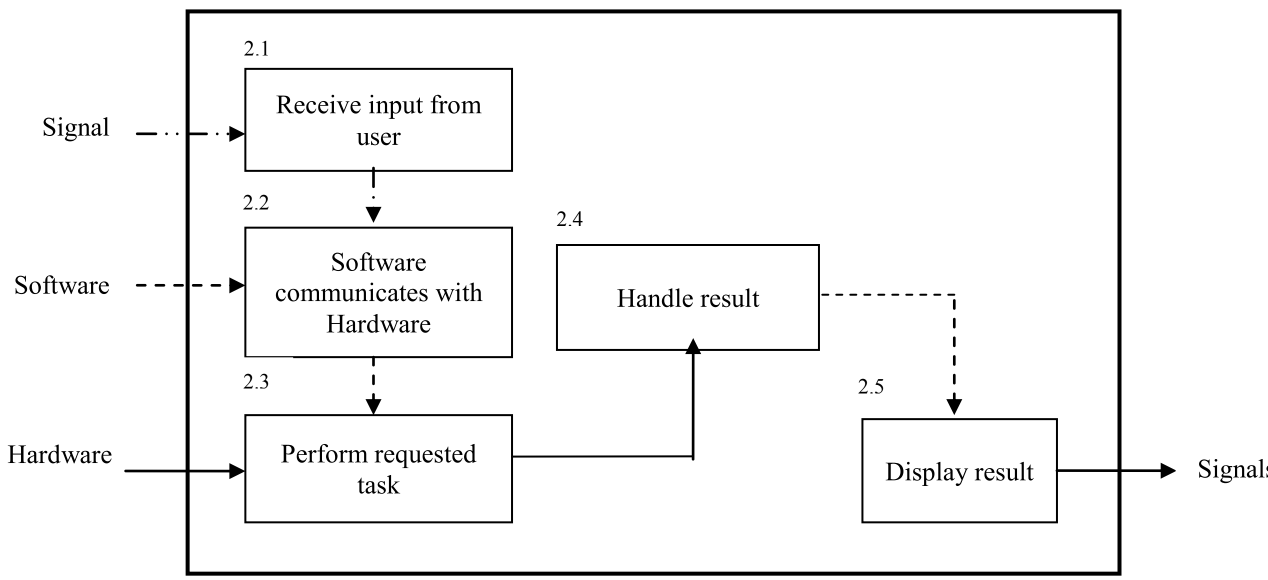
Top level block diagram:



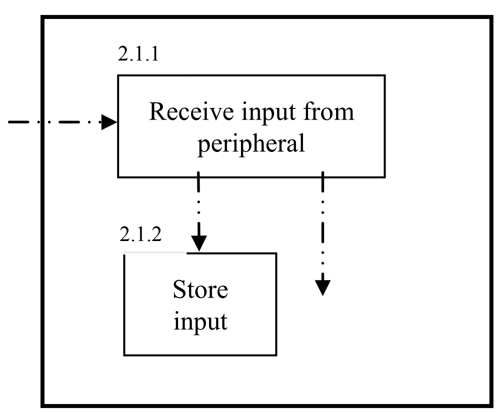
Function 1: Manage energy supply



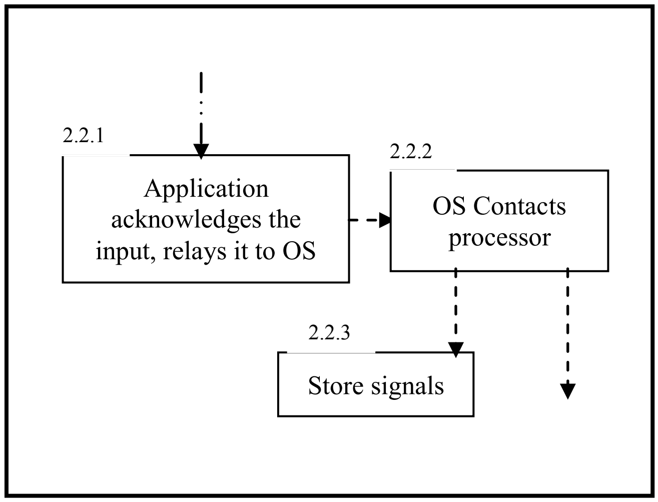
Function 2: Processing



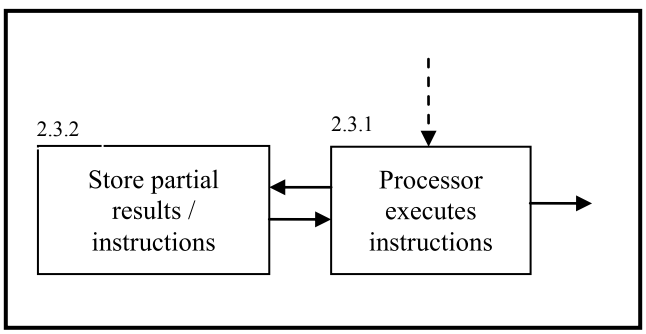
Function 2.1: Receive input from user



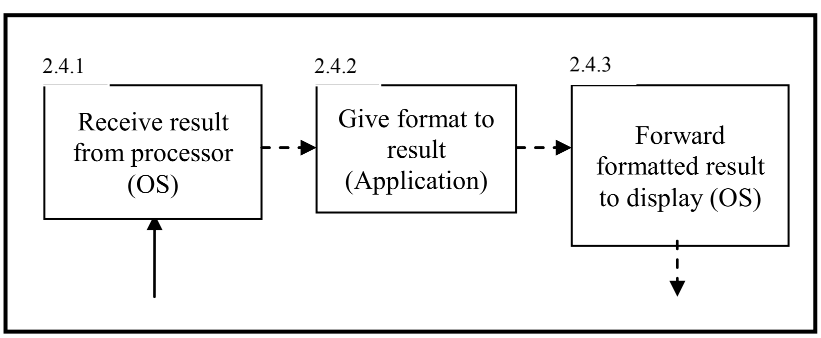
Function 2.2: Software communicates with Hardware



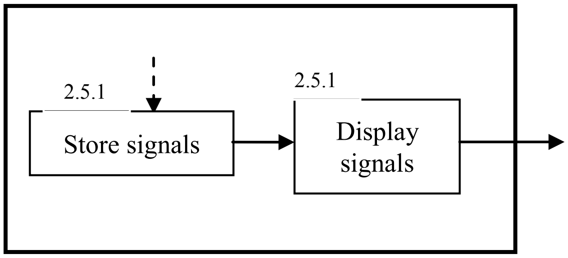
Function 2.3: Perform requested task



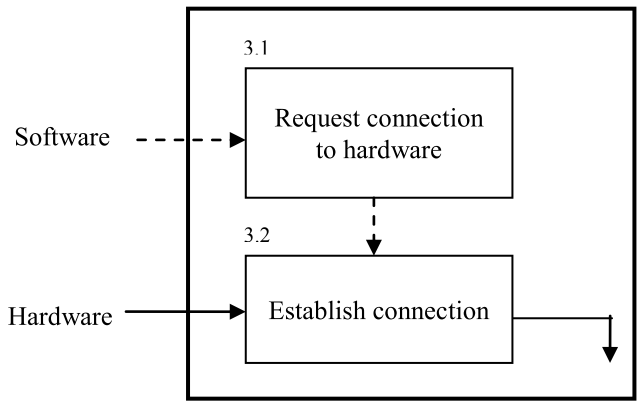
Function 2.4: Handle result



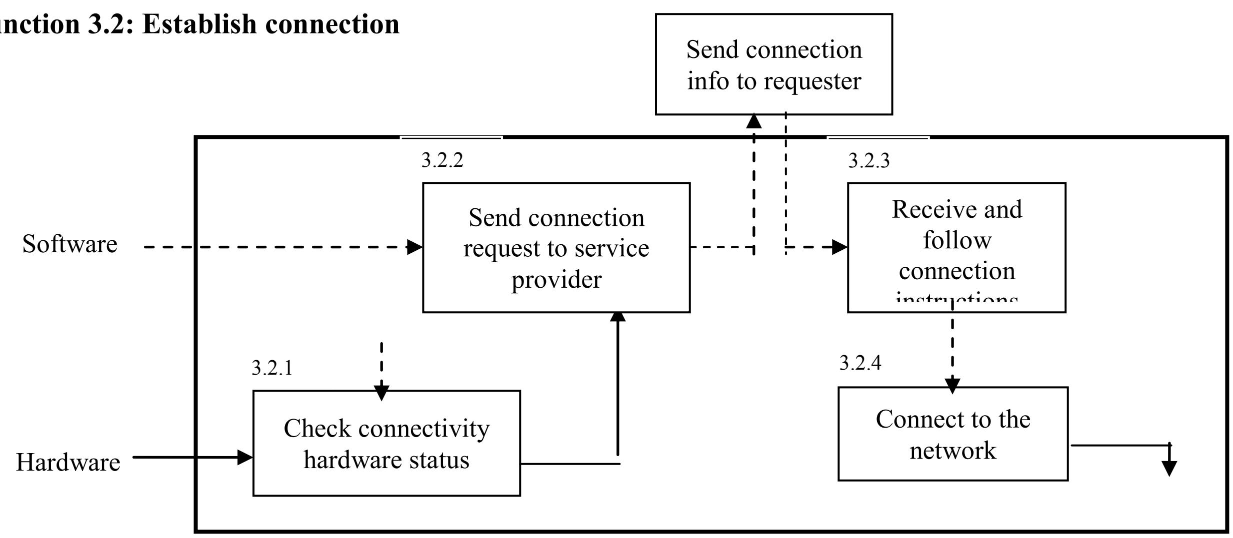
Function 2.5: Display result



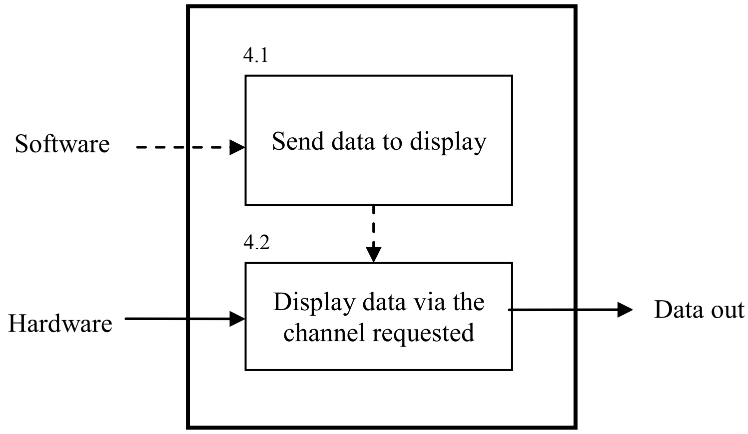
Function 3: Connect to network:



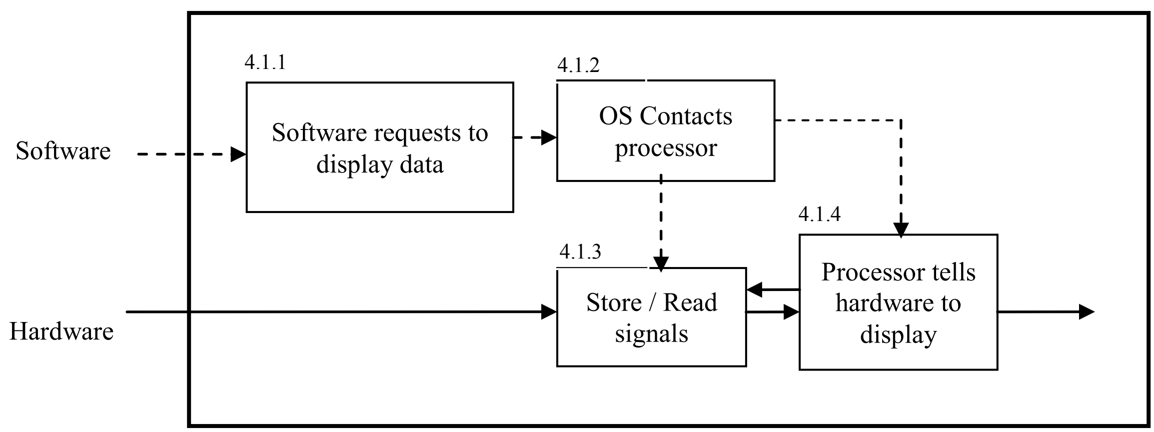
Function 3.2: Establish connection



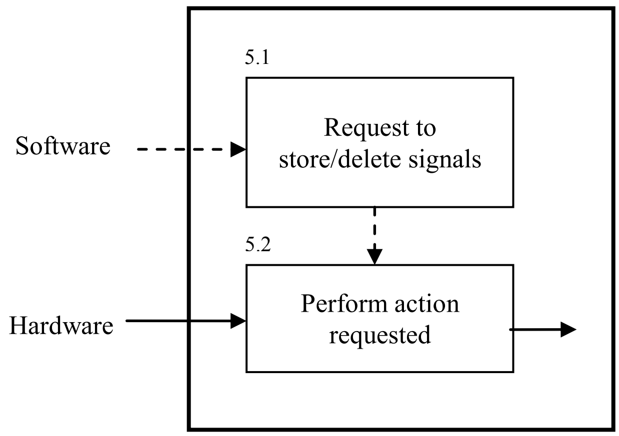
Function 4: Display signal



Function 4.1: Send signal to display



Function 5: Store signal



Function 5.1: Request to store/delete signal