

Safety and Reliability of Embedded Systems (Sicherheit und Zuverlässigkeit eingebetteter Systeme)

Fault Tree Analysis Obscurities and Open Issues

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What are Events?

- ☐ In probability theory, everything that is true with a certain probability is called "event"
- ☐ In software / systems engineering (and in common language), an event is something occurring at a given point in time
- ☐ In FTA, events can be
 - Sudden events ("Bolt breaks")
 - States or conditions ("Valve is blocked")
 - (Informal) propositions ("Fire is not detected by supervisor")
- ☐ Note the differences regarding probabilities
 - States / propositions have a probability (at a given time)
 - Events have a probability density or rate
- ☐ (Out-dated) DIN 25424 features appropriate formulas for probability and probability density

Examples for Problematic Event Semantics

- Priority AND:** Output event occurs when all input events occur in a specific order
- ☐ If FT events are sudden events: When does output event occur?
 - E.g. simultaneously to the last of the input events
 - ☐ If output event is a logical proposition: The proposition is true (all the time!), if the input events do occur in the right order
 - But can input events also be propositions then? How can then Input 1 occur before Input 2?
 - ☐ If FT events are states / conditions / predicates that can be true or false at given times
 - Input 1 can become true before Input 2
 - Output condition is true upon the time when the last input condition is true

Inhibit, Enabler / Conditioning Events

Inhibit:

Output event occurs when input event occurs and inhibit event is not true

- ☐ Inhibit event has state / condition semantics
- ☐ Sometimes enabler events (states) are distinguished from initiator events (trigger semantics)
- ☐ Separate symbols are available



Basic Event / Initiator

Conditioning Event / Enabler



MCS based probability calculation is not suitable for negated events!

The Use of NOT

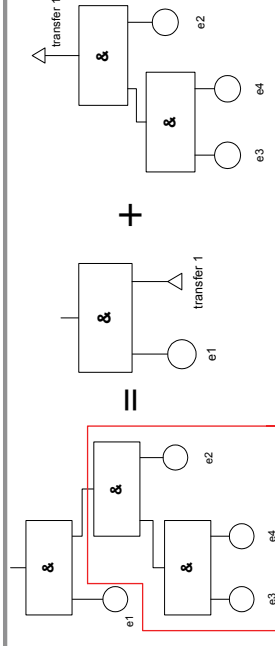
- ☐ A FT without NOT is called "coherent"
 - "A system can never get better if more components fail"
- ☐ Some NOTs are virtual (e.g. in transcriptions of voter, XOR, ...)
- ☐ If FT events are sudden events
 - How can their occurrence be negated?
 - In this case, NOT makes no sense
- ☐ If FT events are states / conditions / predicates / logical propositions
 - Negation makes sense
 - BDD algorithm can handle negated variables
 - Minimal cut sets → Prime implicants (may contain negated events)

cf. John Andrews: "To Not or not to Not"

Generalization vs. Causation Gates

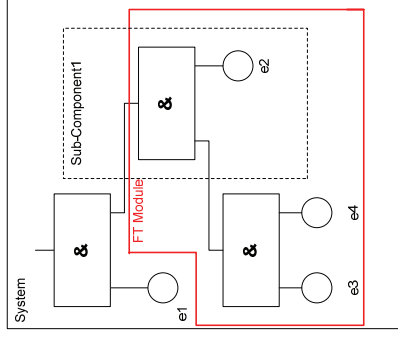
- ☐ Sometimes gates suggest causality
 - Electrical short circuit OR defective gas tube ⇒ fire
- ☐ Sometimes gates suggest generalization / decomposition
 - Engine defective OR tire defective = car defective
- ☐ In original FT standards no distinction, some researchers do distinction
 - Sometimes, two pairs of AND / OR are proposed [Gorski]
 - Some say that AND means causation and OR means decomposition [FT Handbook]
- ☐ Whether or not FTs express causality at all can be discussed...

Issues about Decomposition



- ☐ FTs are hierarchical by nature
- ☐ Traditionally, FTs are decomposed by modules (independent sub-trees)
- ☐ Each module is replaced by a single event with the same probability
- ☐ Each module can be analyzed independently
- ☐ Alternatively, partitioning into pages by transfer symbols

FT Decomposition by Modules



Modules are independent sub-trees

But:

Technical components often influence each other

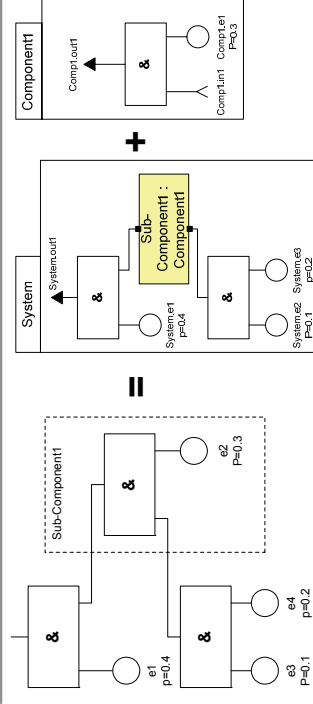


Technical components are not always modules!

Deficiencies of Classical Module Concept

- ☐ Module borders may be orthogonal to component borders
- ☐ Attachment of (partial) fault trees to components is not possible if components have external influences
- ☐ Division of labor (e.g. supplier/integrator) is not possible
- ☐ Modeling of some component by other models than fault trees is not possible
- ☐ Partitioning of fault trees into pages (using transfer ports) is a solution to some degree, but still no division of labor or reuse

Recent Approach: Component Fault Trees



Here, “component” means technical unit.

Components are connected by ports like in architectural models.

New paradigm: Components represent Boolean formulas

Temporal Functions

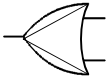
- ☐ Events can be understood as propositions that are true or false at each given point of time
- ☐ Supplying time functions instead of constant probabilities allows to plot reliability/availability function for the complete system
 - Events can be exponentially distributed, Weibull distributed etc.
 - Useful in combination with Markov analysis
 - Mission time for each event or sub-component specifies time
- ☐ Important special case: Exponential distribution
 - $P(t) = 1 - e^{-\lambda t}$, λ : Failure rate, P : Probability, that component has failed
 - OR leads to an exponential function as gate output, but AND does not!



Attention when representing events by their occurrence rate:
Output function is not always exponential!

Temporal Relations between Events

- Standard FTA is based on Boolean logic and cannot handle temporal sequences
- Priority AND expresses probability that event 1 occurs before event 2
 - Only useful if time functions (and not static probabilities) are used
 - Probability of system failure before t is probability that E1 occurs before some intermediate point of time and E2 occurs after that point, accumulated for all points of time between 0 and t



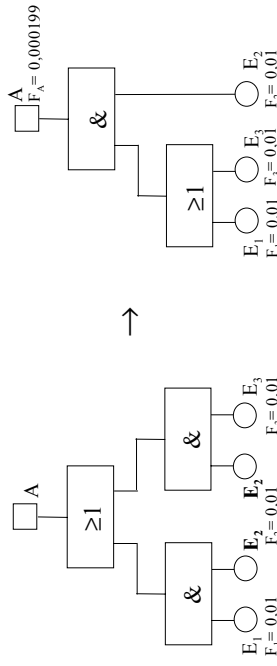
E1 E2

$$P_{\text{failed}}(t) = \int_0^t \int_0^{t_2} f_2(t_2) \left(\int_0^{t_1} f_1(t_1) dt_1 \right) dt_2$$

Dependencies

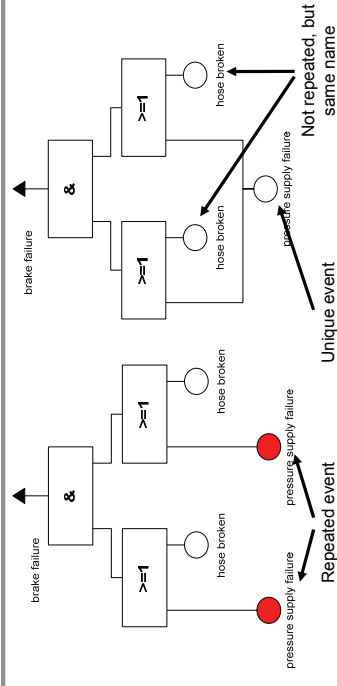
- Stochastic independence is an important assumption for combinatorial approaches
- Repeated events as special case of dependency can be handled by restructuring the Boolean formula
- For special cases (e.g. spares), there are solutions
- When probabilities are small, errors may be negligible if dependencies are not taken into account
- Correct calculation in presence of arbitrary dependency is only possible by state-based models
- Functional dependency gate in DFT allows to express secondary faults

Elimination of Repeated Events



By restructuring the Boolean formula, repeated events can be avoided

Repeated Events: Tree vs. DAG



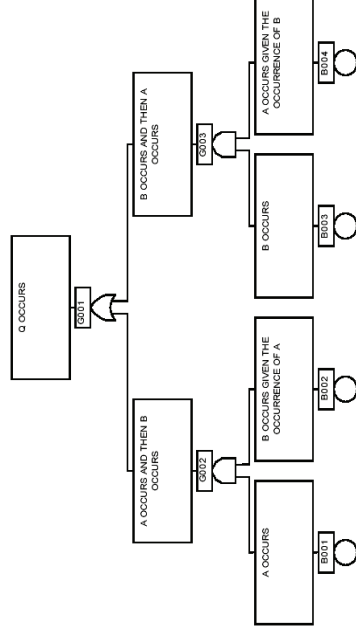
Directed Acyclic Graphs (instead of trees) eliminate repeated events
A namespace concept is desirable (implemented in Component Fault Trees)

Spare and Spare Pools

- ☐ A special case of dependency is the usage of spares
- ☐ System fails if primary unit fails and spare also fails or has already failed before
- ☐ While the primary unit is operating, spares fail
 - not at all → cold spare
 - at a reduced rate (specified by a factor) → warm spare
 - at the normal rate (hot spare)
- ☐ Special spare gates have been proposed
- ☐ Spare pool: Not only one spare unit, but n spare units with identical failure rate

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Explicit Dependencies



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Other ways to deal with dependencies

- ☐ Functional Dependency Gate (in some packages)
 - Output event occurs necessarily if input occurs
 - Output event can also occur spontaneously

Many attempts have been made to bring special cases of dependency into FTA. At a certain point, state-based models (e.g. Markov chains) are a better fit (but analysis is usually much slower!)

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Integration with other models

- ☐ Fault trees can and should be integrated with
 - Markov chains: to describe basic events in presence of dependencies
 - Event trees: to describe consequences of the top-event
- ☐ Fault trees can and should be used in conjunction with
 - FMEA
 - other hazard analysis models (Preliminary Hazard Analysis, Common Cause Analysis, ...)
 - general systems and software modeling techniques

Formal integration with software / systems modeling is desirable, but not yet achieved to a satisfactory degree

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FTA for Software

- ☐ FTA stems from an era when (at least) safety critical systems were purely electrical / mechanical
- ☐ They have "working/failed" semantics
- ☐ They cannot natively capture the dynamic nature of software
- ☐ There have been several attempts to apply FTA to software or to derive FTs from software
 - partly based on source code statements
 - partly based on statecharts or formal methods

 **Applying FTA to software controlled systems is still an issue**

Is there a formal semantics for FTA?

- ☐ FTs are intuitive, but unclear semantics is an issue when
 - constructing FTs automatically
 - integrating FTs with other kinds of models
 - using dynamic extensions
- ☐ Some recent research work about formalizing FTA
 - formalizing the meaning of gates
 - proving that FT is complete and consistent
- ☐ Different formalisms used
 - Z (algebraic specification)
 - Interval Temporal Logic, Duration Calculus (temporal/real time logic)
 - Translation into Markov chains and different kinds of probabilistic Petri nets



Formalization is not agreed upon.
Different researchers use different approaches

Literature

- ☐ Component Fault Trees
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 - On The Quantitative Analysis Of Priority AND Failure Logic, IEEE Transactions On Reliability (R-25 No 5), 1976, p324-326, JB Fussell & EF Aber & RG Rahl
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 - Kaiser, B., Gramlich, C.: State-Event-Fault-Trees - A Safety Analysis Model for Software Controlled Systems, Salecomp 2004, September 21-24 2004, Potsdam, Germany