

Improving Quality, Reliability and Profitability of Mobility Electronics Using Systemic Failure Mode Analysis

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ABSTRACT

Failure analysis (FA) management is insufficiently described by current standards and literature. Previously proposed three-step systemic FA methodology provides effective and efficient alternative to sporadic FA. Organization, methods and results of the first step of the systemic FA, failure mode analysis (FMA), during product/project life cycle, is described. FMA promptly address ~80% of all problems and justify/supports further actions using conventional ready techniques and resources. Original subject matter tools (three FMA levels, joint FMA-FMECA-F5 technique, and P5 failure classification) substantiate, facilitate and illustrate FMA. Multiple examples demonstrate FMA strengths and limitations with uniquely broad range of products and applications. Particular attention is paid to rare combination of high quality, reliability and profitability.

CITATION: Verbitsky, D., "Improving Quality, Reliability and Profitability of Mobility Electronics Using Systemic Failure Mode Analysis," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 7(2):2014, doi:10.4271/2014-01-0229.

1. INTRODUCTION

Proper failure analysis (FA) followed by effective, efficient and focused containment, corrective, preventive and improvement actions (CAPA) could concurrently dramatically enhance quality, reliability and profitability of modern mobility electronics. Indeed, traditional quality and reliability assurance frequently depends on multiple inspections, tests, screenings, and reviews, but do not incorporate an overall schema of failure modes and mechanisms (FMM) cause removal. As a result, high R&D, manufacturing and field losses due to poorly understood weaknesses often undermine company's competitive edge, reputation and product's advantage.

FA organization, methodology and achievements are insufficiently described by standards and literature and lack universal implementation. This reflects and forms non-systemic, sporadic, intuitive, reactive FA approach rather than systemic, methodic, and proactive one. Non-systemic FA frequently ignore both general Physics of Failures (POF) / Reliability Physics (RP) and specific industry-product-project subject matter knowledge and data. Attention is paid to complex FA, normal and wear-out failures and standard parts at the expense of simpler analytical methods, early failures and application-specific components. This frequently leads to waste of resources and to inadequate and costly CAPA [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17].

Previously proposed three-step systematic hierarchical complementary failure analysis (SHCFA) methodology addresses various failures, nonconformities, complaints and defects (failures) in a unified flexible manner at all phases/stages of a product/project life cycle. SHCFA is especially

effective when applied to early failures (EF), i.e., infant mortality phase of demanding mass-produced electronics. In this case, ~80% of EF, R&D, manufacturing and normal life field failures exhibit similar FMM. Therefore, CAPA concurrently improve quality and reliability, reduce losses and support new products/technologies. Early SHCFA are shown to complement and specify popular quality approaches: CAPA, FRACAS, QRIP, TQM, Six Sigma, Kazen and Lean [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

A properly organized first step of the systemic subject matter FA (sometimes called failure mode analysis, FMA) should be an indispensable part of any modern cost-effective and result-oriented quality and reliability assurance. FMA is aimed at determining failed parts and modes; addressing simple, known and some more complex FMM; providing data and preliminary recommendations for further actions using conventional methods and ready resources. It does not replace in-depth root cause analysis (RCA), but rather addresses vast majority of routine and, sometime, non-trivial problems; justifies and supports RCA. Proper basic FMA shall provide fast, confident and sufficient data for containment, fixes and prioritization for ~80% cases.

In reality, practitioners and management frequently mishandle FMA. The goal of this paper is to propose and outline a systemic FMA approach within SHCFA methodology that addresses typical specifics and changing priorities of failure cases during different phases and stages of product's and project's life cycles. The proposed approach is aimed at effective and efficient identification, containment and correction of failures as well as product/process improvement

and loss reduction. The proposals include conventional approaches and methods as much as possible (e.g., see [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]) as well as their customization and development as needed. The paper depicts typical, but not trivial cases of proper FMA, illustrating its strengths and limitations based on the author's experience. This paper continues to fill the gap between market demands and quality and reliability assurance practice of mass-produced electronics (e.g., refer to [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]).

2. PRINCIPLES OF SYSTEMIC FMA

2.1 FMA Role at SHCFA

A three-step SHCFA applies various conventional, customized and original subject matter FA techniques in a systematic, hierarchical, complementary and comparative manner. SHCFA includes three FMA levels: initial FMA-1 of desirably all reported failures, more detailed preliminary FMA-2 and extended FMA-3 of some important and non-trivial failures (e.g., qualification, field, and other considerable cases).

The SHCFA involves the systemic, but adaptable utilization of various organizational structures from existing engineering and manufacturing groups to multidisciplinary FA/material review boards, a specialized FA unit and specialized external lab [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22]). The FA step's boundary criteria, its beginning and the end should be determined by management assessment and directions (MAD) followed by FA database (DB) updating and/or CAPA and/or a task prioritization and support. MAD may be prescribed by standard operating procedure (SOP), FA board, or manager authorization (e.g., QA manager-refer to [Figure 1](#) and [18, 22]).

Within SHCFA methodology, the FMA goal should be to do all of the following (refer to [Figure 2](#)):

1. to preliminary characterize all failure signs and modes
2. to identify obvious and/or known cases
3. to provide information for known CAPA and relatively simple new CAPA development
4. to collect subject-matter data for statistical analysis per specified definitions, methods, criteria and confidence
5. to proactively propose FA escalation and provide RCA or FA R&D support for serious cases as needed.

2.2 Systemic FMA at Various Life Cycle Phases and Stages

Systemic FMA during the entire product/project life is the main difference between SHCFA approach and non-systemic practice. Starting at the R&D, understanding of RP/POF and expected FMM is crucial to satisfy customer needs. FMA could provide designers with quick feedback on the potential drawbacks, their nature and possible fixes [18, 22].

During the manufacturing stage, FMA is an indispensable tool allowing concurrent operational cost reduction and quality growth. Although Six Sigma, Kazen and Lean approaches have similar goals, they sometimes lack FMA specifics and practicality. Indeed, the author's experience confirms one of customized Pareto-Juran rules: about 80% of trivial/routine, but useful, cases are caused by about 20% of mostly known or simple FMM. The trivial cases do not require RCA and could be diagnosed by subject matter FMA and improved complementary statistical process control. Data also show that in spite of common bias, manufacturing FMA2/3 often address various design and purchased part/material issues in addition to process/workmanship ones [10, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

At the field stage, FMA detects and directs attention to customer concerns and maintenance cost reduction. Special attention should be paid to EF because they make up the largest failure group and causes ultimate customer frustration. Studies showed that about 80-90% of the field EF of mass-produced electronics exhibit the same root causes as ~80-90% of failures occurred during normal field life, final manufacturing and the end of R&D. Therefore, early FMA concurrently save supplier's reputation; dramatically reduce its manufacturing losses; facilitate R&D and considerably improve long-term reliability. FMA also provide the basis for refined and more meaningful field data statistical assessments [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

Sometimes conventional preliminary FMA targets solely workmanship faults-failures resulting in an underutilization of FMA as oppose to comprehensive approach suggested by SHCFA. Although FMA capabilities are limited, it could support problem resolution related to design, process, test, inspection, storage, transportation, application, suppliers, etc. during an entire life cycle-the topic of this paper.

2.3 FMA Hierarchy and Administration

FMA normally address three main groups of problems:

1. traditional routine field returns
2. manufacturing and R&D nonconformities (esp., tests, screening, burn-in, pre-qualifications)
3. important cases: formal qualification, field complaints, etc.

Each of the above-mentioned groups would have different goals and organizational structures. The first group may be addressed by a material review board and/or by a specialized unit (e.g., within QA). The second group may be managed by corresponding engineering, and the third group needs to be addressed by a special FA board (refer to [Figure 2](#); [18, 19, 20, 21, 22]).

In the most obvious cases, FMA results in an immediate trouble containment and correction/prevention (CAPA). Examples of self-sufficient FMA, which does not need further in-depth analysis typically include full and consistent single-mode failures with obvious gross signs:

- damage, overstress or misuse
- foreign objects
- obviously open or short circuit of known origin
- other known troubles (e.g., wrong/missing part, assembly, configuration, tests, modes, etc.)
- most irrelevant failures.

Properly organized and utilized FMA is a rather effective and efficient tool and it is able to resolve about 70-90% of all failures with approximately 70-90% confidence. Initial FMA (FMA-1) includes 2-3 layer failure troubleshooting, characterization and description performed per SOP. It uses relatively simple conventional techniques and lasts 0.1-2 days depending on failure mode specifics and resources. Contrary to a popular “Five Why” methodology, FMA-1 typically address “What, where, when and how” questions. FMA-2/3 address first 2/3 “Why”; use broader methods and sample sizes, and might last 1-3 weeks exhibiting a blurred boundary with abbreviated RCA. Unlike RCA, FMA is not aimed at a full knew FMM characterization and strategic resolution, but maximum at FMM identification, containment and quick operative fixes. Yet, root causes and long-term tactical-strategic solutions should be highly appreciated (see details below, [figures 1, 2](#) and [\[18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30\]](#)).

FA may advance to RCA handling the next 2-3 layers of 10-20% of the most important failures. FMA provide first-step data on the bulk of problems and routine CAPA while RCA feeds-back FMM description; P5 classification; joint F5-FTAFMECA; proven focused CAPA stored into an indispensable “lessons learned” DB. Most RCA downgraded later monitoring to FMA-1 using DB (refer to [Figure1-2](#) and [\[18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30\]](#)).

There are two typical FMA-related organizational types of errors: practitioners and management either skip FMA in favor of RCA or, alternatively, use FMA instead of RCA. The errors increase manufacturing and customer risks, respectively. Thus, FA faces classical quality problems: the risk of rejecting true and accepting false hypotheses [\[10\]](#). Per the author's observations, large companies tend to overuse RCA while small organizations typically stop at FMA. Yet, the most typical case is that enterprises ignore the warning signs jumping later on to immature CAPA (see below and [\[18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31\]](#)).

2.4 FMA Classification and Reporting

Practical FMM classifications could help to select particular CAPA approaches and methods, save time and resources. Traditional classifications are rather helpful and are typically

based on failure physics, duration, rates, and signs. A brief overview of classifications affecting FMA administration is presented below (refer to [\[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17\]](#) for other approaches).

Failures may be caused by product specifics (called “relevant” failures), by test, inspection or personnel deficiencies (termed “irrelevant” failures) and by various miscellaneous and mixed problems. A complementary group includes missing failures due to inadequate documentation, inspection, test coverage (e.g., so called “test escapes”). This new class is more dangerous than irrelevant one since misleading and deceptively good results typically enable noncompliant products to pass unnoticed until field deployment [\[1, 2, 3, 4, 5, 6, 7, 8, 22\]](#).

For practical SHCFA purposes, the author have proposed and used a subject-matter, problem-product-project-property-priority, classification. It is based on the failure (problem) peculiarity; occurrence probability/criticality (priority); product and project properties (may be referred to as a P5 classification per [\[22\]](#)). The main classes of the P5 include

- a. Problem/product/project-inherent, deterministic, recurring, predictable, reproducible failures
- b. Problem/product/project-pertinent failures
- c. Problem/product/project-specific failures
- d. Problem/product/project-extraneous, probabilistic, unpredictable, unrepeatable, random, and isolated failures and
- e. Product/project is quality-reliability-cost problem free.

Classes (a) to (d) exhibit variable deterministic-probabilistic, occurrence, reproducibility and criticality weights gradually reducing deterministic fractions to desirable/ideal zero at grade (e). All of the above should be factored by project category (e.g., aerospace, military, commercial, consumer, etc.). The product's business importance and technological complexity further vary within each category adding variables to their class determination. Specific case attribution to one of the P5-based classes formalizes and helps FMM understanding and following MAD [\[18, 21, 22\]](#).

Proper acquisition documentation, accompanying the failed item, proved to be very helpful: questionnaire, DB, manufacturing traveler, complaint, report, etc. (Refer to [Figure 2](#) for guidance). Initial information is so important that it justifies efforts to optimize suitable forms, personnel training and establishing special relationships with appropriate sources.

FMA report should carefully describe its incoming data, goals, methods, and results clearly separating facts, hypothesis and judgments. Thus, serious conclusive FMA reports should be made in collaboration with subject-matter experts in manufacturing, engineering, R&D, quality, purchasing,

application, etc. The reports should use templates and include preliminary P5-based failure classification as much as possible to facilitate data analysis automation and MAD.

One of the most important traditional FA goals is to provide data for subject matter statistical analysis and for MAD regarding serious CAPA and in-depth RCA. This multifaceted task requires proper data recording, classification and organization into “lesson learned” FA DB using well-known, but customized classifications and the above-described F5 and P5 techniques. FA DB should integrate relevant R&D, manufacturing and field data and comparable baselines for similar products and projects. The FA DB may also include relevant scientific POF/RP data obtained from external sources and should be periodically adjusted [5, 6, 7, 8, 9, 18, 22].

Enterprise-wide information systems like Oracle RDBMS® and SAP R/3® may be helpful if properly adjusted. Yet, in some cases a simplified DB has been proven more suitable (e.g., based on Microsoft® Access® and/or Excel®). Data should be compatible with subsequent semi-automated statistical analysis to utilize standard built-in Excel® automated tools. The data security and accessibility should be balanced taking into account all aspects from usefulness to sensitivity. This approach, scripts and Visual Basic® increase automated FMA statistical data analysis success to 95-99%.

Full P5-based classification could be made based on large volume of in-depth RCA and FA R&D data. Nevertheless, preliminary classification of known and/or simple FMM may be performed using FMA results. In this case, P5 classification automatically suggests necessity of further actions: in-depth FA, CAPA or continuing FMA and data gathering.

2.5 Complementary FMA Techniques

FA literature typically concerns various special methods related to microelectronics and bulk constructive materials, rarely addressing generic methodology. Frequently first-step FA reduce to simple microscopes restricting FMA capabilities. SHCFA takes the alternative approach utilizing all suitable complementary tools to accomplish the task [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

FMA should start from the initial case study: the problem's signature, scale, and circumstances (e.g. using acquisition documents and interviews). FMA should not limit itself to trivial problems (e.g., workmanship, EOS, dimensions, wrong/absent/extra parts, etc.) and needs to take a broader approach. Meaningful initial awareness of project status and needs; product spec and technology; application and test conditions/methods is also implied; however, this is often ignored during non-systemic FA. The initial study should also include examining similar cases in the FA DB and utilization of joint F5-FTA-FMECA charts, SOP's techniques and data (figures 1, 2, 3, 4; [18, 22, 31]).

The initial study is being followed by actual FMA of the failed unit: visual inspection, failure verification and initial troubleshooting of the failed product, modules, and suspected components. Destructive physical and chemical analysis should be applied only after exhaustive utilization of non-destructive methods. For example, all possible functional tests, measurements, photos, hermetization/leaks and non-destructive tests like X-ray microscopy, acoustical, fluorescent, contamination, solderability and other process/application-related ones should be conducted before any destructive physical analysis (e.g., refer to figure 2 and [9, 14, 15, 16, 18, 22]).

Sometimes FMA-2/3 involves internal study of the failed part (normally in conjunction with the part's manufacturer). This requires appropriate supportive documentation: reliability and functional diagrams; specifications, drawings and software. Depending on the case specifics, FMA may include diverse techniques: wide magnification, precision measuring devices, special probes, signal analyzers, boundary scans, application-specific environments, tools and chemicals, some software and test equipment adjustment, etc. Numerous violations of these simple rules by non-systemic FA in an attempt to accelerate CAPA resulted instead in wasting time, resources and contracts (see below; [18, 22]).

FMA scale varies depending on P5/F5 specifics described above. For example, microelectronics or advanced modules might require techniques, which are appropriate to RCA of the medium- or high-level devices (e.g., scanning electron microscopy, X-ray, decapsulation, laser's circuit isolation or shortening, and similarly refined methods.). On the other hand, more subtle and/or new important FMM may also require similar tools for the medium- or high-level assemblies. Precision, complex and high-reliability products typically need more accurate and diverse tests, measurements, stresses, software and configuration analysis than regular ones.

FMA may consciously extend to some traditional RCA methods in order to lead to focused CAPA of relatively serious cases when full RCA is deemed yet unnecessary. FMA-2/3 may include the following:

- simple test setup, design, software reconfiguration
- reasonable comparative tests and analysis
- basic environmental and functional stress variations
- simple simulation and statistical analysis
- straightforward work with suppliers and customers.

Complex technological FA, advanced physics, chemical, technological, part, application and statistical analyses and modeling should normally be left to RCA or FA R&D [18, 19, 20, 21, 22].

2.6 Practical FMA Organization

Practical effective and efficient FMA organization is probably the most important and complex part of the process. Although implied by some standards, preliminary FA is neither explicitly specified nor described leaving a room for various errors [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. As usual, there are several ways for FMA arrangement and each specific organization should choose the most suitable for its needs, resources and particular cases.

One of the basic SHCFA concepts is to address as many technical problems as possible, desirably covering 100% of failures. This is especially important in the end of the each life cycle stage since quality costs increase exponentially. Based on our experience, ~70-80% of the problems are useful trivial, recognizable and identifiable ones by FMA and an FA DB. Thus, FMA should be built-in to SOP [10, 18, 19, 20, 21, 22, 28, 29].

Routine FMA may be delegated to operational personnel. For example, trained qualified manufacturing staff may document results of standard operational inspections, tests, troubleshooting, screenings, etc. into FA DB using the abovementioned classificatory and templates. Also engineering R&D, manufacturing, and QA branches may address development/design, operation and field failures, respectively. The branches, and boards may also conduct relatively rare FMA-2/3. A specialized FMA unit may be justifiable for large volume FMA; mass production (e.g., microelectronics); new complex technology and demanding applications (e.g., aerospace, medical, nuclear, etc.).

Besides any important systemic FA starts from non-routine FMA. In those cases, FMA are typically done either by board members or by a specialized RCA unit with participation of FMA personnel as needed. By definition, these important cases automatically proceed to RCA unless FMA revelations are conclusive enough for efficient CAPA [1, 2, 3, 4, 5, 6, 7, 8, 9, 18, 19, 20, 21, 22].

3. FMA Examples During Life Cycle

The following examples from the author practice illustrate typical important not-trivial cases resolved either solely by FMA (mostly FMA-2/FMA-3 levels) or by RCA, but with considerable FMA participation. The examples reflect broad electronics range; various aspects of product/project life cycle; F5 and P5 considerations and appropriate FMA tools and methods.

3.1 Design-Related FMA

Instantaneous reversible EF of the current driver module may exemplify typical high-speed circuit problems addressed by FMA. Reported on-board computer's failure signature exhibited data corruption. FMA-1/2 determined false logical "1" due to increase of saturation voltage U_{sat} of the module's high power outgoing transistors under the stress: high current $I \sim 60\text{mA}$ and low temperatures $T \sim -(20-60)^\circ\text{C}$ (see Figure 5). FMA-3 confirmed significant differences between acceptable and

failed transistors under the stresses, however all parts complied with their specification under nominal stress. Thus the driver's circuitry did not accommodate normal parts' variability. The transistor screening led to full trouble's containment without any losses: the screened out transistors were used by other serious products [18, 25, 27].

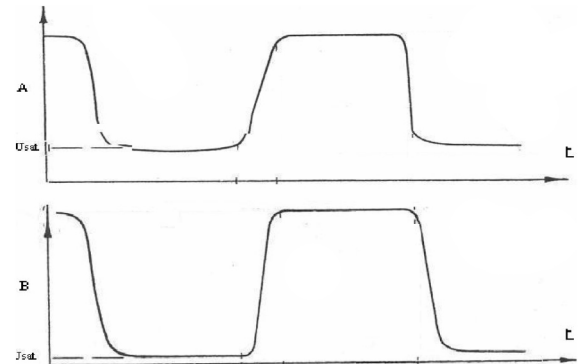


Figure 5. A circuit-part inherent FMM. (A) Logical "0" changes to "1" due to increased U_{sat} at $-(20-60)^\circ\text{C}/60\text{mA}$ vs. (B) nominal mode/part. FMA used refined large size electrical testing of the modules and parts.

Other electrical design-related FMA include absent protection, absorbing and damping resulting in EOS/ESD/latch up/AF/RF overstresses; poor resonators, amplifiers and filtering; poorly selected, overstressed or overused; poor sensor-converter-processor compatibility, etc. [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

FMA is proven a very useful tool to manage some mechanical design issues. Conventional failures of joints in electronics are typically assigned to workmanship or to wear-out fatigue [10, 16, 17]. Our FMA, however, revealed design-related inherent dramatically low reliability of non-bent pin solder to inexpensive mass-produced non-plated printed circuit board (PCB) holes. As a result, a number of massive early cracks occurred along the pin-hole perimeter, especially for heavy parts (Figure 6). Focused CAPA improved assembly's designs (e.g., bent pin-to-PCB's trace solder joint), eliminated this FMM and cut off ~90% of related losses [18, 22, 26, 29].

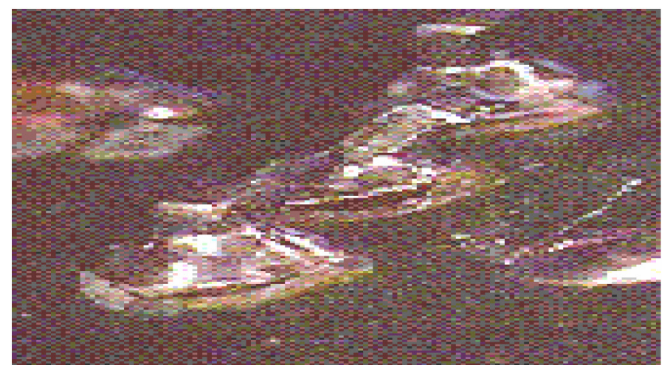


Figure 6. Mechanical design-inherent super-early FMA used traditional low-medium microscopy. Solder joint cracks due to soldering of non-bent parts' pins to non-plated through holes of inexpensive PCBs.