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Symbolic Assurance Refinement

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Assuring Cyber-Physical Systems

DoD Digital Engineering Challenges

Model-Analyze-Build

Late Discovery of Design Errors in DoD Systems is very costly.

Architecture modeling and analysis can **detect** design **error early**

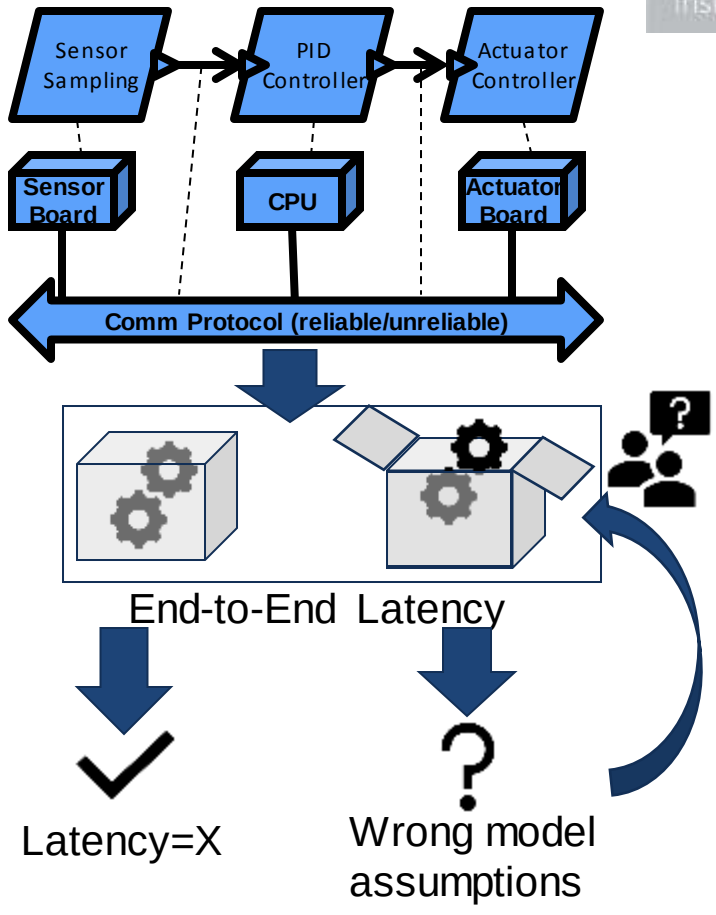
BUT:

Analysis assumptions are often implicit

if analysis **assumptions not met**: analyses break down for reasons not clear to users of analysis tools.

E.g., e2e Latency Assumption: periods multiple of each other (harmonic)

DoD barrier for adoption

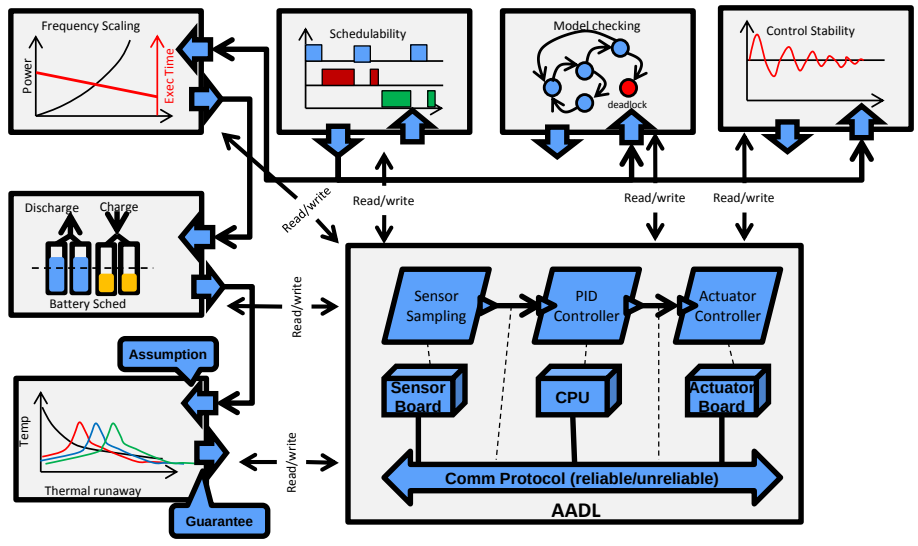


Digital Engineering: Multiple Claims - Multiple Analyses

Different Assurance Claims

- Combine multiple analysis
- Validate assumptions
- Resolve assumption conflicts

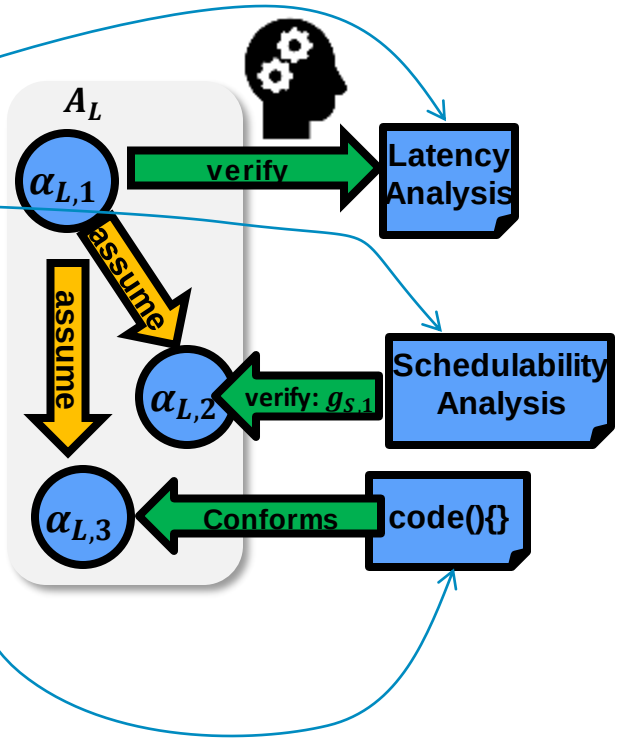
Integrate into arguments to satisfy claims



Analysis Contract: Tracking Assumptions and Guarantees


```
contract{
  inputs:
        E2ELatancies
  assumptions:
        areConnectionsDelayed()
        areDeadlinesConstrained()
        areTasksSchedulable()
        areAllThreadsPeriodic()
  analysis:
        meetEndToEndLatencies()
  guarantee:
        [E2EResponses[i] <= E2ELatencies[i]
          for i in range(len(Responses))]
}
```

$C_L = (A_L, G_L)$ with $A_L = \{\alpha_{L,1}, \alpha_{L,2}, \alpha_{L,3}\}$



Shift Left And Down to the Metal

Early Analysis

- Evaluate design decisions with partial information
- E.g., latency analysis before worst-case execution time (WCET)
  - periods of tasks must be multiples of each other

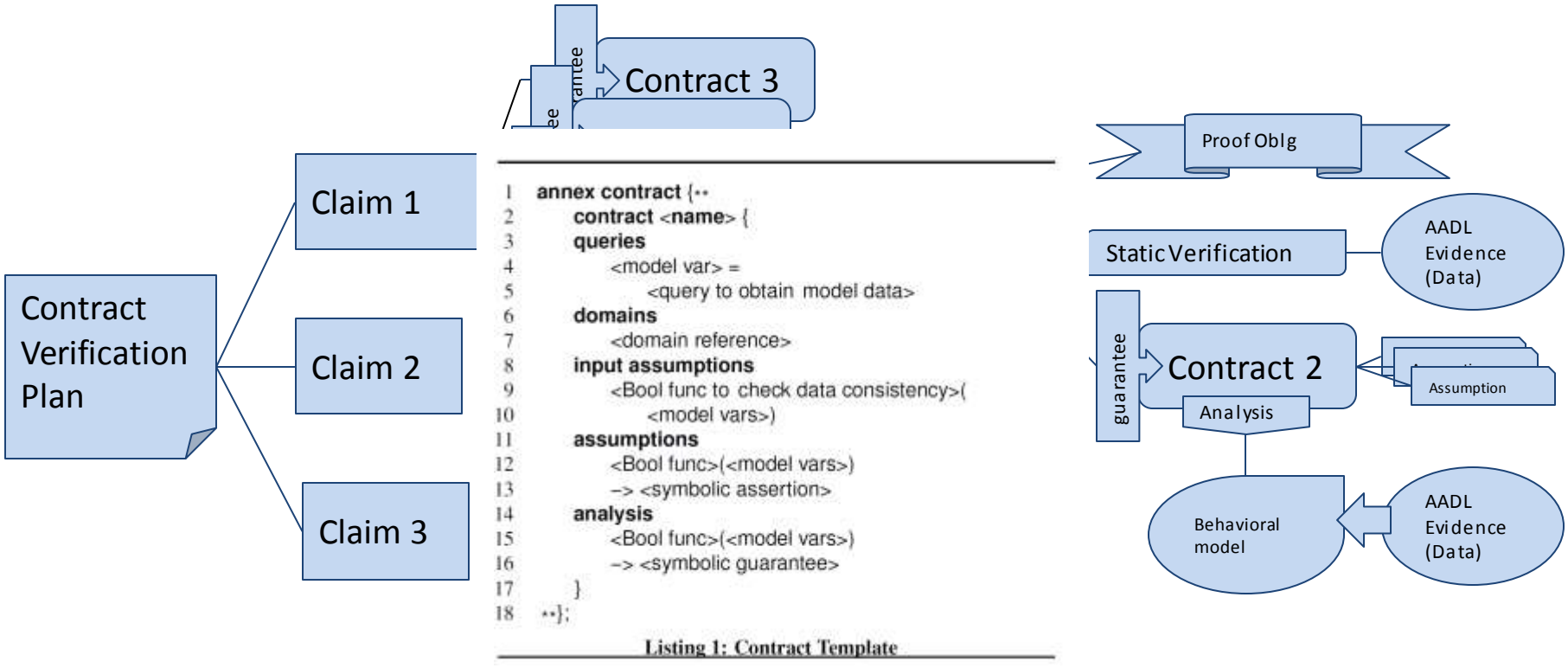
Refinement

- Track pending information
  - WCET
- Track and execute pending verification
  - Schedulability

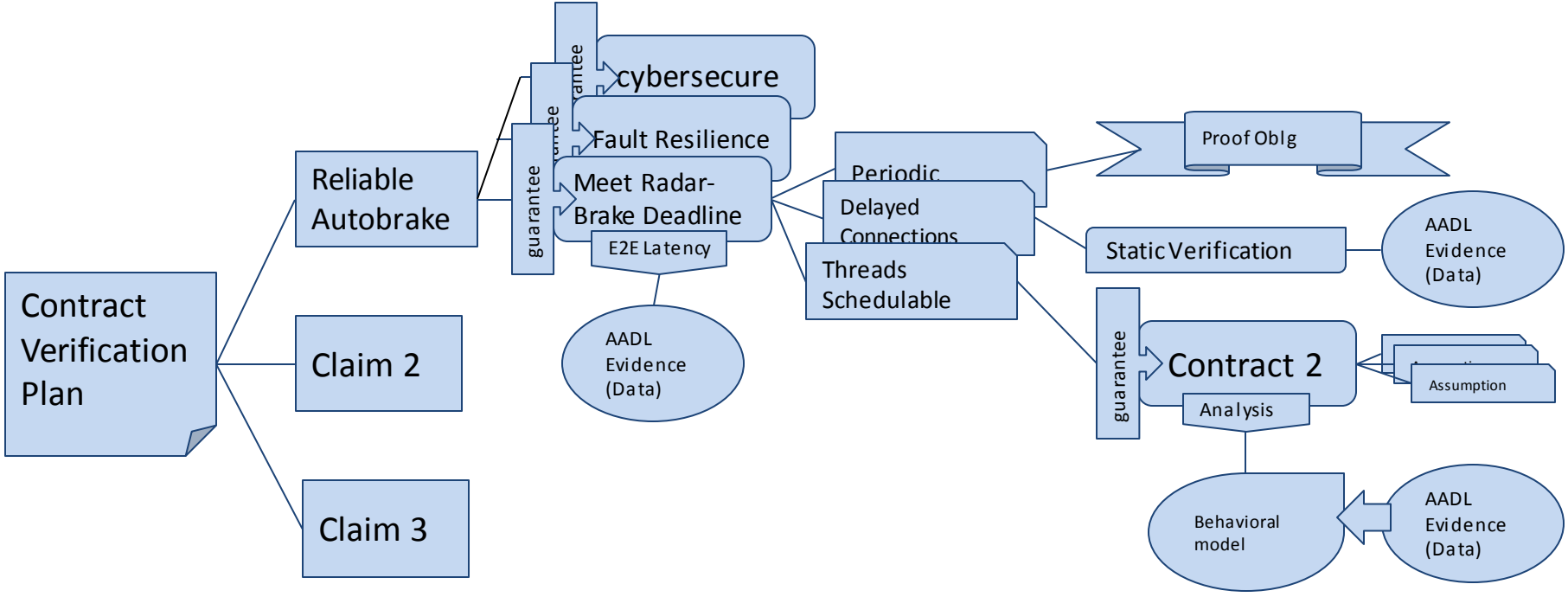
Conformance

- Track implementation assumption
- Verify implementation conformance
  - Task executed strictly periodic $\alpha_{L,3}$

Assurance Contract Argumentation



Assurance Contract Argumentation



Symbolic Contract Argumentation

Assumptions

- Constraints that must be satisfied for a valid analysis

Analysis

- Evaluate whether the guarantee can be discharged

Guarantee

- Assertion presented as a true fact on model

Implementation

- Satisfiability Modulo Theories (Z3)
- Implements contract argumentation
  - Evaluate whether constrains can be satisfied with facts from analysis guarantees
- Validate assumptions
  - Proof obligations: lack of constraints allow any value that satisfy assumption (e.g., RM priorities)

Encoding In SMT

Verification Plan

- $P = (K, D)$
  - $K := \{(k_i, C_i)\}$
  - k_i predicates over symbolic variables

Contract

- $C_i = (V_d, Q, I, A, G, N)$
  - V_d symbolic variables from a domain
  - Q model variables (e.g., from AADL models)
  - I input assumptions (if enough data for analysis)
  - $A = (p, a)$ set of assumptions
  - G guarantee
  - N analysis predicate (imperative Boolean function)

Algorithm 1 getSMTEncoding($Plan$)

1: $F \leftarrow \{k_i | (k_i, C_i) \in Plan.K\}$
2: $T \leftarrow \{C_i | (k_i, C_i) \in Plan.K\}$
3: **while** $T \neq \emptyset$ **do**
4: select t from T and remove it from T
5: **if** t is argument **then**
6: $T \leftarrow T \cup t.C_a$
7: $F \leftarrow F \cup (\text{replG4C}(t.F_a) \implies t.G_a)$
8: **else if** $\bigwedge_{i \in t.I} i$ **then**
9: **for** $p \in \{p | (p, a) \in t.A\}$ **do**
10: **if** p is contract **then**
11: $T \leftarrow T \cup p$
12: $F \leftarrow F \cup (\bigwedge_{\forall \{a | (p,a) \in t.A\}} a) \wedge N \implies t.G)$
13: **else**
14: $F \leftarrow F \cup (p \implies a)$
15: **end if**
16: **end for**
17: **end if**
18: **end while**
19: **return** F

Contract Argumentation Scalability

Exploit Knowledge from Scientific Domain

- Efficient algorithms from specialized domains
  - E.g., greedy worst-case response time in real-time theory
  - Implemented in imperative languages

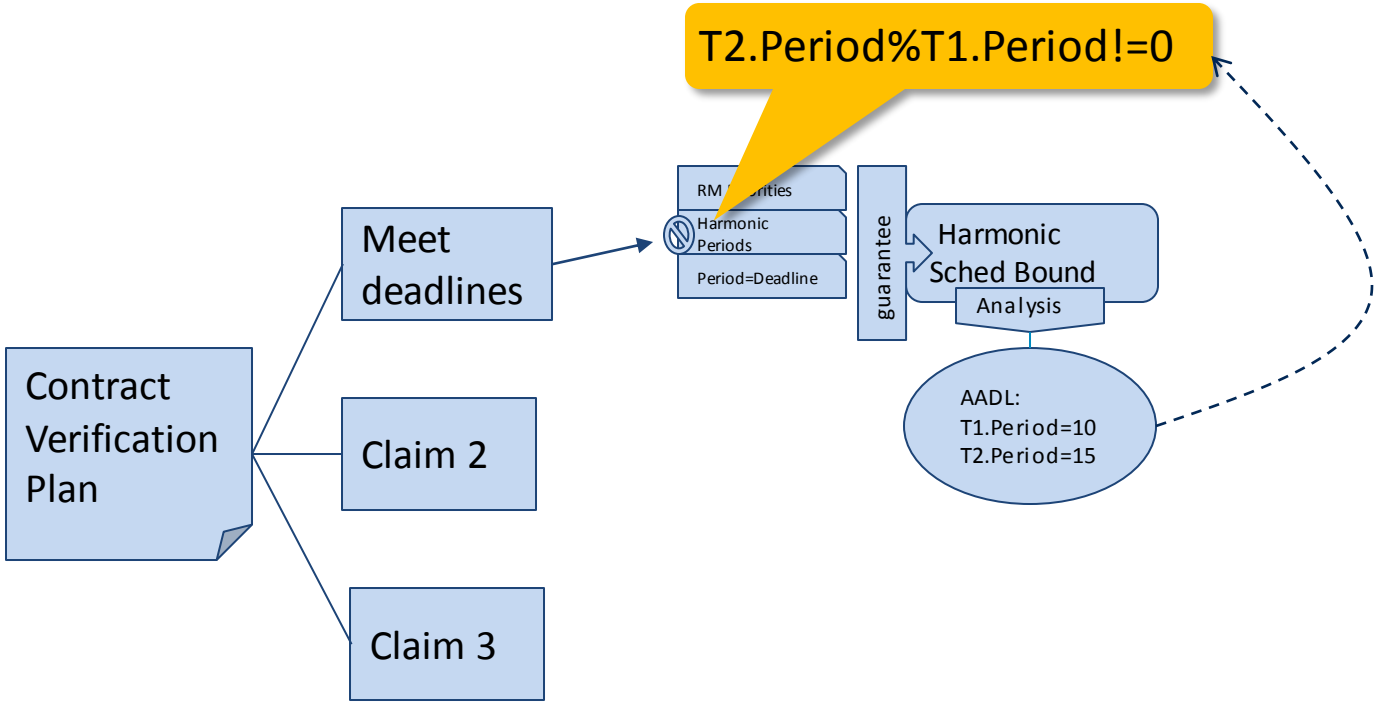
Assume correctness of analysis

- When validating the contract argumentation
- To be connected with other lower-level verification results
  - E.g., PROSA: coq (theorem prover) verification of real-time theory

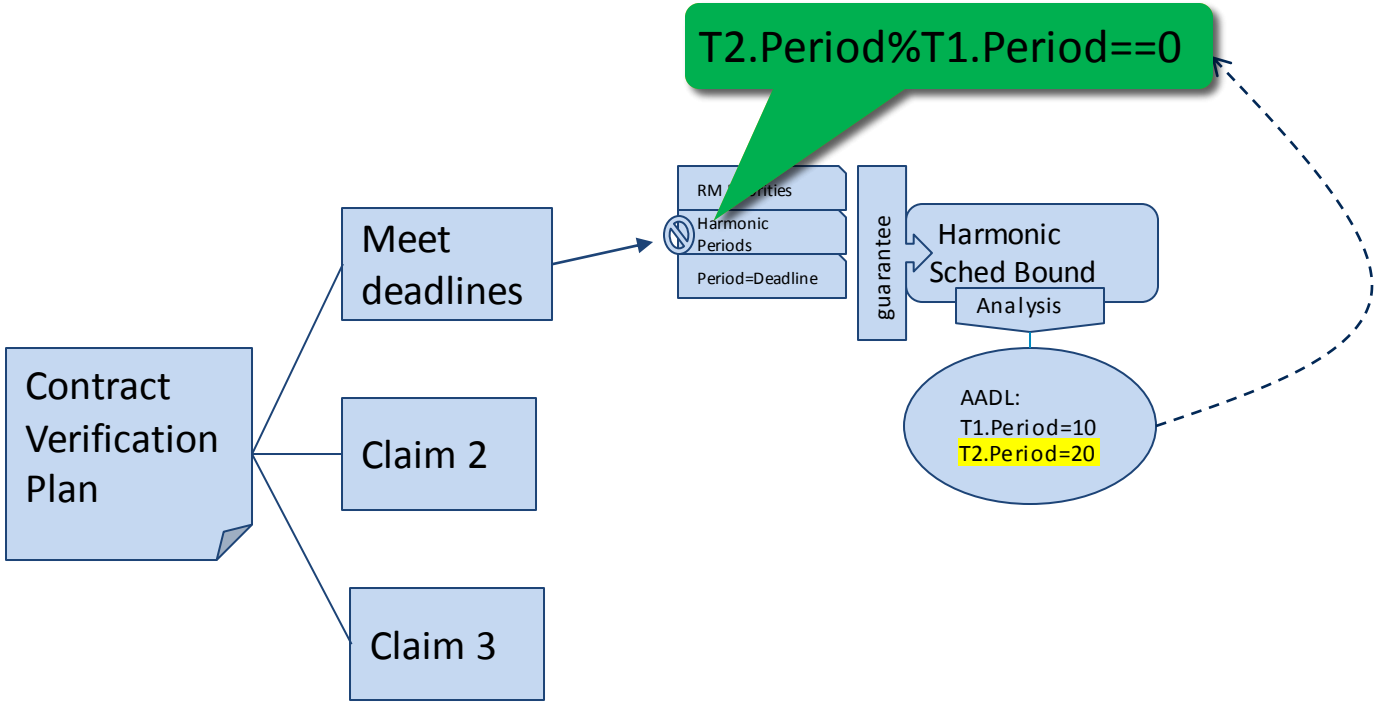
Correctness of implementation

- Exploit proven properties of runtime mechanisms: e.g., schedulers, hypervisors
- Exploit code generation
- Deferred code verification to conform to assumptions

Repairing Assumptions



Repairing Assumptions



Repairing Assumptions

T2.Period%T1.Period!=0

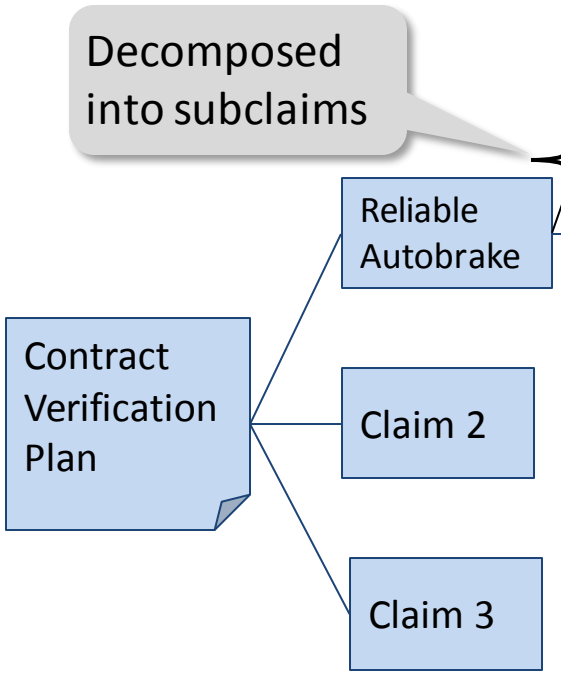
Contract Verification Plan

```
1  annex contract {**
2  argument schedulability
3      argument
4          Or(RMBound, RTA)
5      ...
6  }
7
8  contract RMBound {
9      assumptions
10         RMPriorities(periods,  priorities )
11     analysis
12         RMBoundTest(...)
13 }
14
15 contract RTA {
16     assumptions
17         ...
18     analysis
19         RTATest (...)
20 }
21 **}
```

Listing 3: Path Selection Based on Assumptions

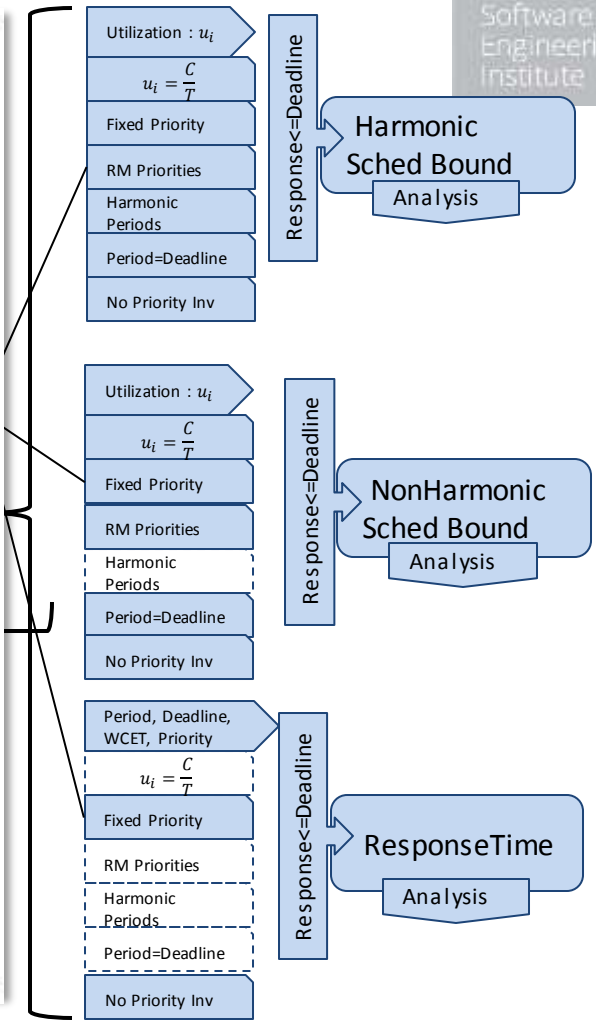
Sugg
Non
doe
periods

Argument Modularity

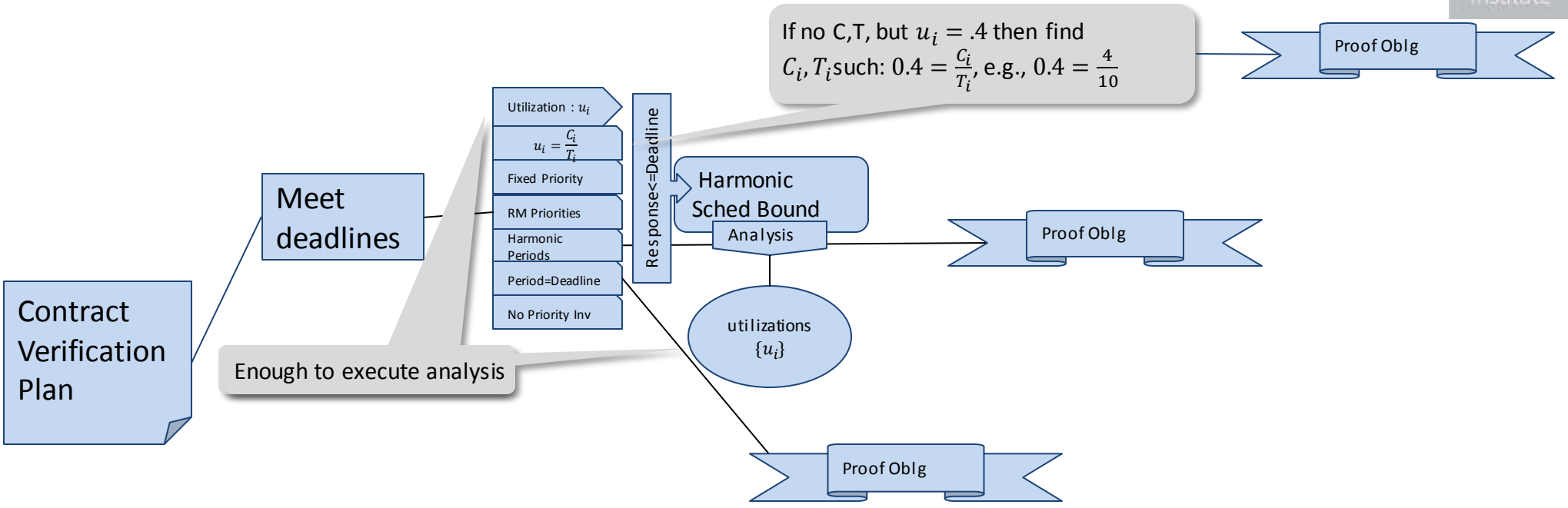



```
1  annex contract {**
2  verification plan myPlan {
3      claims
4          EndToEndDelayArgument->
5          And([E2EResp[i] <= E2ELatency[i]
6                  for i in range(len(E2EResp))]
7  }
8
9  argument EndToEndDelayArgument {
10     argument
11         Or(E2ESched, E2ESFlowSpec)->
12             And([E2EResp[i] <= E2ELatency[i]
13                     for i in range(len(E2EResp))]
14 }
15
16 contract E2ESched {
17     input assumptions
18         allSchedDataPresent()
19     ...
20 }
21
22 contract E2EFlowSpec {
23     input assumptions
24         notAllSchedDataPresent()
25     ...
26 }
27 **}
```

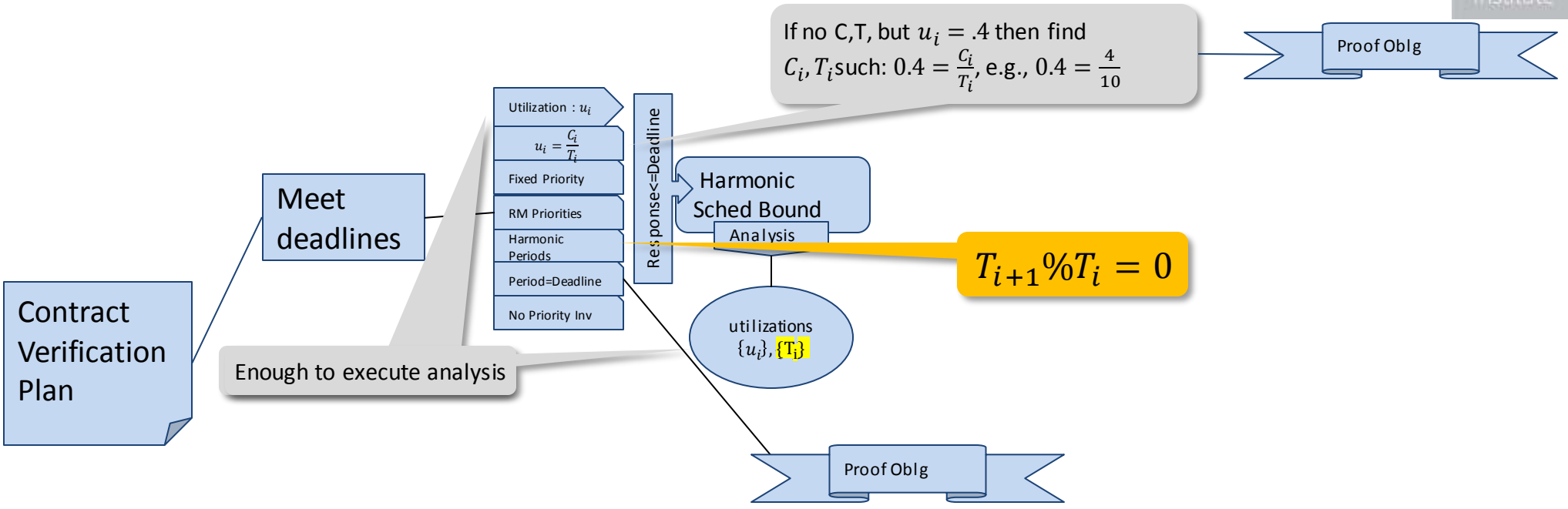
Listing 2: Path Selection Based on Refinement



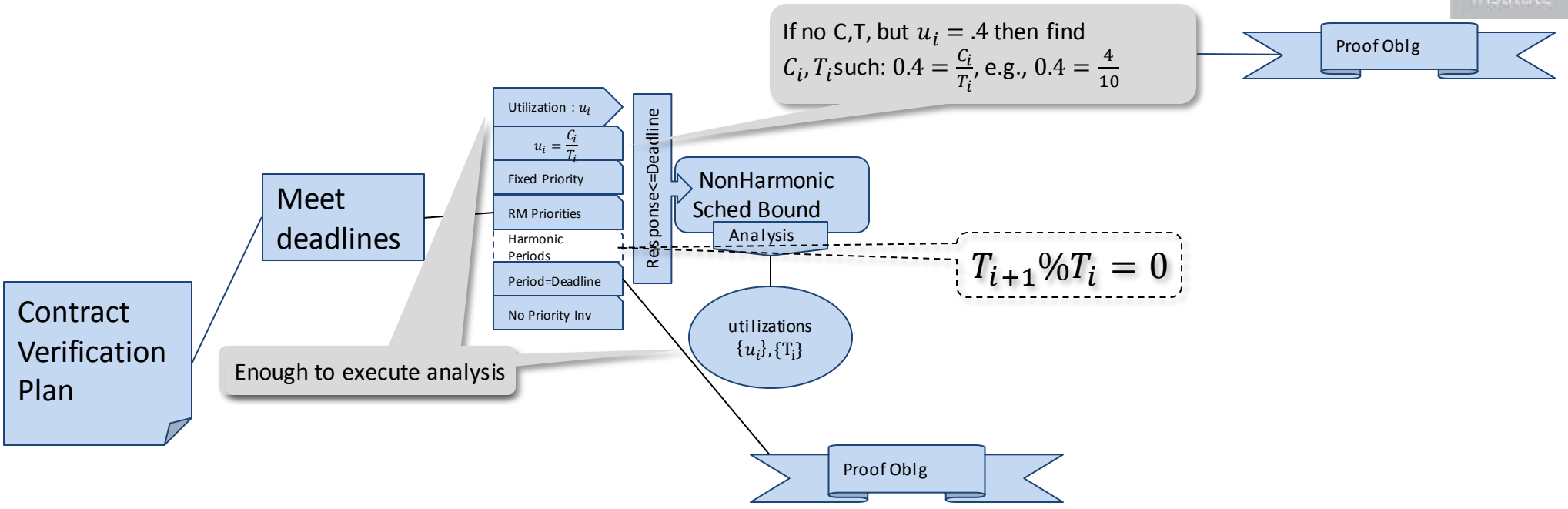
Refinement throughout development (1)



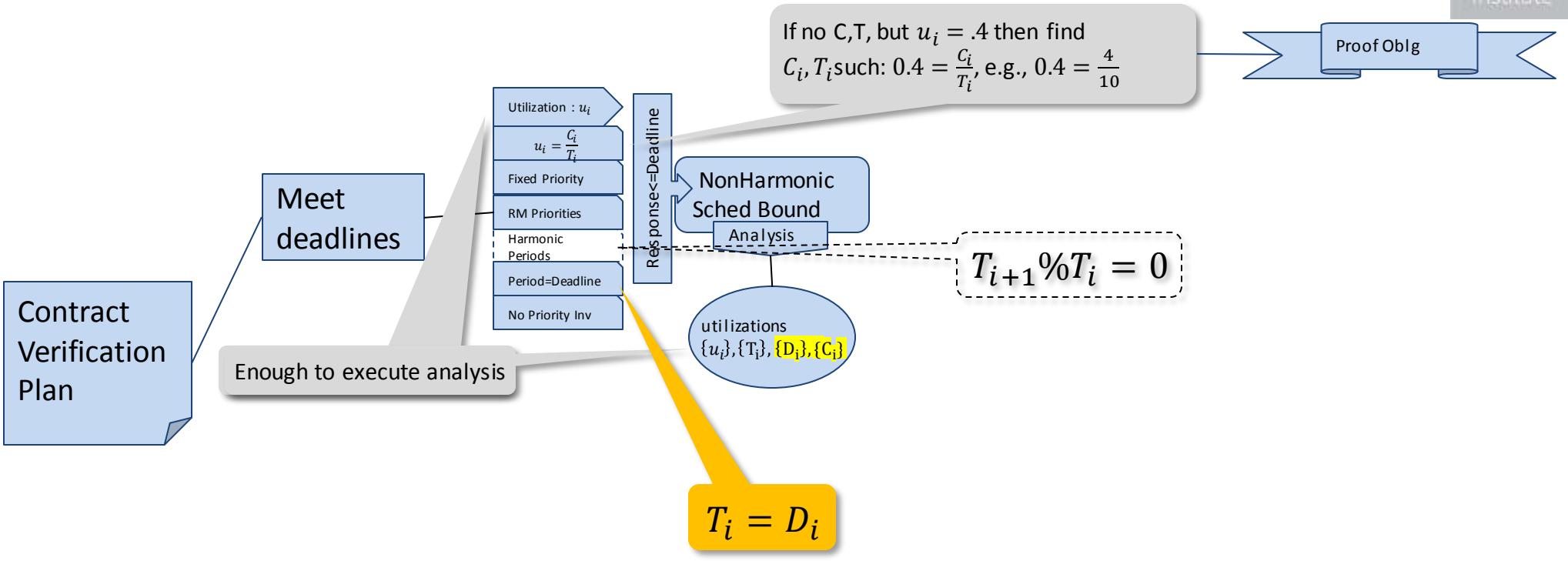
Refinement throughout development (2)



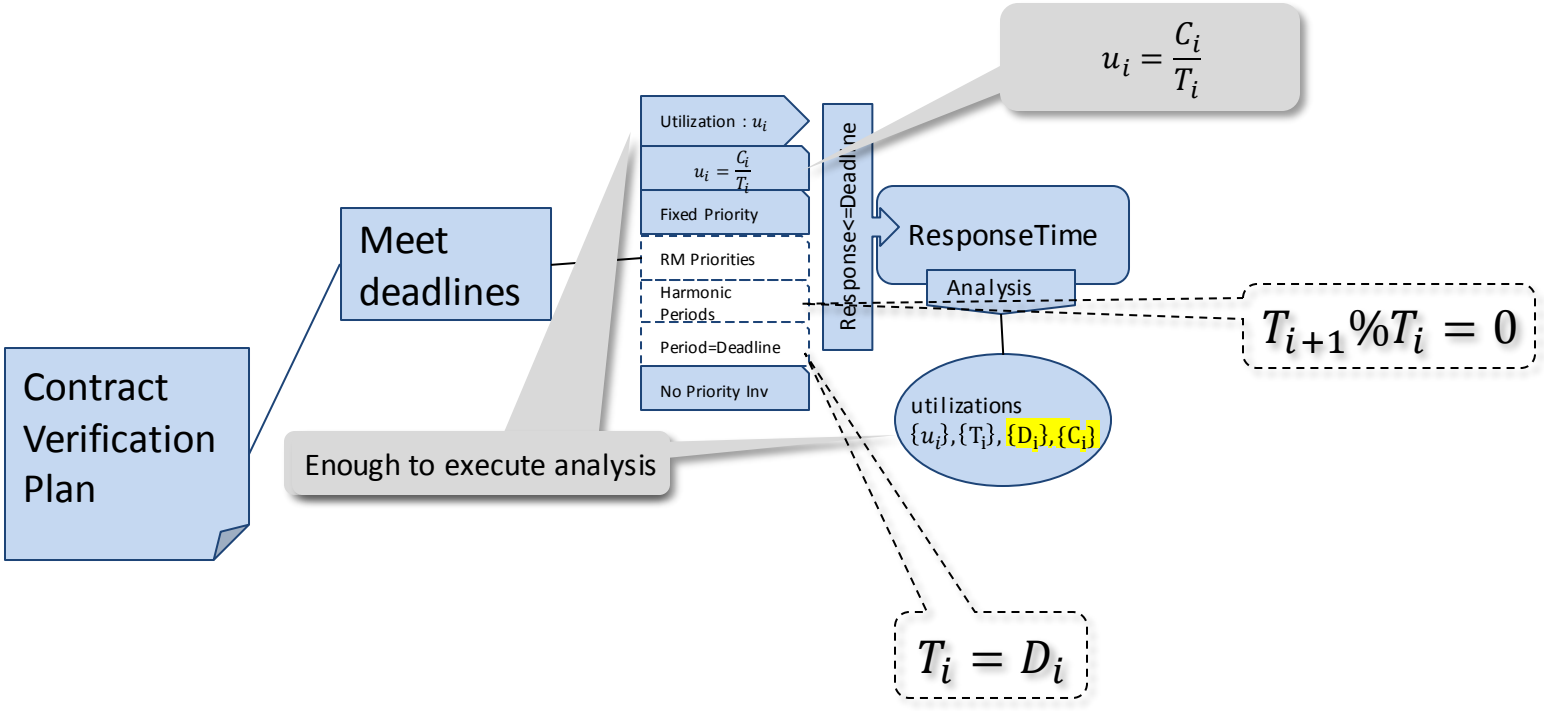
Refinement throughout development (3)



Refinement throughout development (4)



Refinement throughout development (5)



Concluding Remarks

Assurance Argumentation

- For Execution Architectural Models (e.g., AADL)
- Encoded as Constraint-Satisfaction Problem (SMT) for automatic evaluation
- Enables Incremental Refinement
  - unassigned variables take satisfying values (proof obligations)
- Encodes alternative contracts based on refinement/design

Takes Advantage of Previous Analyses Proofs / Efficient Implementations

- Encoded as imperative implementation of predicates over model variables

Currently Experimenting with Avionics Models and Argumentation