A Structured Method for Requirements Analysis with Application to CFR-14 Part-21 Subpart-G

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Abstract

Standards are the bottleneck of any aviation industrial action. Thus, meeting standards is not an option but an obligation throughout a given product life cycle. The implementation of the standards and the evaluation process are complicated and need considerable resources. Simultaneously, Extra costs and concerns may be imposed on the aviation industry due to improper requirements. Thus, the quality of standards should be comprehensively assessed to obtain a satisfactory final result. System engineering introduces requirement analysis to solve this problem. As a significant contribution, this paper provides a method of requirement analysis based on the structured strategy. The criteria were defined practically. Diagram, process, sub-process, and techniques including RTM and WBS were either developed or deployed to investigate the conformance of requirements with the criteria. Applying this method, any sort of requirement is evaluated accurately. Plus, it shows a specific and root cause of the problems if the requirement is unacceptable. Furthermore, a novel way to measure system affordability is proposed through the application of DFMEA. Lastly, the model is applied on CFR-14 Part-21 Subpart-G (FAA production organization requirements) to show the need for systematic improvement of aviation standards' requirements of production organization.

Keywords
Requirement analysis, Aviation requirements, Structured requirement analysis, System engineering, FAA requirements

1. Introduction
As standards are the bottleneck of any aviation industrial action (Sheng, and Lu. 2014) and (Spence et al. 2015) meeting standards is not an option but an obligation throughout a given product life cycle ranging from design, production, maintenance, training to operation (De Florio 2016). Therefore, the quality and safety of all the above-mentioned organizations' activities should be evaluated based on the relevant standards (Jilian et al. 2011). The implementation of the standards and the evaluation process are complicated and need considerable resources. (Yang, and Cunxi 2011) and (Bhopatkar 2014). However, this is an inescapable price to pay for safety and quality (Kuklev et al. 2019).
Simultaneously, there is a risk of dealing with an unreasonable cost due to the lack of standards quality itself (Müller and Wittmer 2014). Thus, the quality of standards should be comprehensively assessed to obtain a satisfactory final result. Otherwise, all the resources allocated to drafting, implementing, and evaluating those standards would be wasted (Dick et al 2017). Plus, extra costs and concerns are imposed on the aviation industry due to improper hierarchy, complicated, ambiguous, unachievable, incomplete, unverifiable, and inconsistent requirements (Bhukya and Pabboju 2019) and (Lightsey 2001). At the same time, there are other sorts of considerations like the strategy of

requirements analysis when it comes to the rulemaking process as it can affect the quality of requirements systematically (Grady 2014).
Probably, aviation is one of the most developed industries in terms of standards and requirements (De Florio 2016) and (Spence et al. 2015). Yet, this research uses proper methods and techniques to explore the possibility of systematically analyzing and improving aviation standards' quality, including those introduced by systems or requirements engineering theories to assure an acceptable level of requirements quality (Grady 2014) and (Lightsey 2001).
Thus, the problem is as systems or any products and services should meet the standards' requirements, in the best-case scenario, the result may approve that the system complies with the requirements. However, in the first place, it needs to be investigated whether the requirements could be met anyhow; plus, whether the final result would be satisfactory and reliable.

1.1 Objectives

This research analyses the requirements of aviation standards, particularly those applicable to "Production organization" under the discipline of Federal Aviation Administration (FAA) Code of Federal Regulation (CFR) 14 Part 21 subpart G, based on systems and requirements engineering theories.
The objective is to develop a method to evaluate various requirements. It is critical to define all aspects of this method to ensure the result of this evaluation is accurate and precise.

2. Literature Review

No matter what sort of system is intended to consider, the principal goal of a system is to fulfill the requirements (Zhao and Freiheit 2017). The requirement is any sort of needs to be satisfied.
The requirements have been divided into various categories based on where they come from. There are six requirements' categories as follows.

- Customer Requirements: The operational requirements showing the fundamental needs are categorized as customer requirements. Measures of effectiveness and suitability (MOE/MOS) are some instances of the expectations from the systems in the form of mission, objectives, environment, and constraints.
- Functional Requirements: The requirements that come from requirement analysis are the highest level of function for functional analysis. They are required functions, tasks, actions, or activities that must be carried out.
- Performance Requirements: The boundaries of a mission or function that must be accomplished. They can be in the form of quantity, quality, timeline, etc. Performance requirements are developed according to the system life cycle of all defined functions. Plus, the certainties, importance's degree, and relations to other requirements are depicted.
- Design Requirements: How to build, buy, or carry out the product or processes shown as technical manuals or data packages.
- Derived Requirements: The requirements come from higher-level like for high-speed vehicles, a low weight design may be required.
- Allocated Requirements: These types of requirements are a result of dividing or breakdown a high-level requirement into multiple lower-level requirements.

Although some researches have attempted to implement aviation standards in a design and a production organization based on integrating various requirements from diverse authorities (Yang, and Cunxi 2011), and (Bhopatkar (2014), none concentrate on the requirements. Thus, it seems it is assumed that the requirements are flawless and acceptable to be met by all available means (Laleau et al. 2006). As a result, the compatibility analysis of various standards applicable to specific aviation organizations has been developed (Bhopatkar 2014).
In contrast, lack of requirements analysis posed the risk of unsatisfactory results even on the occasion of well-implementation of any systems, including those mentioned above (Laleau et al. 2006).
Inevitably, the process of meeting requirements is a sophisticated subject. However, there would be no guarantee to reach a satisfactory result ultimately unless, at the first step, the requirements would be investigated appropriately. In other words, if the requirements have not been defined correctly and adequately, there would be no possibility to fulfill them correctly and adequately (Arrillo et al. 2011).
System engineering theory insists on the order of actions to develop a system, as figure 1 depicts (Lightsey 2001). The system engineering process phase begins with requirements analysis.
Requirement's analysis generally should result in a clear understanding of functions i.e. what the system must do, performance i.e. how well the functions must be executed, interfaces, i.e. the system executes in which environment, and, other requirements and constraints (Lightsey 2001).

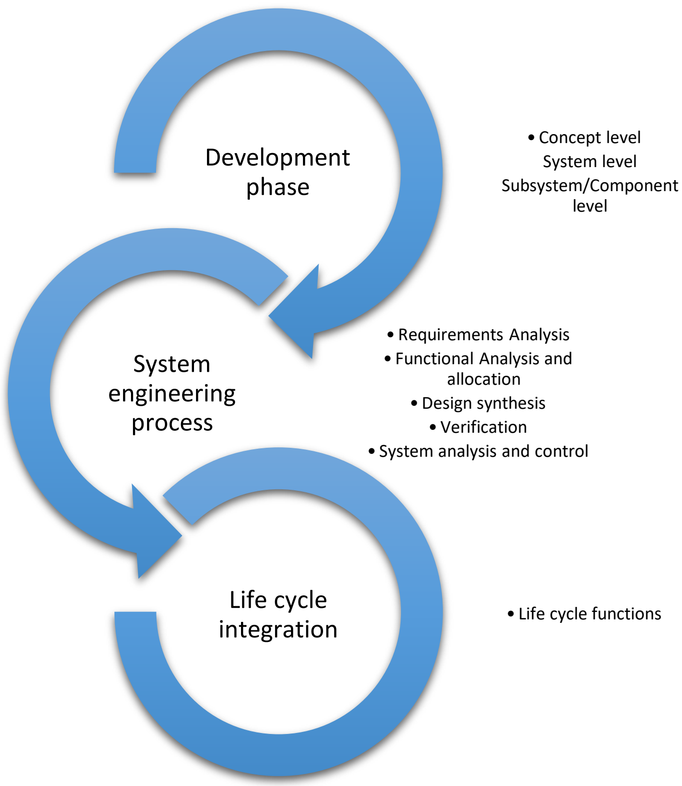

Figure 1. System engineering diagram

3. Methodology

The quality of requirements is a generic term that needs to be more specified to take practical action. It is essential to categorize all possible quality concerns to have reliable and efficient criteria for analyzing the requirements accurately and precisely. Studying various sources shows conformance with seven requirements' attributes can result in an acceptable level of requirement quality (Lightsey 2001) and (Beasley et al. 2014) and (Laleau et al. 2006).

1. Achievable: A requirement is achievable when it shows a need for a solution at an affordable cost.
2. Verifiable: The quantity of a need should be clearly defined, which permits verification. Excessive, sufficient, resistant, etc. are not acceptable.
3. Unambiguous: A requirement should be clear and non-vague. Plus, it needs at least one meaning.
4. Complete: It must include all information needed to understand customer requirements, mission profiles, operational and maintenance needs, and other constraints like environments.
5. Need: It must not address the solution like how to meet the requirement. Instead, it should be shown in the form of need like what and why.
6. Consistent: There should be consistency between all requirements. Any sort of conflict should be avoided.
7. Hierarchy: The level of requirements should be suited for the intention and compatible with the others. Neither too detailed nor too general.

The process of determining conformance of the requirements with the attributes is a crucial subject to work on. Plus, there are further sub-processes and criteria to take into account at each step. Eventually, the requirements will be analyzed to know whether they are acceptable or not. It enables system engineers to negotiate with requirements owners about a possible opportunity for improvements.

The process of evaluation of the requirement's quality begins with determining conformance with the need attribute as depicted in figure 2. If the requirements include the solution, it is not acceptable. Inevitably, there should be a need for a solution. In the case of a solution without a need, the need is missing. As a result, there would be no further steps to take. The next step is to breakdown the requirement as much as possible to reach the lowest level of required actions to analyze the requirement hierarchy. Work Breakdown Structure (WBS) is a technique to breakdown the different levels of a system. Once the requirement has been singled out, any pertaining predecessor should be identified. Any of them must be defined as either a new one or an existing one. In the case of consistency, the interface should be identified. Provided that the requirement has any interface, it may be internal, external, or a mixture of both. Thus, the relation between interfaces should be determined, which could be one of the following options. Conflict, redundancy or repetition, and compatibility. Repetition means any possible action probably has been taken at the first occurrence. In the case of conflict, there would be no further action to take. However, when it comes to a compatible option, the next step should be taken. A requirement should be verifiable. Thus, if it is not, it would be failed. Otherwise, the process leads to the result as the figure 2 shows.

3.1 Sub-process and criteria

Besides the primary above-mentioned process, sub-processes need to be considered and explained for a). Hierarchy or the number of needed actions derived from a single requirement should be apparent based on the WBS application. The average number of actions within the requirements is an acceptable level of hierarchy. Either Higher or lower numbers should be registered as an unacceptable level of hierarchy and b). Verifiable. In accordance with the definition, the requirement should be measurable. Therefore, any requirement without obvious boundaries cannot meet this criterion.

3.2 Requirement traceability matrix

The process of identifying, documenting, and managing stakeholder needs and requirements to achieve objectives is collecting requirements. The primary merit of this process is that it supplies the basis for defining the product and the project scope and other sorts of processes, resources, and required actions (Duraisamy and Atan 2013).
A traceability matrix is a table related to the requirements in which intended information is mentioned from the base to the outcome. This tool provides an opportunity to trace that each requirement adds business value. In doing so, the relationship between the outcome of requirements and project objectives could be verified. It means eliminating the chance of missing a requirement throughout the project life cycle or its approval. Plus, it is a change management structure.
It can include the following items but is not restricted to them. Business needs, opportunities, goals, and objectives; Project objectives; Project scope and WBS deliverables; Product design; Product development; Test strategy and test scenarios; and High-level requirements to more detailed requirements.
Attributes associated with each requirement can be recorded in the requirements traceability matrix. These attributes help to define critical information about the requirement (Project Management Institute, Inc. 2017)
In this research an RTM is formed to manage the requirement analysis from beginning to the end.

3.3 Analysis of the result

When the result comes out from the diagram shown in figure 2, the next step is to analyze it. Previous steps clarified if a requirement fails to meet specific criteria, including need, hierarchy, consistency, and verifiability. However, the other criteria, like unambiguous, complete, and achievable, are more complicated. Thus, to determine the conformance of the requirement with them, more analysis is needed.
There are three possibilities as follows:

- The analysis is left incomplete
- The analysis resulted in requirement review at some point
- The analysis has reached the result

In the case of the two first options, it should be determined if the requirement is ambiguous or incomplete. Plus, it may be a mixture of both. While, if the analysis leads to the result, the next step is to clarify whether the requirement is achievable.
The keyword is the affordable cost to investigate whether the requirement is achievable or not. When it comes to the affordable cost, it can be considered what would happen if the requirement were disregarded. In this scenario, the consequences of intentionally disregarding a requirement are the subject of matter. On condition either nothing happens, or the consequence is not related to value-added activities, the requirement probably is not value-added.
System affordability means spending money not only on value-added activities but also on those activities supporting value-added activities. Their functions are required for the system. Thus, it is the correct cost of the system. While the system is not affordable to pay for non-value-added activities, which are waste and wrong cost (Odomirok 2016). What the customers desire to pay for is value-added, and anything else is non-value-added. Therefore, it is not affordable for the system to support a non-value-added activity. In doing so, the best technique is Design Failure Mode and Effect Analysis (DFMEA) (Prabaharan and BEML Ltd 2015).

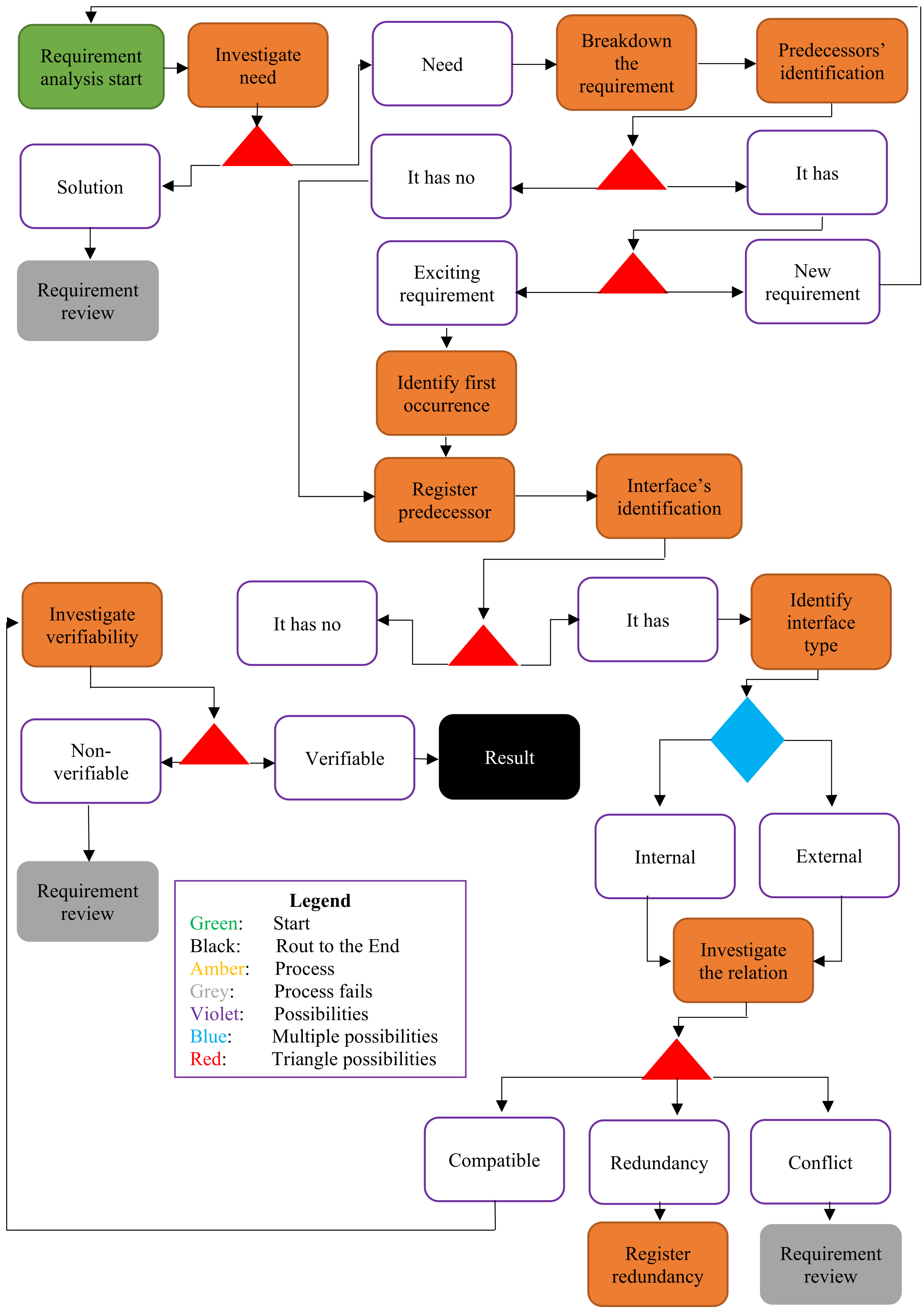

Figure 2. Requirement analysis diagram

3.4 DFMEA

Initially, the system structure is analyzed to determine the scope of the DFMEA. It results in the definition of the structure and limits of the system. Thereafter, a functional analysis is carried out. To do so, from various disciplines, subject matter experts build a cross-functional team. Once the function of the system has been described, various possible failure modes are determined (Filz et al. 2021).

A couple of practical techniques are available to figure out the potential causes, including root-cause analysis and cause-and-effect diagram (Evans and Lindsay 2015). The potential failure effect is determined within the identified items as the severest.

By performing tests and analysis to better understand the probability of failure, the prediction of the reliability of a product can be improved. Thus, the probability of failure may be decreased. This decrease is characterized by a detection score (PD) for each cause activity combination (Li and Mobin 2018).
The DFMEA technique provides not only the results needed for affordability analysis but also the other sorts of information that are helpful in terms of reliability.

Based on the previous steps, the risk priority number (RPN) is calculated as follows. It is the product of the multiplication of the severity of effect (SE), probability of failure occurrence (PFO), and probability of detection (PD). These three terms represent the three categories of contributing factors to the RPN (Society of Automotive Engineers International 1994).

To calculate RPN following equation is applied (Prabaharan and BEML Ltd 2015).

$$RPN = SE \times PEO \times PD$$

Through table 1, SE, PFO, and PD levels for each failure mode are determined on a scale from 1 to 5. However, the scale of the following table could be modified based on the nature and specifications of the intended project.

Table 1. Failure mode levels

Titles	Level 1	Level 2	Level 3	Level 4	Level 5
Severity	Low risk to the system	Moderate risk to the system	High risk to the system	High risk of mission fail	Mission fail
Occurrences	Unlikely probable	Low probability	Moderately probable	Highly probable	Extremely probable
Detection	Extremely probable	Highly probable	Moderately probable	Low probability	Unlikely probable

4. Data Collection

As mentioned, this research's main objective is to investigate the requirements of standards applicable to production organizations operating in aviation industries. Since most of the aviation industry and its products are under the influence of two leading authorities, FAA and EASA, one of them could be an acceptable option to be chosen. One of the most important standards that may be applied to such organizations is the Code of Federal Regulation (CFR) 14 part-21 subpart-G which belongs to FAA.
The data collecting method is clustered. The unit in a clustered sample is subgroups of the population rather than individuals. The clusters result from the deviation of the population into subgroups, which are randomly selected. All members of the chosen clusters are included in the study in single-stage cluster sampling (Admin 2010). The FAA requirements applicable to a production organization are selected through this method. Sixteen codes of CFR14 - Part 21-Subpart G were collected as data set to apply the proposed method and validate it.

5. Results and Discussion

The sixteen codes of CFR-14 Part-21 Subpart-G were decomposed to 65 requirements (items) which provides the possibility of analysis. This approach is known as Structured requirements analysis. Otherwise, due to complexity, a flawed process would be probable.

The data is entered into an RTM to trace from beginning to end. Moreover, it provides the possibility of applying other tools and conducting further investigation, as necessary. As the data is entered, the analysis process is followed based on the proposed method. Any non-conformity in the RTM is highlighted in red to simplify identification.

Furthermore, supplementary information, such as the internal or external interfaces or the reason for the requirement incompleteness or ambiguous is mentioned in the RTM.
As there is no access to the initial goal of each requirement, when it comes to potential failure mode and its effect, the apparent option is taken into account.

5.1 Numerical Results

Sixty items out of sixty-five were found unacceptable due to various reasons. It means almost 92% of 16 CFR-14 Part 21 sub-Part G codes are unacceptable and need to be improved.
Nineteen items are found problematic with three non-conformities. Plus, eleven items are not acceptable with regard to two non-conformities. Even, there is an item with four non-conformities.

5.2 Graphical Results

Figure 3 shows the Pareto chart which depicts the most influential factors contributing to reaching the analysis result (Sarkar et al. 2013). It shows that thirty-seven items are found unacceptable regarding the completeness, which is the most significant non-conformity among this data set. The next problem is with Hierarchy. There are thirty-three non-conformities with regard to this attribute. More than 80 % of total issues are caused by non-conformities with the two mentioned attributes.
While consistency-related issues are twenty-two, and verifiability non-conformities (NC) are twelve to take the following places. In terms of need or unambiguity, no NC is founded. Regarding Achievability, all five items are acceptable with no other NC. It means there is no problem with this attribute.

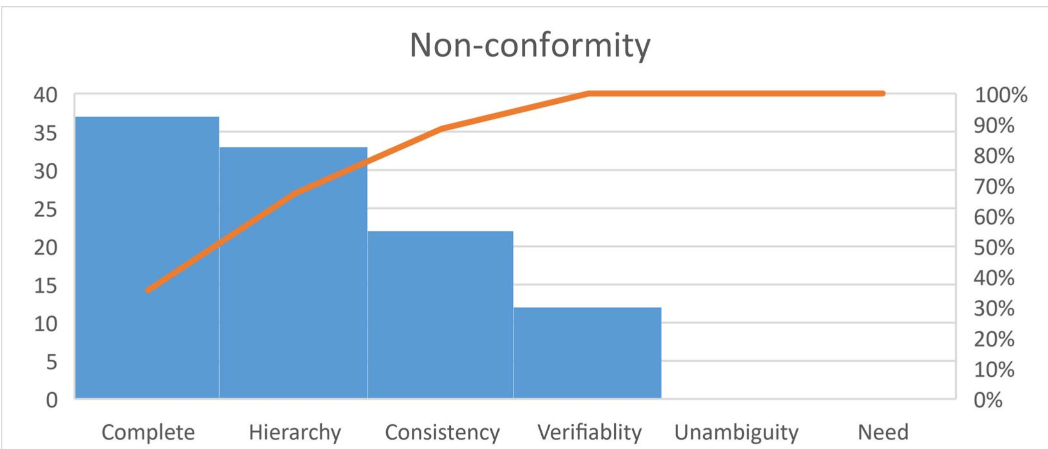

Figure 3. Non-conformities Pareto chart

As the nature of a requirement needs to be acceptable from all aspects of the seven attributes, it is crucial to conform to all attributes. Although most of NC is due to the complete attribute, improving a requirement merely regarding this attribute would not make it acceptable if it has more than one non-conformity. Therefore, the mixtures of non-conformities need to be considered. There are thirteen mixtures of non-conformities. The following Pareto chart, figure 4, shows more information on the mixtures.

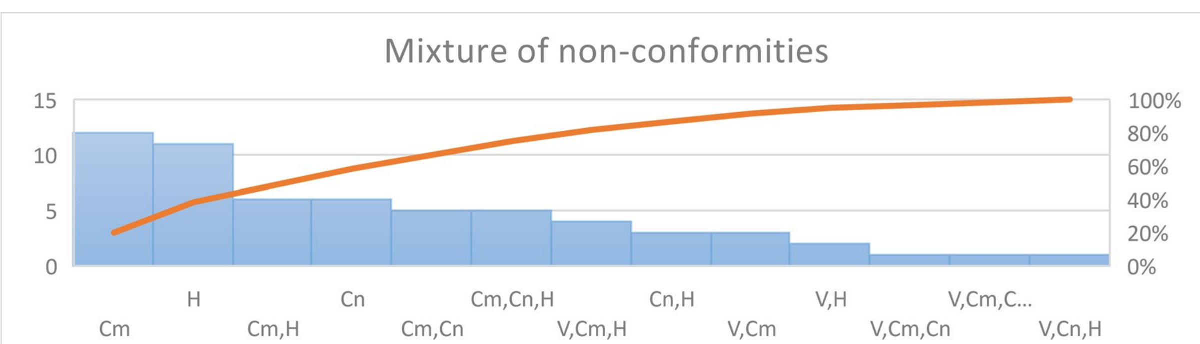

Figure 4. Mixtures of non-conformities Pareto chart

As the Pareto chart shows, twelve items merely encounter completeness (Cm) problems. The second problematic issue is a hierarchy (H) that is solely responsible for eleven items. The first mixture is complete-hierarchy (Cm, H) which accounts for six items. Thereafter, Consistency (Cn) with the same number is found. Besides, the mixture of complete-consistency (Cm, Cn) and complete-consistency-hierarchy (Cm, Cn, H) each account for five items. The last mixture to reach 80% of the problematic issues is verifiable-complete-hierarchy (v, Cm, H) which is the reason for four unacceptable items.
Through the requirements analysis, all internal and external interfaces of requirements have been identified and registered in the RTM. However, to facilitate and further use of this vital data, the following building block diagram, figure 5, shows the interfaces of CFR-14-part 21 subpart G with internal and external entities.
A building block diagram visualizing system interaction at a high level which permits system engineers to separate requirements analysis from system design and start system-level design before finishing component-level designs (Qureshi et al. 2010).

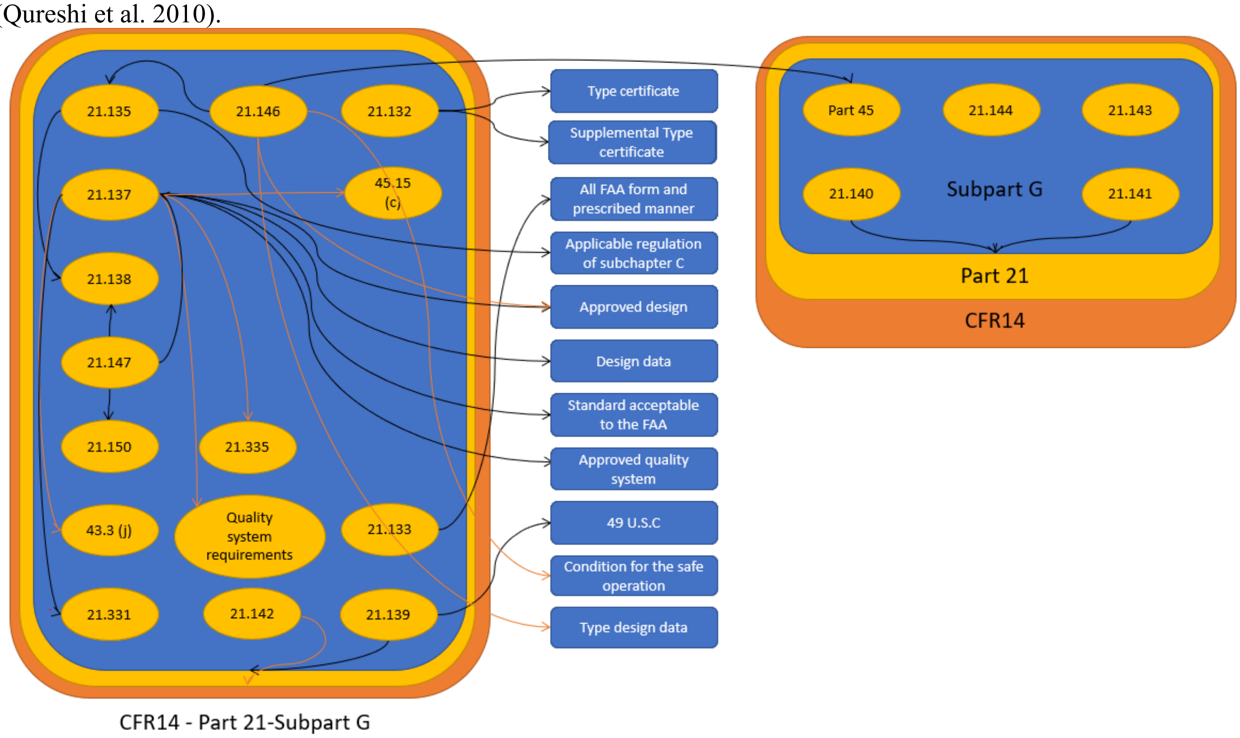

Figure 5. Building Block Diagram

5.3 Proposed Improvements

It is interesting that although there are some papers related to this subject, there is no previous work with the same approach. Most of the previous work concentrated on how to implement the standard instead of the standards themselves. It means they ignored the initial steps like requirements analysis or a structured requirements analysis.

The distribution of this paper to the requirements analysis provides a versatile tool. This tool could be applied to various subjects ranging from purchasing a cup of coffee to defining and realizing a complicated aerospace project.

There are diverse aspects of its effects on industries, like how much it could save resources by preventing reworks. Working on these advantages may encourage the user to consider this sort of improvement more seriously.
Indeed, the quality of aviation standards itself is a significant subject of matter. Whereas the quality of the rulemaking process even is more important. Now that it can be a quality assurance consideration that can continuously improve the quality of aviation rulemaking.

Moreover, if a system will be established to monitor the effects of aviation standards' requirements on all stakeholders, including the industry, customer, environment, etc., there would be an opportunity to assess how a modification or improvement is effective. Plus, where is the most critical area to consider and other important information will be available.

As the building block diagram shows, a couple of other standards have interfaces with this one. Evaluating them for quality is necessary to have a more accurate and precise analysis result.

The analysis also provides further details on the contributing factors. It shows that 80% of unacceptable requirements do not meet two attributes: complete and hierarchy. In other words, they do not have sufficient and clear information to identify correctly the action required. In addition, they are either too general or too detailed when it comes to hierarchy. Complete and hierarchy are the most crucial factors to improve the quality of this code of regulation. Consistency and verifiability are the next ones.

5.4 Validation

As the graphical results showed, two different approaches to identify the potential non-conformity (problems) of requirements led to the similar results. Figure 3 shows that thirty-seven items are found unacceptable regarding the completeness, which is the most significant single non-conformity among this data set. The next problems are with hierarchy in the same pareto chart. While figure 4 shows more information on the mixtures of non-conformities. There are thirteen various mixtures. However, twelve items merely encounter incompleteness problems. The second problematic issue is the hierarchy that is solely responsible for eleven items. The first mixture is complete-hierarchy which accounts for six items. The mixtures of complete-consistency and complete-consistency-hierarchy account for five items. The last mixture to reach 80% of the problematic issues is verifiable-complete-hierarchy which causes four unacceptable items.

This comparison reached to certain meaningful similarities between two different approaches results, mixtures and single non-conformity. In both cases, the main problems are the same. It can be a way to validate the result.

6. Conclusion

As an effective method, system and requirement engineering was chosen to evaluate the quality of the requirements. Several strategies to conduct requirements analysis were studied. As a result, the best of them, the structured strategy was followed to take further steps. There are a couple of other actions to take when it comes to system engineering methodology. However, the central concern of this paper is the requirements analysis.

Thus, requirement analysis was conducted to investigate whether the requirements were acceptable or not. No matter how well-designed the system is, there is no guarantee that a system may meet the requirements and the final result would be satisfactory unless the requirements' quality is acceptable.

Studies have provided seven essential attributes as the most comprehensive criteria to evaluate the quality of requirements, including complete, hierarchy, need, unambiguity, consistency, verifiability, and achievability.

Diagrams, processes, and sub-processes are defined and developed to provide a method that turns this theory into practical work. This detailed solution allows applying an engineering response to this problem instead of a freestyle strategy of requirement analysis, which may not be accurate and precise.

A requirement traceability matrix is formed to organize and trace the requirements from beginning to end. An Excel file contains all information pertaining to requirements ranging from WBS to requirements analysis attributes.

Because of the influential role of FAA in the aviation industry, we collected the data set from CFR-14 Part 21 subpart G and transferred it to an RTM. Sixteen national codes were decomposed into sixty-five items, which provided a more understandable and logical analysis.

Thereafter, analysis was conducted. Based on the proposed method, the data set was analyzed, and the details on each item and its results were mentioned in the RTM. The analysis consisted of various steps and sub-processes, including WBS and DFME.

According to the analysis results, 92% of sixty-five items are not acceptable, including sixty items. It shows an opportunity for improvement to reach an acceptable level of quality when it comes to this code of regulation.

Meanwhile, interfaces of the requirements with all internal and external entities were investigated. This investigation results in a building block diagram showing how the requirements depend on the other requirements and standards. In addition, it depicts how complicated they are to be met.

Based on the analysis result, CFR-14 Part 21 subpart G needs a plan of improvement. This plan should include the improvement of the process of rulemaking as well.

The method proposed by this paper provides the possibility to systematically approach the requirement analysis and prevent problematic requirements by improving the process of rulemaking.

Based on the analysis results, the current requirements quality probably leads to rework, errors, improper system design, and consequently, improper system implementation. They are all barriers to investment and innovations.

As a significant contribution, this paper provides a method of requirement analysis based on the structured strategy. The criteria were defined practically. Diagram, process, sub-process, and techniques were either developed or organized to investigate the conformance of requirements with the criteria.

Applying this method means that there is a way to evaluate the quality of any sort of requirements accurately and precisely for any project. Plus, it shows a specific and root cause of the problem if the requirement is unacceptable. Thus, rapidly the requirements may be improved to become acceptable. Furthermore, in a novel way to measure system affordability, the application of DFMEA is proposed.

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